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Aquaculture in the Ancient World: Ecosystem Engineering, Domesticated Landscapes, and the First Blue Revolution

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Abstract

Aquaculture is the world's fastest growing food sector and accounts for more than 50% of the world's fish food supply. The significant growth in global aquaculture since the middle of the 20th century has been dubbed by the Blue Revolution. However, it is not the first Blue Revolution to take place in human history. While historically classified as low-ranking, seasonal, or starvation resources in the archaeological discourse, marine foods were vital resources that ancient communities developed and exploited using a vast array of strategies. Among these aquatic strategies was aquaculture. This first Blue Revolution was initiated during the Early Holocene, some 8,000 years ago in China, with archaeologists now documenting aquaculture across the globe. This review considers the commonalities between ancient aquacultural systems including evidence of ecosystem engineering and the development of domesticated landscapes as production systems. People of the past constructed agroecosystems to not only enhance and diversify aquatic resources, but to control the reliability of key subsistence foods and to meet the demands of ritual practice and conspicuous social stratification. These aquaculture systems were maintained for centuries, if not millennia. Worldwide research conducted on ancient aquaculture can provide critical insights into developing more ecologically sustainable, resilient, and diverse marine production systems for coastal communities today, thus, achieving industry sustainability and limiting negative environmental impacts to the world's shorelines and overexploited fisheries.

Keywords Archaeology · Sustainable aquaculture · Historical ecology · Resilience · Ecosystem engineering · Domesticated landscapes

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Introduction

Global fish consumption has been on the rise in recent decades. Since the 1960s, the average annual growth rate of fish consumption (3.1%) has significantly outpaced the annual growth rate of the world's population (1.6%). In per capita terms, the average annual consumption of fish has risen from 9.9 kg in 1961 to 20.5 kg in 2018 (De Silva et al. 2009; FAO 2020; Teletchea and Fontaine 2014). More than 80% of the fish consumed in the world has historically come from marine capture fisheries (Tidwell and Geoff 2001). However, since the intensive fishing of the mid to late 20th century, these fisheries have been in decline and 80% of the world's fish stocks have now reached their maximum capture fisheries potential or are considered overexploited (Pauly et al. 2002; Teletchea and Fontaine 2014). As a result, current wild-caught fishing practices have lost long-term viability (Hutchings 2000; Morato et al. 2006), with experts warning that "fishing capacity will have to be significantly reduced worldwide to ensure sustainable harvests and to maintain biodiversity and ecosystem functions" (Teletchea and Fontaine 2014, p. 182; see also Pauly et al. 2002, 2003). To meet the world's current and increasing levels of fish consumption, fish must be farmed (De Silva et al. 2009; Teletchea and Fontaine 2014).

Aquaculture is the world's fastest growing food sector and has expanded dramatically over the past 50 years to meet the global demand for seafood. Aquacultural production, including finfish, mollusks, and crustaceans, now accounts for more than 50% of the world's fish food supply (Botta et al. 2020; Garlock et al 2020; Kobayashi et al. 2015; Troell et al. 2014). This trend is only increasing, with the estimated global fish supply projected to reach 204 million tons in 2030, an increase of 25 million tons since 2018 met entirely by aquacultural production (FAO 2020).

Currently, the world is faced with a critical challenge of feeding the growing population that is expected to reach 9.6 billion by 2050. Global food and nutritional security must be achieved through increasing sustainable food production, improved nutritional quality of food produced, and reduced food waste in a context where the resources necessary for food production (land, water) are increasingly scarce (Kobayashi et al. 2015). In this challenging situation, aquaculture is becoming an essential food-producing system.

There are many benefits associated with aquaculture, including year-round fish supplies, reduction of pressure on wild fish stocks, and incomes for producers. It can also "provide ecosystem services in the form of wastewater treatment, bioremediation, habitat structure, and the rebuilding of depleted wild populations through stock enhancement and spat dispersal" (Troell et al. 2014, p. 13258). However, the rapid increase in seafood demand since the 1980s has prompted fishery scientists to call for improved industry management, notably to reduce the susceptibility of aquaculture to major disease outbreaks and achieve sustainable seafood economy (FAO 2020; Kobayashi et al. 2015). Concerns regarding the wild-caught fisheries and aquacultural industries have also permeated into modern mainstream culture, with documentaries and exposés receiving extensive popular media coverage (Hamrud 2021; Narula 2021). Notably, intensive aquaculture has been criticized for pollution and destruction of coastal habitats and aquatic ecosystems, increased disease and parasite transmission between farmed and wild populations, the introduction and spread of invasive species (biosecurity threats), increased stress on freshwater resources, depletion of wild fish populations to stock aquaculture operations, and overfishing of wild fish populations for aquaculture feed (Delgado et al. 2003; De Silva et al. 2009; Kobayashi et al. 2015; Naylor et al. 2001; Primavera 2006; Troell et al. 2014). Reducing these negative environmental impacts is a key issue for ensuring long-term sustainability of the industry (Troell et al. 2003).

The significant growth in global aquaculture since the middle of the 20th century has been dubbed by the Blue Revolution. Yet this Blue Revolution is not without historical precedence. While historically classified as low-ranking, seasonal, or starvation resources in archaeological discourse (e.g., Bailey 1975; Cohen 1975; Osborn 1977; Parmalee and Klippel 1974; but see Erlandson 1988; Glassow and Wilcoxon 1988), marine foods are now considered to have played a significant role in the survival and development of early modern humans (Bailey and Milner 2002; Broadhurst et al. 2002; Jerardino and Marean 2010; Marean 2010, 2016; Marean et al. 2007). Indeed, archaeological research has revealed that humans have been foraging for mollusks and catching finfish for at least 165,000 and 140,000–50,000 years, respectively (Henshilwood and Sealy 1997; Jerardino and Marean 2010), and perhaps even longer (Erlandson 2001, p. 306, table 1). Marine foods also may have facilitated human dispersal and expansion out of Africa (Oppenheimer 2009; Walter et al. 2000), through Southeast Asia (Sunda) into greater Australia (Sahul) (Bulbeck 2007; Erlandson and Braje 2015; Erlandson and Fitzpatrick 2006), and across the Americas (Erlandson et al. 2007, 2015, 2019).

Humans developed a vast array of strategies to exploit aquatic resources, including specialized toolkits for fishing (hooks, sinkers, lures, spears, nets) and fish trapping (e.g., weirs, fish traps) and watercraft (Johns et al. 2014; Moss 2013; Pedergnana et al. 2021). Adaptations also included knowledge associated with seacraft construction, navigation, and species-specific ecologies (e.g., processing and consumption of toxic fish such as porcupine and puffer fish, seasonal availability of desirable species) (Anderson et al. 2010; Irwin 1992; O'Connor et al. 2011). Among the aquatic strategies was aquaculture. This first Blue Revolution took place during the Early Holocene, and archaeologists have documented ancient aquaculture across the globe. Given the current difficulties faced by the aquaculture industry, can ancient aquaculture systems, which operated successfully for millennia, provide insight into future directions?

Since the early 2000s, the fields of conservation paleobiology and historical ecology have been rapidly expanding with the aim of sharing insights from paleontological and archaeological data to contribute to present-day issues (Dietl 2016; Rick and Lockwood 2013; Tyler and Schneider 2018, p. 1). These fields contribute the temporal scope and historical perspective that is lacking from the relatively short time spans covered by modern ecological studies to assist them in combatting changing climate, environmental degradation, loss of biodiversity, and overexploitation of resources (Braje et al. 2009; Erlandson and Fitzpatrick 2006;

Jokiel et al. 2010; Morrison and Hunt 2007; Tyler and Schneider 2018). In New Zealand, Wood et al. (2012) used coprolites to reconstruct the diet of the critically threatened kakapo (owl parrot, *Strigops habroptilus*). The authors determined that the kakapo was an important but previously unknown pollinator of the threatened wood rose (parasitic flowering plant, *Dactylanthus taylorii*) and were able to inform on present dispersal and population demography of both species and contribute to conservation and biodiversity planning. Similarly, in Chesapeake Bay (USA), Rick and Lockwood (2013; see also Braje et al. 2009; Garland et al. 2022; Thompson et al. 2020a) tracked abundance, size, and growth rates of eastern oyster (*Crassostrea virginica*) populations from the Late Holocene to modern times. The researchers determined that that premodern oyster populations were significantly more abundant and grew at a faster rate. As oysters are crucial to the maintenance of ecosystems, food webs, and water quality, this research provided an understanding of long-term ecological responses and oyster resilience and a context for effective contemporary conservation and population restoration. Similarly, Reeder-Myers et al. (2022) recently reviewed ancient Indigenous oyster fisheries in Australia and North America that persisted for millennia, detailing the importance of traditional ecological knowledge relating to oyster harvest and ecology. These ancient aquaculture systems that operated successfully for centuries to millennia may provide valuable long-term perspectives on sustainable aquaculture strategies and the societies that maintained them. Here, a system is considered sustainable through the successful long-term production of food for millennia, without wider natural resource depletion.

This paper reviews current archaeological research on ancient aquaculture and considers system functioning (how products were farmed, the issue of domestication), how aquacultural systems arose (intensification versus extensification), and the role of aquaculture in the wider social system (food production, social control, ritual, and symbolic functions). The review prompts a discussion of ancient peoples as ecosystem engineers and developers of early agroecosystems, and considers the knowledge long-term ancient aquacultural fisheries may contribute to present-day food security challenges.

Aquaculture and the Issue of Domestication

Aquaculture is defined as the controlled cultivation (farming) of aquatic plants and animals (Teletchea and Fontaine 2014, p. 189). Farming implies some form of intervention in the rearing process to enhance production, such as regular stocking, feeding, or protection from predators. It also implies an aspect of ownership over the stock being cultivated. Broadly speaking, farmed products are domesticated. Domestication can be defined as that condition wherein the breeding, care, and feeding of organisms are more or less controlled by people (Hale 1969; Liao and Huang 2000). According to Teletchea and Fontaine (2014, p. 185), the indispensable prerequisite to fish domestication is the consistent control of reproduction year after year in successive generations of fish that are maintained and bred in captivity. The fish lifecycle must be fully closed in captivity, independent of wild sources such as eggs, larvae, juveniles, or breeders. However, domestication is not a true requirement or forgone outcome of aquaculture, as many modern aquaculture products have not attained this level of domestication (Teletchea and Fontaine 2014, pp. 185–187).

Malindine (2019) notes that ancient aquaculture generally fails to meet two important attributes used to define domestication, requiring that domesticated species be (1) reliant on humans for survival and (2) genetically unique from wild relatives. Malindine (2019) challenges these prerequisites, arguing instead that early forms of aquaculture represent food production rather than food collection and, therefore, must be considered true aquaculture.

In conceptualizing early terrestrial plant and animal domestication, Terrell et al. (2003, p. 327) similarly considered the conventional requirement of morphological or genetic modification an unnecessary stipulation that would risk "greatly underestimating the generality and force of domestication in the world." Instead, domestication could be measured more effectively by its conduct and characterizing skills rather than by its consequences (Terrell et al. 2003, p. 327), and that domesticating a species is knowing how to harvest it (Terrell et al. 2003, p. 350). Terrell et al. (2003) decried the dichotomy of forager and farmer and the arbitrary point at which one transforms into the other; a similar view should be taken in regard to aquaculture, one where aquatic food production is represented by a range of management behaviors, and there is no transformative point where fishers and gatherers become aquaculturalists. Instead, there were a variety of aquatic production systems around the world that operated within broad subsistence networks.

In this review, aquaculture is present when people are intentionally increasing the survival fitness of target species through environmental manipulation. Survival fitness is considered a quantitative representation of reproductive success and/or survivorship rates to adulthood (or preferred consumption size). This may be done by exerting control over some aspect of target organism's life cycle (e.g., collection and transport of spat [larvae], breeding in captivity), habitat creation, enhancement (e.g., predator exclusion), introduction (e.g., range expansion), or other survival necessities such as feeding. While some instances evidence higher degrees of manipulation and control, these interventions all describe active food production rather than passive food collection.

Teletchea and Fontaine (2014, p. 187) proposed a classification of domestication based on the level of human control over the life cycle of farmed species in captivity. This classification has five levels of domestication with 1 the least and 5 the most domesticated, and level 0 used for wild caught fisheries (Table 1). A domestication classification was assigned to each case to describe the level of control that was exerted over the target species and the skills characterizing the production system (Terrell et al. 2003, p. 327). Level 1 was assigned in cases where only stocking of adults in a created or enhanced habitat had occurred.

Intensification and Extensification

Understanding domestication and skill classification is important for interpreting how and why aquaculture arose through the concepts of intensification and extensification. Here, intensification is defined as the additional input of labor, capital,

Table 1. Domestication classification in fish (Teletchea and Fontaine 2014, table 2) and associated archaeological behavior.

Domestication level	Description	Behavior
0	Capture fisheries (wild caught).	Toolkit (e.g., fishhooks, sinkers, watercraft, processing or preserving material culture).
1	First trials of acclimatization to captivity and the culture environment. It may include the presence in a constructed habitat or feeding.	As above Environment creation or expansion Transfer of adult populations Population management, such as through continued habitat improvement, feeding, and/or removal of predators.
2	Part of the life cycle is controlled in captivity. Generally, “seed” material is collected from the wild and subsequent rearing in captivity to marketable size using aquaculture techniques takes place. “Seed” material can be from early-life stages (larvae, fingerlings) to adult stages. In this level, there are often key bottlenecks that impede closing the life cycle in captivity, such as problems that affect growth, reproduction, and/or immunity. For example, European eel (*Anguilla anguilla*) elvers cannot be maintained in captivity (Liao and Huang 2000).	As above Collection and transplanting of spat/eggs or juveniles into controlled environment.
3	The entire life cycle is closed in captivity, but with wild inputs. Reaching this level requires gonadal maturation and spawning in captivity, control of egg fertilization and incubation, and larval and juvenile rearing. Wild inputs are still regularly used either to avoid modifying significantly the captive individuals from their wild counterparts or to reintroduce genetic variability.	As above Captive breeding within constructed environment Intentional interference in breeding cycle Contribution of wild stock.
4	The entire life cycle is closed in captivity without wild inputs, but no selective breeding program is used.	As above, excluding contributions from wild stock.
5	Selective breeding program is used focusing on specific goals (growth rate, fillet yield, flesh quality).	Physical or genetic change in target taxa Inability or reduced ability of taxa to survive without human interference.

and skills devoted to increasing the output of currently exploited resources within a given area of land (Beaton 1991, p. 951; Brookfield 1972, p. 31, 2001, p. 200). Increased labor input also refers to labor-organization restructuring (Beaton 1991, p. 951). Capital refers to landesque capital, where there are physical structures (a built environment) that require heavy investments and result in permanent improvements to the land (Brookfield 1972, p. 32; Erickson 2006a, p. 348). Skills indicate the technologies that are applied to production and may represent high technological investment, particularly where skills are applied in the creation of capital (e.g., developing water management systems) (Beaton 1991, p. 951; Brookfield 1972, p. 32). Intensification is usually adopted by groups where geographic expansion is constrained by dense populations and/or environmental or social barriers (e.g., inhospitable, land-claiming neighbors) (Beaton 1991, p. 951; Brookfield 1972, p. 31, 2001, p. 200). Extensification is conversely defined as "additional labor and material devoted to the capture of new resources either within or without the estate" (Beaton 1991, p. 951). Extensification is usually adopted by groups who are relatively unconstrained (low population density and/or the opportunity to expand or move geographically) and is visible when new land or resources are used (Beaton 1991, p. 951; Brookfield 1972, p. 31, 2001, p. 200).

The primary purpose of intensification is the substitution of "inputs for land, so as to gain more production from a given area, use it more frequently, and hence make possible a greater concentration of production" (Brookfield 1972, p. 31). For extensification, the absence of increased inputs is offset by a larger absolute scale of production (cultivated land expansion) (Styring et al. 2017, p. 1). Intensification and extensification are not mutually exclusive and may occur together (e.g., Evans et al. 2013; Styring et al. 2017; Tao et al. 2022; Ur 2015). Intensification should not be taken as evidence of hierarchical social structures or state-level control, as heterarchical societies and other alternative organizational structures also practice intensification (Erickson 2006a, pp. 338–340).

Historical Artistic and Textual Evidence of Ancient Aquaculture

Mid-century historians and archaeologists first recognized ancient aquaculture from artistic and textual evidence. In Egypt, tomb paintings and bas-reliefs depicting men fishing in square-edged, constructed ponds indicate the successful farming of fish as early as 2500 BC (Balarin and Hatton 1979; Bequette 1995; Brewer and Friedman 1989; Chimits 1957; El-Sayed 2013, p. 102; Nash 2011, p. 30). More widely accepted tomb relief evidence of aquaculture showing men line fishing for Nile tilapia (*Oreochromis niloticus*) in irrigated ponds dates to 2000–1500 BC (Costa-Pierce 1987, pp. 322–323, fig. 2; Harache 2002; Nash 2011; Teletchea and Fontaine 2014, p. 185). The ancient Mesopotamian civilizations (Sumer, Assyria, and Babylon) also created fishponds. Relief depictions of the Garden of Sargon II dating to 722–704 BC show ponds stocked with fish (Fig. 1) (Dalley 1993, p. 5, fig. 1; Saggs 1962, p. 122). The existence of fishponds in Mesopotamia is further confirmed by written records dating to 422 BC, which describe merchants taxing the public to access fishponds (Nash 2011, p.

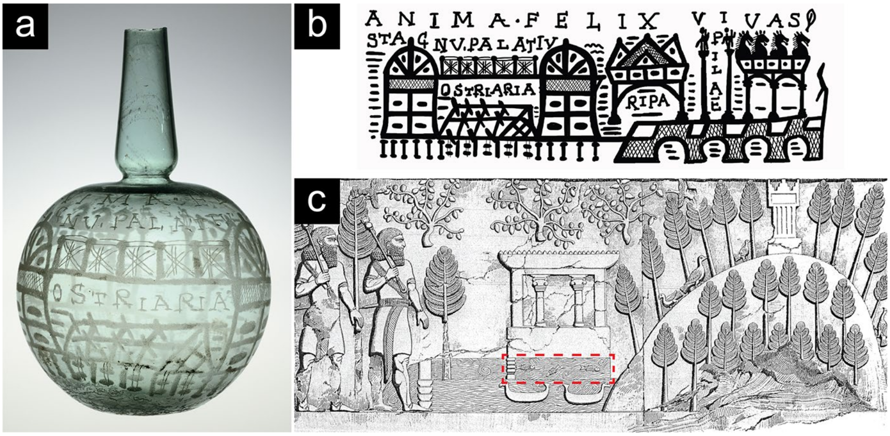

Fig. 1 Ancient artistic depictions of aquaculture: **a** Populonia Bottle (Image: CMoG 62.1.31, The Corning Museum of Glass, Corning, NY (www.cmog.org), under CC BY-NC-SA 4.0); **b** the engraved scene on the Populonia Bottle (Image: Maggie Popkin); **c** relief sculpture of the Garden of Sargon II at capital Dur-Sharrukin, fish in the pond indicated by red-dashed line (Image: Stephanie Dalley; Dalley 1993, fig.1).

16; Yoder 2015, p. 38). Evidence for aquaculture in India is similarly preserved in written records. Nash (2011, pp. 14–15), citing Indian philosopher Kautilya, writes that early occupants of the Ganges and Indus Rivers were using reservoirs to maintain stocks of fish at 300 BC. Descriptions of methods for fattening fish in ponds in India appear later in AD 1127 in King Someshvara III's text, *Manasollasa* (Nash 2011, p. 15). The earliest written evidence of formal fish farming was the prominent textbook, *Yang Yu Jing* (*Treatise on Pisciculture*), written by government bureaucrat Fan Li at approximately 475 BC. This textbook details how to initiate and run a carp aquaculture system (FAO 1983; Li and Mathias 1994; Nakajima et al. 2019) and was thought to have arisen due to the desires of an emperor to have a constant supply of his favorite fish (Teletchea and Fontaine 2014). In Japan, a woodblock print dating to the Tokugawa era (AD 1600–1800) depicts oyster farming with the use of rocks and bamboo branches as substrate (Cahn 1950, p. 10). Oyster farming was also recorded in China during the Han dynasty (270–220 BC), although information is limited (Botta et al. 2020; Hishamunda and Subasinghe 2003, p. 64; Kangmin 2009, p. 243). Lastly, much evidence has arisen from historical texts of aquaculture during the Roman Empire. Cicero, Pliny the Elder, and Diodorus Siculus all described the construction of fishponds (*vivariae piscinae*) in the first century BC across Italy, with massive hydraulic concrete rectangular tanks (identified as fishponds) commonly found in villas of important Romans (Lambeck et al. 2018). Pliny the Elder also described the collection and cultivation of oysters in artificial reefs along coastal southern Italy (*ostrearum vivarium*) at approximately 97 BC (e.g., Lucrinus and Fusaro Lakes, Naples, Gulf of Taranto) (Botta et al. 2020; Günther 1897, pp. 360–361; Nash 2011, p. 21). Oyster cultivation during the Roman Empire is depicted on two preserved vases (Fig. 1) (Günther 1897, pp. 363–364, figs. 1, 2; Jenkins

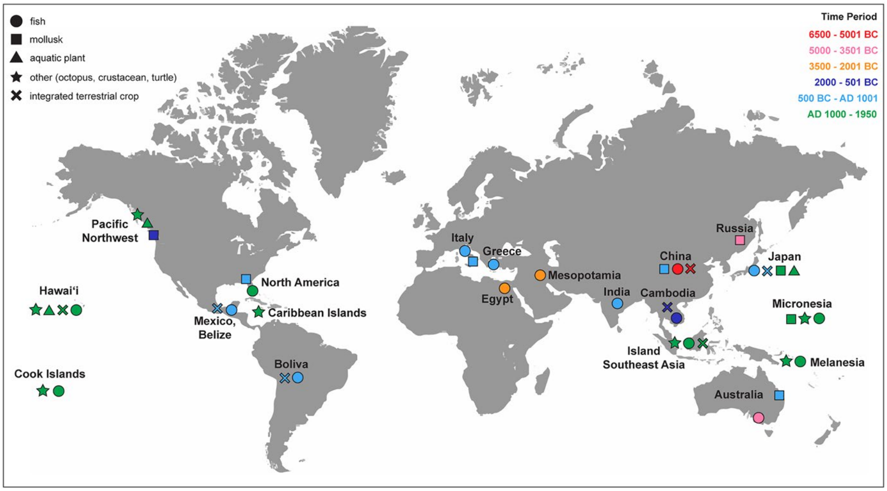

Fig. 2 Regional appearance of aquaculture documented in the archaeological literature (in color online).

2017, p. 75; Popkin 2018, figs. 3, 7). From these early references, historical and archaeological research has greatly expanded present knowledge of ancient aquaculture worldwide (Fig. 2, Table 2, Supplemental file).

Ancient Aquaculture

The review of current archaeological research on ancient aquaculture is presented by geographic region not only to facilitate a comparison of aquacultural systems across time and space, but also to illustrate the current level of research interest regionally. A supplemental file presents all studies in a table, with additional instances of ethnographically described ancient aquaculture not discussed in the text. Dates are reported in the supplemental files as described in the original texts. Dates reported as "before present" (BP) were determined through radiocarbon dating, while other dates may have been ascertained using material culture (culture history period), documentary evidence, or other scientific dating techniques (i.e., 230Th/U coral dating). For the purpose of comparability, calendar (BC/AD) dates are reported in the text, tables, figures, and supplemental materials. All mentioned sites are shown in Fig. 2 and listed in Table 2.

Traps are not included in this review (e.g., fish traps, weirs), which are tidally dependent and designed to capture and hold finfish for a short period of time (e.g., tidal cycle) before they are retrieved by people. Fish traps and weirs are found globally and some have been in use for centuries (e.g., McQuade and O'Donnell 2007). Extensive regional reviews on fish traps have been published elsewhere (Bannerman and Jones 1999; Hine et al. 2010; Langouet and Daire 2009; Mobley and McCallum 2001; Moss 2013; Rowland and Ulm 2011).

Table 2 Timeline and domestication classification of aquaculture primary product type by region.

Location	Calendar date	Domestication classification	Mollusk	Fish	Turtle	Aquatic plants	Terrestrial crop	Other[a]
China	6200 BC	3		X			X	
Australia	4650 BC	2		X				
Russia	4550 BC	2	X					
Egypt	2500 BC	1		X				
Mesopotamia	2500 BC	1		X				
Pacific Northwest	1500 BC	2	X					
Cambodia	920 BC	1		X			X	
Japan	400 BC	3		X			X	
India	300 BC	1		X				
China	220 BC	1	X					
Greece	200 BC	3		X				
Rome	100 BC	3		X				
Rome	97 BC	1	X					
Bolivia	50 BC	3		X			X	
Mexio, Belize	50 BC	3		X			X	
North America	AD 400	1	X					
Australia	AD 750	2	X					
North America	AD 1070	1		X				
Micronesia	AD 1180	2	X					
Island Southeast Asia	AD 1200	1		X			X	X
Hawai‘i	AD 1400	2		X		X	X	X
Pacific Northwest	AD 1479	2				X		
Japan	AD 1600	2	X			X		
Pacific Northwest	AD 1750	1						X
Caribbean Islands	AD 1750	1			X			
Cook Islands	AD 1800	2		X	X			

Table 2 (continued)

Location	Calendar date	Domestication classification	Mollusk	Fish	Turtle	Aquatic plants	Terrestrial crop	Other[a]
Micronesia	AD 1800	2		X	X			
Melanesia	AD 1900	2	X	X	X			

All dates are reported as BC/AD for comparability. Refer to text and Supplemental file for detailed descriptions

[a] Other products are crustaceans (Island Southeast Asia, Hawai‘i) and octopuses (Pacific Northwest)

Pacific Northwest: Clam, Estuarine Root, and Octopus Gardens

Along the northwest coast of America, from Alaska to Washington state, rock-walled beach terraces known locally as "clam gardens" have been identified as ancient systems of clam cultivation (Deur et al. 2015; Lepofsky et al. 2015, 2021; Moss and Wellman 2017; Neudorf et al. 2017; Williams 2006), with clam gardens on Quadra Island, British Columbia, dating to 1550 BC (Table 2, Figs. 2, 3) (N. Smith et al. 2019; Neudorf et al. 2017). At that time, "large settlements increased in number in Kanish and Waiatt Bays, filling all inhabitable coastal landforms and reflecting an increase in local human populations" (Toniello et al. 2019, p. 22110). By constructing clam garden features, First Nations communities created new or increased existing bivalve habitat and, through continued management and maintenance practices, enhanced clam resources (Groesbeck

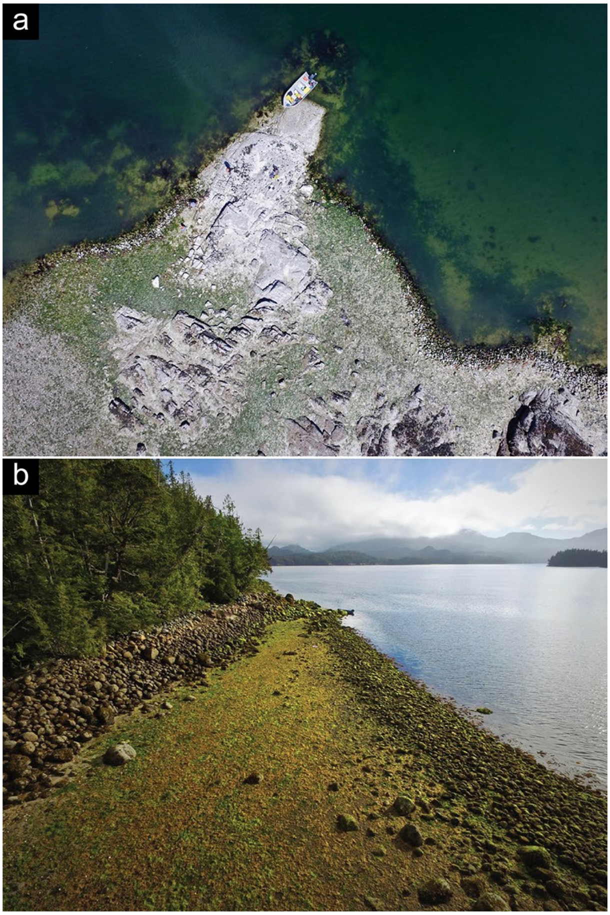

Fig. 3 Quadra Island clam gardens: **a** and **b** extensive rock-walled clam gardens adjacent to the waterline (Images: Keith Holmes—Hakai Institute).

et al. 2014; Lepofsky et al. 2015; Neudorf et al. 2017). Clam garden production focused on butter clams (*Saxidomus gigantea*) and Pacific littleneck clams (*Leukoma* [*Protothaca*] *staminea*), with horse or "gaper" clams (*Tresus nuttallii*) and cockles (*Clinocardium nuttallii*) also harvested from some gardens (Deur et al. 2015; Toniello et al. 2019).

Clam gardens most commonly are composed of a rock wall constructed within the intertidal zone and a flattened terrace on the landward side of the wall (Fig. 3) (Deur et al. 2015; Neudorf et al. 2017). The construction of the rock walls in the lowest intertidal zone functioned to trap loose sediments and, thus, create or expand clam habitat (Neudorf et al. 2017). Indeed, modified clam gardens have been observed to contain a higher abundance of gravel and shell hash content (preferred by clam species) compared to nonwalled beach substrate, which tended to have more fine silt and clay sediments that can smother newly settled larvae (Groesbeck et al. 2014). The construction of the gardens meant that water retention was greater, increasing the opportunity and success of larval clam recruitment and survivorship, essentially functioning to trap and hold clam spat within the garden (Groesbeck et al. 2014). The water retained in the gardens may also have increased in temperature, known to enhance bivalve growth rates and trigger bivalve spawning events (Groesbeck et al. 2014).

Beyond construction of these rock-walled intertidal terraces, a variety of cultivation techniques enhanced clam productivity and abundance (N. Smith et al. 2019). Clam managers created a "substrate-enhanced environment" by adding gravel, shell hash, and whole shells that, taken together with the natural accumulation of coarse sediments in a relatively flat terrace, increased settlement cues for larval clams and oysters (Cox et al. 2019; Groesbeck et al. 2014; Lepofsky et al. 2015, p. 256). This process turned less-productive areas into valuable clam harvesting locations and increased productivity in existing clam habitat. These human modifications created novel and distinct types of soft sediment communities, with taxonomic diversity and density closely correlated with the amount of shell and gravel within each habitat (Cox et al. 2019). Further, clam garden building activities, such as rolling rocks or "turning over beaches" also assisted in reducing anoxic conditions that are less favorable for infaunal species and reduced productivity (Groesbeck et al. 2014, p. 8). Anoxic conditions were further reduced through consistent harvesting behavior that entailed actively digging sediments, causing aeration and fine clays and silt to wash away (Deur et al. 2015). Groesbeck et al. (2014) also hypothesize that predators such as sea stars (*Pycnopodia helianthoides*, *Pisaster brevispinus*), large crabs (*Metacarcinus magister*), and mammalian coastal predators (e.g., river otters, sea otters) may have been intentionally excluded from these gardens to decrease both direct predation and negative nonlethal predator effects on clam productivity. Further, ethnographically recorded traditional ecological knowledge illustrates how consistent harvesting increased clam growth rates, maximum size, and abundance through thinning practices (Cox et al. 2019, pp. 2369–2370; see also Deur et al. 2015; Toniello et al. 2019) and also records the returning of juveniles for later harvesting and/or transplanting (Lepofsky et al. 2015, p. 251). The domestication classification is level 2, where adults live in an artificially constructed and managed environment, and juveniles are transplanted into the controlled environment.

Currently, modified clam gardens encompass twice the biomass and density of unmodified beaches (Jackley et al. 2016; Lepofsky et al. 2015, p. 244), and clam species can be two to four times more productive in clam garden beaches than in nonwalled beaches in the same area (Cox et al. 2019; Leposkfy et al. 2015, p. 244; N. Smith et al. 2019). Transplant experiments by Groesbeck et al. (2014) showed that juvenile clams grew 1.7 times faster and were more likely to survive in clam gardens than nonwalled beaches (Lepofsky et al. 2015, p. 244). Clam gardens also provided enhanced habitat conditions for a range of non-clam marine foods. They contained elevated biomasses of a wide variety of other traditionally important foods, including red rock crabs (*Cancer productus*), sea cucumbers (Holothuroidea spp.), chitons, snails, octopus, and a variety of seaweeds (Holmes et al. 2020, p. 153; Matthews and Turner 2017, p. 184; Williams 2006, p. 85). The enhancement and, to a degree, creation of an artificial ecosystem provided the clam garden managers with not only their primary product but an array of other resources to exploit.

Clam garden construction and maintenance would have required additional input of capital (built environment) and skills (technology) and would have been facilitated through labor-organization restructuring, all evidence of intensification. People may have been spurred toward clam production through social or ecological factors, such as increasing human population, increasingly formal systems of ownership/control, or natural declines in clam populations that had been exploited from at least 7,050 BC (N. Smith et al. 2019, p. 14; Toniello et al. 2019, p. 22110).

Peoples along the Pacific Northwest coast excelled at ecosystem-enhancement aquacultural production. Deur (2000, 2006, p. 319) has recorded cultivated estuarine root gardens in British Columbia, dating a garden site in Clayoquot Sound, Vancouver Island, to approximately AD 1479–1575. Estuarine areas, such as tidal flats and saltmarshes, were modified through soil mounding or rockwork construction to expand productive land (Deur 2000, 2006, p. 311, fig. 11.5). The primary product of these gardens was estuarine plants with edible starchy roots, such as springbank clover (*Trifolium wormskjoldii*), Pacific silverweed (*Potentilla anserina* ssp. *pacifica*), northern riceroot lily (*Fritillaria camschatcensis*), and Nootka lupine (*Lupinus nootkatensis*) (Deur 2006). Waterfowl attempting to eat the cultivated plants could also be caught in traps, contributing a secondary dietary benefit (Deur 2006).

Ethnographically described plant cultivation methods include the seeding or transplanting of propagules, the intentional fertilization or modification of soils, improvements of irrigation or drainage, and the clearing or “weeding” of competing plants such as grasses, rushes, and sedges (Deur 2006, pp. 304, 307, 313–314). The seeding or transplant of propagules classifies this form of aquaculture as level 2, where part of the life cycle is controlled in captivity. Archaeological investigations of estuarine root gardens support ethnographic descriptions, with Deur (2006, pp. 13–14) reporting that managed root gardens, unlike adjacent natural sediments, displayed texturally diverse and structurally amorphous soils that enhanced the size and quality of estuarine roots. This soil profile would be expected in sites that had been subject to regular churning, weeding, and root digging, and are not characteristic of any known natural sedimentary process within saltmarsh environments. Moreover, Deur (2006) reported that laboratory analysis indicated that the gravel and sediments underlying the well-churned soil, on the apparent ancestral beach surface, represented a “buried soil” that had been covered in rapid, singular deposition events.

While currently not highly reported, Pacific Northwest mariculturists also cultivated octopuses (giant Pacific octopus: *Enteroctopus dofleini*) by constructing and managing octopus houses in low intertidal ponds (domestication classification level 1) (Ellis and Swan 1981; Ellis and Wilson 1981; Matthews and Turner 2017, table 9.2; Wilson et al. 2022). These shelters were made by gathering rocks into a circular dome-shaped pile approximately 1 m in height and diameter, simulating the piles of detritus octopuses build when constructing their den (personal communication, Haida Watchmen, 2016; Wilson et al. 2022). The houses had stone doors that could be removed to collect an octopus (Fedje et al. 2010; Wilson et al. 2022). Octopus were the primary target of these constructions; however, the novel rock structure would have provided increased habitat for other intertidal macroinvertebrates and macroalgae, including sea stars, red rock crabs, mussels, sculpins, and a diversity of marine snails including abalone (Wilson et al. 2022).

Octopus houses have been recorded at Vancouver Island and Haida Gwaii, British Columbia (Ellis and Swan 1981; Ellis and Wilson 1981; Fedje et al. 2010; Matthews and Turner 2017, table 9.2). Relative sea level history for these areas suggests that they were constructed within the last 2000 years (Fedje and Mathewes 2005). The octopus houses recorded near the village of Tanu, Haida Gwaii, are presumed to be contemporaneous with village settlement in the mid-1700s AD (MacDonald 1983; Wilson et al. 2022).

North America: Watercourts, Oyster Mariculture, and Chinampas

Outside the Pacific Northwest, evidence of aquaculture in North America is virtually unknown, in contrast to an abundance of evidence for the use of tidal fish traps (Fitzpatrick 2020; Moss 2013; Prince 2014). However, recent research by Thompson et al. (2020b) at the southwest Florida site of Mound Key in Estero Bay provides an example of aquacultural production through habitat creation and containment of adult fish in a controlled environment (domestication classification level 1).

Mound Key was the capital of the Calusa, the most powerful and politically complex polity in Florida by the 16th century AD (Thompson et al. 2020b). The site covers approximately 51 ha and is a complex arrangement of midden mounds (reaching elevations up to 10 m), canals, watercourts, and other features (Thompson et al. 2020b, p. 8374). Thompson et al. (2020b) investigated the creation and use of watercourt features using light detection and ranging (LiDAR), ground-penetrating radar (GPR), sediment coring, and excavation, dating initial watercourt use to corrected AD 1070–1475. Watercourts are lagoon-type features: subrectangular constructions created from shell and other sediments around centralized inundated areas (Lulewicz 2020, p. 109). They are essentially walled enclosures and were connected to the sea by canals. Sediment coring revealed darker, organic-rich mud indicating poor water circulation (that the area was enclosed), thereby confirming it was the result of artificial construction and not natural deposition (Fig. 4).

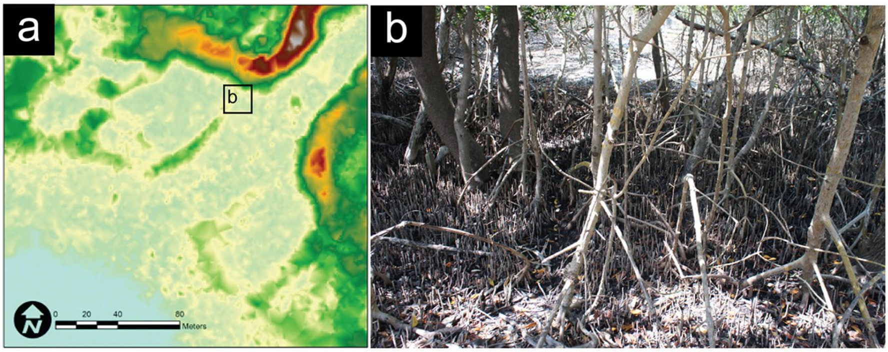

Fig. 4 Mound Key, Florida: **a** LiDAR of the watercourts (insert indicating the location of image b); **b** view southwest to "gate" area of the West Court, now infilled with mangroves (Images: Victor Thompson).

Thompson et al. (2020b) proposed that surplus aquatic captures were stored and managed in the watercourts. The combined size of the largest ones at Mound Key (West and East Courts) were over 6000 m^2, and canals provided ample space for boats to maneuver. Excavations revealed preserved wood chips, cordage, and small postholes, suggesting the presence of fishing-related activities, such as canoe building, fish net manufacturing, and smoking or drying racks (Fitzpatrick 2020; Thompson et al. 2020b). Archaeological fish remains from West Court excavations included high numbers of mullet (*Mugil* spp.), sea catfishes (Ariidae), sheepshead (*Archosargus probatocephalus*), burrfishes (Diodontidae), and gulf toadfish (*Opsanus* spp.) (Lulewicz 2020). Watercourts would likely have been stressful environments. Berms would have decreased exchange with open water, thereby limiting water circulation and dissolved oxygen content, and increased nutrient content within the water that risked excessive primary production and eutrophication (Lulewicz 2020, pp. 140–141). The dominant fish taxa identified at the site would have been able to endure the varying environmental conditions as they occupy muddy or sandy bottoms in estuarine waters and tolerate a range of salinities and dissolved oxygen levels. Notably, toadfish can even survive out of the water for an extended period (Lulewicz 2020, p. 139). The high density of fish remains at West Court, compared to very low densities found in estuary cores away from the site, further support the notion that these watercourts were intended for fish storage and subsequent capture. Overall, it appears that the inhabitants of Mound Key created watercourt habitats to intensify (i.e., store for later processing) the production of mullet and other fish and shellfish (Thompson et al. 2020b).

Unlike the agrarian societies of the interior river valleys of southeastern North America, the Calusa polity did not engage in any type of maize agriculture and relied primarily on aquatic resources for protein (Thompson et al. 2018, p. 30). Fish were the economic base of Mound Key. Aquaculture may therefore have developed to provide and sustain food supplies for a large population (over 20,000 people across 50–60 Calusa communities) through the process of intensification (Thompson et al. 2018, p. 30, 2020b, p. 8375). Intensification, in an area of land previously fished, is indicated by the additional input of (1) capital, represented by watercourt construction and maintenance as a built environment; (2) skills, in the form of technology required to create the capital; and (3) labor-organizational restructuring to create and subsequently maintain the built environment and to exploit the expanded fishing opportunities. Aquacultural intensification at Mound Key may have emerged due to resource depression, documented in the zooarchaeological record as an earlier (AD 500–850) decline in the availability in the number and diversity of fishes (Marquardt 2014; Marquardt and Walker 2013, pp. 878–879). Alternatively, it may have been a response to climatic and environmental stability resulting from the appearance of favorable warm and wet conditions at the onset of the Medieval Warm Period (AD 850–1200) (Marquardt 2014, p. 11; Thompson et al. 2014, 2018, p. 31).

The ability of individuals or groups to mobilize labor to construct monumental structures (e.g., watercourts) and the creation of surplus production are strongly associated with increasingly centralized power and social stratification. Highly complex systems, like the Calusa polity, require a large degree of confidence among participating groups to build and maintain such a system, often gained through food security and surpluses (Thompson et al. 2020b, p. 8380). So, while aquaculture may have developed at Mound Key as a means of producing food for a large population during an environmentally stable time, it simultaneously served to legitimize the social system, centralize power, and contribute to state formation (Thompson et al. 2018).

At Shell Mound (8LV42), a Woodland period site on Florida's Gulf Coast, Jenkins (2017) identified oyster (*Crassostrea virginica*) mariculture. Shell Mound was occupied in three phases from AD 200 to 700. During that time, oysters were added to the arm of a relict sand dune, creating a 7-m-tall U-shaped mound. Mariculture may have taken place in the form of shelling (or clutching), a technique where oyster shells are returned to extant reefs to enhance substrate for larval settlement (Jenkins 2017). As oyster spat settle most readily on smooth flat surfaces of their own species, contemporary oyster reef restoration efforts use recycled oyster shells to implement this technique. Shelling criteria are (1) a higher rate of left to right valves in a sample, and (2) evidence of culling (the removal of dead or small oysters from a harvested clump or burr of oysters) in the form of shells with attachment scars, biofoul such as spat and barnacles, and sometimes sponge parasitism (Jenkins 2017, p. 76). According to Jenkins (2017), there were three distinct levels of oyster management at Shell Mound, with the middle phase (AD 400–550) yielding the most significant evidence of oyster management. This was in the form of high rates of sponge parasitism (49%), attachment scars (72%), and ratio of left (65%) to right (35%) valves indicating artificial reef construction (domestication classification level 1). This period of potential oyster management coincides with the initial phase of mound building at the site. By the end of this phase (AD 550), Shell Mound had become a prominent civic-ceremonial center, characterized by large gatherings, feasting, monumental construction (terraforming), and ritual activity associated with mortuary facilities (Jenkins 2017, p. 77; Sassaman et al. 2016).

Some of Jenkins (2017) criteria for mariculture may be explained through other mechanisms. Differences in valve side ratio can be explained through the different taphonomic stability of each valve, with right valves being more fragile and easily broken. Similarly, sponge parasitism occurs especially in high salinity water, which may be accounted for by changing harvesting locations or environmental fluctuations. Additional research is required to demonstrate evidence of oyster mariculture more comprehensively. Oysters were undoubtedly an incredibly important and intensively harvested resource in North America (Andrus and Thompson 2012; Reeder-Myers et al. 2022; Thompson et al. 2020a). Studies of oyster exploitation, however, have noted that growth in oyster size and long-term sustainability of oyster fisheries could be the result of human management practices and social control (Andrus and Thompson 2012, p. 225; Thompson et al. 2020b, pp. 4–6). According to Thompson et al. (2020b, p. 6), villages, largely dependent on local resources, “likely enacted practices to encourage the health and productivity of near reefs (e.g., perhaps seeding them with old oyster shells).” Further research is required to discern what these resource management practices may have been along the Pacific and Atlantic Coasts of North America and elsewhere across the globe (Thompson et al. 2020a, p. 6).

Integrated wetland agriculture-aquaculture raised field systems have been identified across southernmost North America and Central America (Armillas 1971; Coe 1964; Denevan 1970; Ortiz et al. 2015). In the Basin of Mexico, these systems are known as chinampas (floating gardens), and their development has been dated to approximately 50 BC at Xochimilco, Mexico (Coe 1964, p. 96; Morehart 2012; Morehart and Frederick 2014). Farther south in the Central American lowlands, these systems are known as wetland field systems and date to a contemporaneous period (Beach et al. 2011; Canuto et al. 2018; Dunning et al. 2019). In Belize, the construction of the Maya Birds of Paradise wetland field system has been dated to 190 BC–AD 80 (Beach et al. 2019, pp. 21470, 21473; see also Krause et al. 2019). Prior to the documented appearance of wetland field systems, sea level rise in c. 1000 BC had inundated low-lying landscapes, and settlement and monument building had begun across the Maya Lowlands (1000–400 BC) (Beach et al. 2019, pp. 21470, 21474; Krause et al. 2019, p. 282). The massive built environment that resulted from raised field systems is thought to indicate large populations that were spread over a wide area, with complex, large-scale, and diverse economies (Beach et al. 2019). While many of these systems are associated with complex sociopolitical formations and system-wide control, raised field agriculture does not necessarily depend on centralized political control and can be managed from the bottom up (Luna Golya 2014; Morehart and Frederick 2014).

These intensive raised field systems were in shallow lakes or marshes/wetlands and consisted of elevated, narrow platforms used as fields (about 100 m long by 5–10 m wide: Coe 1964, p. 95), surrounded by water canals connected to ditches (Morehart and Frederick 2014; Ramos-Bello et al. 2001; Torres et al. 1994). Raised field systems were constructed by digging canals and mounding the excavated earth on platforms along with dryland crop silage, silted muck, and manures in precise layers between reed fences (Aghajanian 2007, p. 9; Ebel 2020; Lhomme and Vacher 2002). Aghajanian (2007, p. 9) reported that fast-growing willow trees were planted on chinampas field edges to prevent the erosion of the raised ground and also to provide shade and firewood and restrain crop-damaging pests (Aghajanian 2007, p. 9). Domesticated food crops, such as maize, arrowroot, squash, avocado, and other fruits, were grown on the raised fields, while the canals and ditches contained abundant aquatic resources, including fish, crustaceans, mollusks (e.g., apple snails, *Pomacea flagellate*), blue-green algae, cattails, waterfowl, and salamanders (Supplemental file; Aghajanian 2007, p. 13; Beach et al. 2019; Fedick 1998, p. 123; Rosales-Torres e al. 2022). Puleston (1977) reported that the most common fish remains recovered from the San Antonio (Albion Island, Belize) raised fields were swamp eels (*Synbranchus marmoratus*) and small cichlids (*Cichlasoma* spp.). Water levels and salinity were controlled through a multiplicity of causeways and dikes, which divided the water bodies into compartments (Aghajanian 2007, p. 85; Morehart and Frederick 2014, p. 534). The construction of chinampas and wetland field systems in shallow lakes and marshes likely prevented fish and shellfish taxa from exiting the system, so that the entire life cycle of aquacultural products was enclosed within what was, effectively, large fishponds. For this reason, the raised field systems of the Basin of Mexico and Central American lowlands are classified as domestication level 3 where the system trapped and held breeding organisms and their progeny.

Bolivia, South America: Raised Field Systems and Savanna Ponds

Across ancient South America, aquatic resources (finfish, shellfish, and aquatic reptiles) were of great economic significance (e.g., Béarez et al 2012; Béarez and Lunniss 2003; Garson 1980; Prestes-Carneiro et al. 2016; Stahl 2003), with many archaeological sites located in coastal regions or near large water bodies yielding evidence of aquacultural development (Nash 2011, p. 36). Research in South America has focused on Amazon basin regions, as, during the first millennium AD, these areas were densely populated with villages spread across savanna and forest environments (Erickson 2006b, p. 249; Neves and Petersen 2006; Rocha 2017).

In the Amazon basin of Bolivia (Llanos de Mojos), archaeologists have discovered an organized infrastructure of earthworks that consist of mounds, causeways, canals, and ponds (Erickson and Balée 2006). In the Baures region, Bolivia, Erickson (2000; see also Blatrix et al. 2018) identified one such anthropogenic landscape, characterized by large settlement mounds, earthen causeways, weirs, channels, and raised fields in ponds (forest islands). Erickson (2000; Erickson and Balée 2006; see also Morehart and Frederick 2014, pp. 533–534) dated wood remains in the earthworks to AD 1490–1630, although research in the Amazon area more broadly dates constructions of these features to approximately 50 BC or even earlier (e.g., Carson et al 2016; Duncan et al. 2021; Erickson 1995, 2006b; Schaan et al. 2012). Since approximately 650 BC, the southwestern Amazonian region was increasingly characterized by wetter climatic conditions, rising water tables leading to permanent flooding, and deep, freshwater environments (Duncan et al. 2021). By AD 300, wetlands and floodplains had been established (Duncan et al. 2021).

Fish, such as armored catfish (*Hoplosternum* sp.), tucanare peacock bass (*Cichla monoculus*), piranhas (*Serrasalmus* sp.), and black prochilodus (*Prochilodus nigricans*), as well as freshwater apple snail (*Pomacea gigas*), may have been raised and managed in these features (Erickson 1995, p. 73, 2000). Remains of *Pomacea gigas* have been recovered from pre-Columbian sites in Bolivia and Brazil, indicating that they were a subsistence resource (Erickson 2000, p. 191; Mann 2006, p. 344). These fishponds existed as part of a raised field system, where people actively improved soil drainage and fertility through the incorporation of pottery, burned clay, charcoal, ash, and other organic matter (Carson et al. 2016; Erickson and Balée 2006). Vegetation is commonly associated with fishponds, particularly the cultivation of palms, including the moriche palm (*Mauritia flexuosa)* (Erickson (2000, p. 191; Erickson and Balée 2006, pp. 211–212). These palms are incredibly high yielding: one tree may produce 5000 edible fruits, with ground tissue providing edible starch, edible palm beetle larvae thriving in decomposing trunks, and fibers of the fronds and trunks useful in the manufacture of various items (e.g., basketry, bowstrings, and thatch).

The creation of the ponds and raised fields created important ecotones: transitional areas (i.e., marshland) where two ecological communities—aquatic and terrestrial—meet. These ecotones were vastly productive habitats that attracted birds, reptiles (turtles, crocodilians), and amphibians (Erickson 2000, p. 191; Erickson and Balée 2006, p. 220). The constructed network or channels and fishponds regulated water levels and enhanced resource abundance, as well as providing a means of managing fish and shellfish. Essentially, the people of Baures domesticated the landscape, converting much of their environment into an aquatic farm covering 12,000 km^2 (Erickson 2000, 2010, p. 623).

Blatrix et al. (2018) recently dated a system of these monumental earthworks on the San Joaquín floodplains, Bolivia, to AD 1030–1180 and AD 1310–1424. They found that ponds were significantly spatially associated with weirs and causeways and suggested that V-shaped structures may have been used to channel water into ponds (Fig. 5) (Blatrix et al. 2018, p.3). Ponds would have captured, provided habitat, and stored fish such as swamp eels and armored catfish, constituting reservoirs of fish for people to harvest through much of the dry season (Blatrix et al. 2018, p. 10). This was particularly the case for some taxa (e.g., swamp eel and lungfish, *Lepidosiren paradoxa*) that can survive in just moist sediments (Blatrix et al. 2018, p. 10, fig. 8). Depending on the longevity of ponds, fish in these floodplain systems may have reproduced. Certainly, some fish entered ponds as juveniles and were subsequently raised and managed in water features, indicating a domestication classification of level 2 (Blatrix et al. 2018, p. 10). However, the largest, permanent ponds (10–30 m diameter, 0.5–2 m depth) likely held breeding fish and their progeny (Erickson 2000, p. 191) (domestication classification level 3). Perhaps during periods of high inundation, some taxa could escape or new taxa could enter this system. If so, this would class as "wild inputs" and is still appropriate for this level of domestication classification. Overall, the life cycle of target species would be closed within the integrated agriculture-aquaculture raised field system.

Monumental earthworks have also been documented in drier floodplain/savanna zones of the Llanos de Mojos, Bolivia (Prestes-Carneiro et al. 2019). At Loma Salvatierra, Beni Province, (AD 500–1400), researchers recorded a network of circular walled ponds connected to a system of canals radiating out from a monumental mound (Prestes-Carneiro et al. 2019, figs. 2–4). Loma Salvatierra is associated with the Monumental Mounds culture that emerged toward the end of the Holocene and inhabited the southeastern region of the Llanos de Mojos, at the

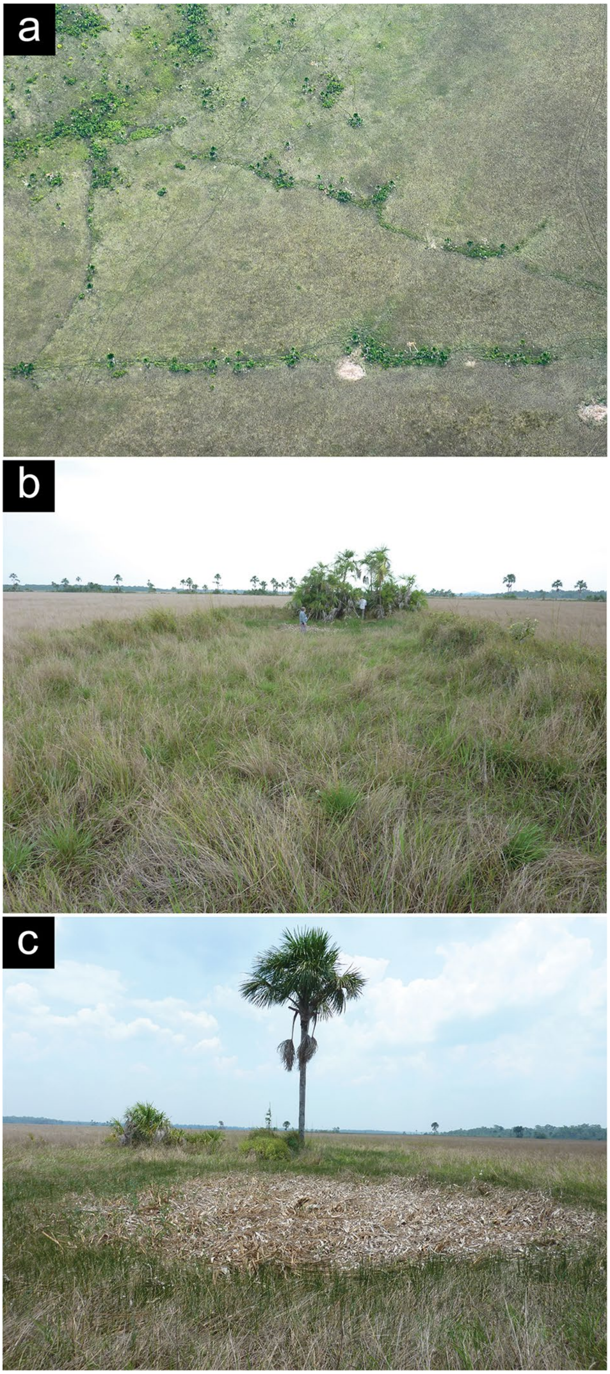

Fig. 5 Pre-Columbian earthworks in the San Joaquín floodplains, Bolivia: **a** aerial view of a V-shaped structure; **b** ground view of a V-shaped structure, looking downstream to dense vegetation growing at the elevated point of the V; **c** ground view of a dry pond (Images: Rumsaïs Blatrix).

right margin of the Mamoré River floodplain. The system of earthworks is located in an interfluvial/savanna environmental setting and likely acted as a funnel, draining rainwater toward ponds and canals during the period of receding waters (Prestes-Carneiro et al. 2019). Canal and pond construction at Loma Salvatierra dates to at least AD 1000–1200.

Prestes-Carneiro et al. (2019) identified over 35 fish taxa from the site, with the dominant fish swamp eels, armored catfish, lungfish, and tiger fish (*Hoplias malabaricus*)—all characteristic of the shallow and stagnant waters typical of temporary pond habitats (e.g., lentic unstable environmental conditions from low levels of oxygen and fluctuating water levels). The assemblage further indicated the likelihood of aquacultural production as these fish were small. Deep water bodies would have been required for the growth of larger fish, while shallower, temporary ponds, like the constructed ponds at Loma Salvatierra, can typically only support small fish. Similar suites of fish taxa in Amazon basin sites have been recorded by Roosevelt (1991) at Teso de los Bichos and Zucchi (1984) at La Calzada de Paez.

Beyond the highly managed, integrated raised field systems and floodplain fishponds of the Amazon basin, other aquacultural systems existed in South America. Stone-walled fishponds on the central coast of Manabí, Ecuador, were likely built during the pre-Columbian Manteño period (AD 750–1532). Recent research by Dubois et al. (2019) revealed that these specialized stone structures functioned as fish traps to catch parrotfish (*Scarus perrico*), lookdown or carita (*Selene* sp.), mullet (*Mugil* sp.), and torpedo sand perch (*Diplectrum* spp.). The authors also suggest a second functionality where the artificial structures would have expanded the reef ecosystem and retained and attracted a greater number of edible species (i.e., urchin, sea cucumber, mollusks, fish). The possibility that seaweed/algae was curated and consumed by humans from these ponds is very likely (Dillehay et al. 2008). The expanded and abundant environment would encourage fish to remain within the stone structures even during high tides that could have facilitated their escape.

Pre-Columbian people heavily modified the savanna and forest landscape of the Bolivian Amazon, creating a complex, highly structured, engineered cultural landscape (Erickson 2006b, p. 247). Raised field systems and floodplain fishponds represent intensification, as they would have required enormous initial investment in monumental earthworks (capital and skills) and continued labor input through landscape management to prevent natural or anthropogenic pond sedimentation and maintain productive systems. These elaborate earthworks evidence widespread integrated agriculture-aquaculture food production that sustained "large dense populations in what many would consider a marginal environment" (Erickson 2000, p. 193). Together, the dense populations and built environment attest to the development of large, sedentary societies in the region (Prestes-Carneiro et al. 2019). Prümers et al. (2022), using LiDAR in the Llanos de Mojos savannah, revealed civic-ceremonial architecture including stepped platforms, rectangular platform mounds, and conical pyramids belonging to the Casarabe culture (AD 500–1400). This degree of formalized infrastructure implies the presence of low-density urbanism in the Llanos de Mojos region (Prümers et al. 2022). Urbanism and social stratification through ownership rights (Stanish 2004) is indicative of societies with high degrees of institutionalized control and complexity.

Australia: Budj Bim Eel Aquaculture and Moreton Bay Oyster Farming

At Budj Bim Cultural Landscape, Mt. Eccles lava flow, southwest Victoria, Australia, the Gunditjmara people actively manipulated hydrologies and ecologies to enhance accessibility and production of desirable resources. This was done using basalt boulders to construct artificial water control structures, such as channels, weirs, barriers, dams, and traps, across 40 km of lava flow to the ocean (Builth 2014, 2016; Builth et al. 2008). These features regulated and extended wetland habitat to facilitate the production and management of the kooyang or shortfin eel (*Anguilla australis*) (Builth et al. 2008, p. 413; Crook et al. 2014; Richards 2011; Rose et al. 2016; see also Lourandos 1980a; Malindine 2019, p. 67).

McNiven et al. (2012, 2015; A. Smith et al. 2019) dated initial construction of the stone-walled Muldoons Trap Complex located on the southwest edge of Tae Rak (Lake Condah), Budj Bim, to 4650 BC, contemporary with palynological evidence from the region for increased precipitation (Bowler 1981; Jones et al. 1998) and maximum Holocene water levels (Builth et al. 2008, p. 422). The link to aquaculture at 4650 BC is based on the construction of artificial channels to alter eel habitats through controlled manipulation of local hydrologies and eel movements to aid capture (Fig. 6).

The Budj Bim Cultural Landscape was continuously inhabited by the Gunditjmara after the eruptions of Mt. Eccles and Mt. Napier (c. 18,000–28,000 BC) and during the subsequent formation of Lake Condah around 9000–6000 BC (Builth et al. 2008; Rose et al. 2016, pp. 590–592). The Gunditjmara constructed closely grouped dry-stone houses from basalt rocks and inhabited them on a permanent to semipermanent basis (Clark 1991). Population levels were high, and the eel fishery provided an abundant source of food that may have also been smoked for storage (Builth 2002; Builth et al. 2008; Clark 1991). According to Wettenhall with the Gunditjmara (2010; see also Rose et al. 2016, p. 592), eels were a valuable trade commodity at large, intergroup meetings (up to 1000 people). Ethnohistorical observations at European contact record an economy based on complex exchange systems (Builth 2002, p. 7; Lourandos 1980a, b, 1991).

The enormous landscape modification at Budj Bim resulted in artificial spatial expansion and temporal extension of wetland ecosystems (Builth 2014; McNiven et al. 2012, pp. 44–45). This wetland enhancement regulated and augmented eel production by allowing juvenile eels (elvers) the physical means to reach suitable, expanded wetland habitats and, as eels are catadromous fish, also allowed the means to return to the ocean to spawn (Builth 2016, pp. 12, 16). Once in the system, young shortfin eels were contained and grown in anthropogenically modified waterbodies, creating a long- and short-term eel fishery where the management of elvers was an investment in their future production. Furthermore, suitable expanded environmental conditions ensured greater numbers of adults for spawning (Builth 2016, p. 12;

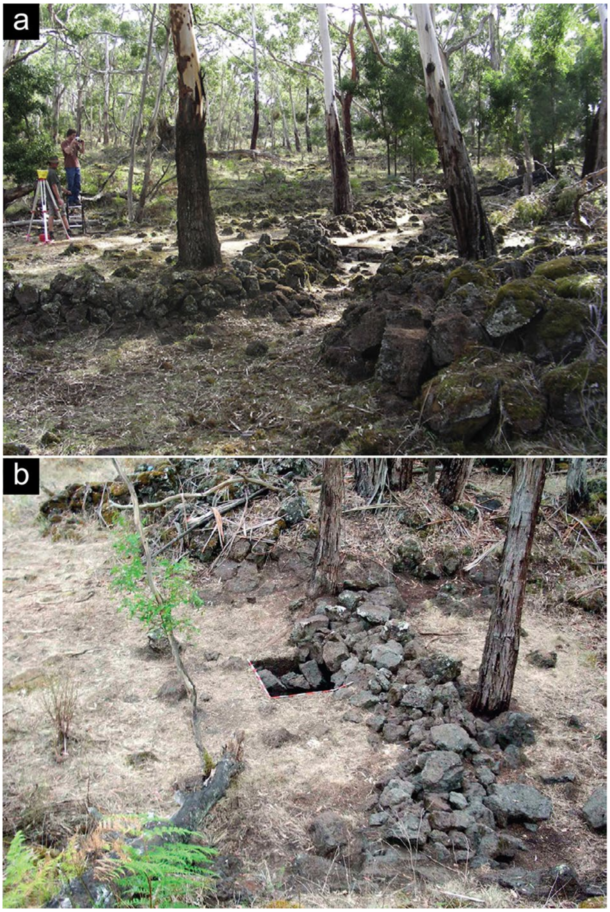

Fig. 6 Muldoons Trap Complex, Budj Bim Cultural Landscape: **a** funnel entry; **b** barrier/dam feature (Images: Ian J. McNiven, used with permission of the Gunditj Mirring Traditional Owners Aboriginal Corporation).

McNiven et al. 2012, pp. 44–45). As this system involved controlling a part of the eel life cycle (movement of juveniles into captive environment), it is classified as domestication level 2. This system not only ensured perennial availability of younger eels, but habitat expansion would also have ensured greater availability of other wetland resources including freshwater fish, such as tupong (*Pseudaphritis urvillii*) and common galaxias (*Galaxias maculatus*), and swamp vegetation, such as tubers, corms, and roots of reeds, beyond their normal seasons (Builth 2016, pp. 4–5; Builth et al. 2008, p. 414; Rose et al. 2016). Builth et al. (2008, p. 414) also suggested that the extensive system of channels would have "…countered rainfall variability by facilitating controlled drainage in periods of heavy rainfall and retaining water during dry periods. The system would have therefore contributed to the stability of the economy and population." In addition, downstream migrating eels in autumn would have been highly nutritious, containing at least 55% greater fat content compared to feeding eels (Builth 2016, p. 11). This anthropogenic system facilitated the easy capture of shortfin eels (juveniles and adults) throughout the year (Builth 2016, pp. 4–5, 16; Builth et al. 2008, p. 414; McNiven and Bell 2010; Rose et al. 2016).

As the Gunditjmara were already inhabiting the area and exploiting eel and other wetland resources, development of this aquaculture system strongly indicates the process of intensification. The enormous landscape modification that took place would have required additional input in terms of capital, skills, and labor to an area of land already under exploitation. The construction of artificial channels indicates investment in landesque capital and skills (technology) that permanently made the land and associated waterways more productive. This would have required additional labor for system construction and maintenance and exploitation of an expanded area. Interpretations of intensification here may have some overlap with the concept of extensification. Certainly, by expanding productive wetland environments, previously unused land was being brought into production. However, it was the improvements to capital (through investment) that facilitated the enlargement of arable land and, here, still falls under the category of intensification (Brookfield 2001, p. 20). Other evidence of landscape modification for eel habitat extension and trapping in this region has been recorded at Toolondo (Lourandos 1976, 1983, 1997; Richards 2011), Bessiebelle (Williams 1988), and The Morass (Nekeeya Swamp) (Williams 1985, 1988).

At Peel Island, Moreton Bay, southeast Queensland, Ross et al. (2015; Ross with members of the Quandamooka Aboriginal Land Council 1996; see also McNiven et al. 2021, pp. 19–20) has documented a tradition of oyster farming since at least AD 750. Archaeological evidence indicates that Aboriginal people have lived in Moreton Bay for at least 20,000 years, with the subsistence economy principally based on marine resources (Neal and Stock 1986; Ulm 2002), and populations are thought to have become semisedentary from the early- to mid-Holocene (Smith 2016, p. 222).

The dominant taxa (oysters [*Saccostrea* sp.] and mussels [*Trichomya hirsuta*]) in the Peel Island midden demonstrated considerable temporal variation in abundance, with one or the other increasing or decreasing in abundance at various points (Ross et al. 2015, pp. 181–183). Ross et al. (2015) determined it was unlikely that environmental influences or numerous cultural effects sufficiently explained mollusk patterning. Using oral history and collaborating with the Dandrabin-Gorenpul of Quandamooka, the authors instead concluded that oyster populations were farmed. Aquacultural strategies for oyster management included moving small individuals into optimal growth conditions in deeper water to encourage growth and increase fat content, restocking depleted oyster beds from neighboring reefs, and the construction of artificial reefs (islands) using old oyster shells to extend oyster habitats (McNiven et al. 2021, pp. 19–20; Ross et al. 2015, p. 187). Variation in the discard rates of oysters was interpreted as evidence of oyster abundance (when remains are discarded at the site) or reef maintenance (when remains are used to rebuild artificial oyster reefs) (McNiven et al. 2021, pp. 19–20; Ross et al. 2015, p. 187). This oyster industry is classified as domestication level 2, as it displayed control over a part of the life cycle by the collection and transplanting of juveniles.

During the Holocene marine transgression, the rocky land mass of Peel Island would have been a high point on the Moreton plain and a prominent island at varying times of low and high sea level, respectively (Ross et al. 2015, p. 178). Sea level at Moreton Bay stabilized by 50 BC, almost 1000 years prior to the establishment of the Peel Island midden (Ross et al. 2015, p. 183), although southeast Queensland climatic and environmental conditions became more variable around 550 BC–AD 450 (Smith 2016, pp. 205–206). The last 1000 years are associated with a dramatic increase in the establishment of sites in southeast Queensland, possibly reflecting a reordering of land use, permanent coastal occupation, socioeconomic reorganization, and increased population pressure or population variability (McNiven 1999; Ulm and Hall 1996, see also Smith 2016, pp. 215–220). It is in this context of climatic and environmental instability and increasing coastal occupation (possibly increasing sedentism) that oyster mariculture emerged in southeast Queensland. Cultural landscapes and ecosystem modification to enhance resources is beginning to be widely recognized across Australia. McNiven et al. (2021) recently summarized a range of terrestrial and aquatic enhancement practices, where Aboriginal Australian groups modified ecosystems using intimate knowledge of local ecological processes.

China: Integrated Rice-Fish Farming

In China, aquaculture for raising common carp (*Cyprinus carpio*) in artificial fishponds was thought to have taken place as early as 3500 BC (Fagan 2017, p. 212; Malindine 2019, p. 66; Nash 2011, p. 11; Parker 2002, p. 6; Spalding et al. 2013). However, Nakajima et al. (2019) have recently dated archaeological evidence for Chinese aquaculture at the Early Neolithic site of Jiahu in Henan Province to 6200–5700 BC (Jiahu culture period III). The authors compared reconstructed body lengths from archaeological specimens at Jiahu to measurements of modern carp raised in a traditional rice-fish farming system and found that rice-fish systems produce a single-species concentration of smaller fish with bimodal body length distributions, indicating the presence of both immature and mature individuals when water was drained from ponds and fish were harvested (Nakajima et al. 2019). This pattern differs greatly from wild fish populations and earlier archaeological assemblages (Nakajima et al. 2012, 2019). The authors suggested that the Jiahu inhabitants managed water levels using ponds and ditches to encourage natural spawning and to allow control of mass harvesting of fish. Further, the archaeological remains of fish, freshwater mussels, turtles, water chestnuts, and lotus nuts at the site may indicate that system integration was also beginning at this early time (Nakajima et al. 2019). The appearance of aquaculture in China corresponds with a warm, wet climate (Early Holocene Optimum, 6050–5850 BC) and lake high stands between 6550–3550 BC (Chen et al. 2005; Feng et al. 2004, p. 152; Zhuang and Kidder 2014, p. 1605). The Early Holocene in China is characterized by rapid population expansion, increased landscape management, and domestication of crops (Chen et al. 2005; Zhuang and Kidder 2014). Land use and economic intensification were closely linked to changing sociopolitical organization, and labor management would have played a central role in this process, including the construction of large-scale water control systems that increased the economic investment in carp aquaculture (Zhuang and Kidder 2014).

The earliest written evidence of aquaculture in China dates to 1400 BC, where there are records of criminal prosecutions of fish thieves (Spalding et al. 2013). Records dating to approximately 1112–221 BC) detail the keeping of fish in captivity (Nash 2011, pp. 12). The *Yang Yu Jing* by Fan Li details pond layout, construction and maintenance, carp breeding and broodstock selection, and fry and fingerling rearing techniques (Liao 2000; Nash 2011, p. 13; Spalding et al. 2013). As captive breeding took place within a constructed environment, the system is classified as domestication level 3, as the entire life cycle is closed in captivity. Fan Li also describes how some ponds featured artificial depressions where carp would segregate themselves by size (Fagan 2017, p. 213). Fan Li is said to have planted mulberry trees along his fishponds that supported silkworms for silk production and also fed goats. Carp were, in turn, fed silkworm casings (Fagan 2017, p. 213; Malindine 2019, p. 66) (Supplemental file).

Other contemporaneous written records dating to the Han dynasty (206 BC–AD 220) describe farmers growing rice, lotus, marine algae, foxnut, and water chestnut for human consumption and also to feed herbivorous fish (Drews 1951, pp. 2–3; Edwards 2004, p. 24). Turtles may also have been cultivated in these artificial ponds (Fagan 2017, pp. 213–214), as evidenced by a red pottery model of an intact rice field recovered from a Han tomb at Lao Tao Si, Mian Country, Shanxi Province (dela Cruz et al. 1992, p. 18). The model contained 18 pieces of miniature pottery that depicted aquatic plants and animals, including lotus flowers, lotus leaves, lotus seeds, water chestnuts, duckweeds, soft-shelled turtles (*Trionyx sinensis*), grass carp (*Ctenopharyngodon idella*), and goldfish (*Carassius auratus*) (dela Cruz et al. 1992, p. 18; Edwards 2004, p. 24; Guo 1985).

Fish were an essential part of the integrated agriculture-aquaculture system. Historical records describe fishermen of Guangong Province releasing small grass carp fry into rain-flooded rice fields to clear the area of weeds prior to cultivation during the Tang dynasty (AD 618–907) (Fagan 2017, p. 215; Lin 1991, p. 2). This method reduced undesirable weeds, fertilized the fields, and produced fish (dela Cruz et al 1992, p. 18). Research by Xie et al. (2011; see also Lansing and Kremer 2011) on contemporary rice-fish farming indicated that the presence of the fish benefits the rice by reducing insects, diseases, and weeds. The researchers reported that the insect removal rate was increased greatly by fish bumping rice stems, which led to insects falling into the water. The bumping activity of fish also caused moisture to be shaken off plants, reducing the risk of spore generation and mycelium penetration of rice blast disease in the leaves. Further, the carp eat or uproot many weeds, resulting in an almost weed-free paddy. The rice is also beneficial to the fish by attracting insects as a fish food source, providing shade that reduced water temperature in hot seasons, and acting as a nitrogen sink and reducing ammonia concentrations in the water (Xie et al. 2011; Lansing and Kremer 2011). The rice-fish polyculture employed by ancient aquaculturists in China exploited the synergies between species to produce a highly productive and healthy system (Supplemental file).

During the Tang dynasty, Chinese fish culturalists began to cultivate several carp species whose wild fry could be easily obtained in the large rivers and transported in bamboo baskets to be reared in ponds in fine-meshed cloth cages, safe from predation (Balon 2004, p. 3; Beveridge 2004, p. 6; Drews 1951; Edwards 2004, p. 24; Li and Mathias 1994, p. 11; Liao 2000; Nash 2011, p. 15). These species included silver carp (*Hypopthalmichthys molitrix*), bighead carp (*Aristichthys nobilis*), black carp (*Mylopharyngodon piceus*), and grass carp (*Ctenopharyngodon idellus*) (Li and Mathias 1994, p. 12; Liao 2000, p. 110). The polyculture of numerous carp species is still practiced today in China (FAO 1983, p. 19, table 7), where farmers report that incorporating filter-feeding species, such as bighead carp and silver carp, into the system reduced excessive growth of phytoplankton induced by intensive pond culture, thereby improving water quality (Edwards 2015, p. 7). Grass carp may also have functioned as a trash fish to feed silver carp and bighead carp (Edwards 2004).

Japan: Farming Rice, Fish, Oysters, and Seaweed

The system of rice-fish farming flourished in China and spread into Japan and Southeast Asia. Emperor Suinin (29 BC–AD 70) has been credited with having built the first fishponds in Japan and establishing rice-fish systems with the common carp (Drews 1951, pp. 62–63; Edwards 2004). However, Nakajima et al. (2010, 2019) argue that Japanese cyprinid management began earlier than previously thought. Using the same criteria applied to the Neolithic fish assemblage from Jiahu, China, the authors identified a bimodal body length distribution and taxonomic focus on carp at the Iron Age Yayoi culture Asahi site. Nakajima et al. (2019) hypothesized that, by the Middle Yayoi period (~400 BC–AD 100), intensive aquaculture was taking place. This intensive system may have included human control over reproduction and specialized holding facilities such as fishponds or paddy fields (domestication level 3) (Nakajima 2006).

The Yayoi period is characterized by (1) paddy-field rice agriculture, (2) the procurement and manufacture of bronze and iron tools, (3) exchange and diplomacy with Korea and China, and (4) the emergence of social stratification, political bodies, large regional centers, and warfare (Nakajima et al. 2010; Nakao et al. 2020). In contrast, the preceding Jomon period (12,000–300 BC) was characterized by a hunter-gatherer-fisher economy and a sedentary lifestyle. Carp were a major resource that were captured in large numbers during spawning season and may have been smoked and dried (Nakajima et al. 2010; Uchiyama 2007). Much of the Final Jomon period (~1000–300 BC) is associated with lower population densities and repeated cooling that may have promoted the formation of tidal flats (Imamura and Fujio 2009; Nakao et al. 2020). Warming temperatures around the end of the eighth century BC corresponded with an increase in the population growth rate and high population densities (Crema and Shoda 2021, pp. 19–20; Nakao et al. 2020, p. 370). Nakajima et al. (2010) proposed that fish cultivation started as a by-product of artificial water control in the rice paddy fields characteristic of the Yayoi period in Japan. The cooling climate and associated expansion of low-lying alluvial land likely played a role in the implementation of rice-fish paddy farming. Much as in China, the development of aquaculture in rice paddy fields in Japan strongly indicates intensification, where a utilized area of land received increased inputs to increase productivity of an exploited resource.

Centuries later, during the Tokugawa era (AD 1600–1800), records of aquaculture in Japan increased dramatically, describing polyculture fishpond cultivation of striped mullet, carp, and eel (Drews 1951, pp. 67–68, 74), seaweed farming through construction of artificial substrate (Buchholz et al. 2012; Tamura 1966), and oyster farming through substrate creation within the intertidal zone of shallow water bays and inlets, possibly also to culture pearls (Cahn 1950, pp. 10–11, fig. 1; Tamura 1970, p. 9, fig. 18.2).

Greater Angkor Region, Cambodia: Rice-Fish Farming and Spiral Mound Ponds

In Southeast Asia, raised field-fishpond systems and rice-fish systems may have been used in the Greater Angkor region in northwestern Cambodia for millennia. Excavations of the Koh Ta Meas necropolis (920 BC) near Angkor revealed significant quantities of fish bones, with identified fish remains belonging to a relatively few species that are all fished in rice paddies today, possibly indicating that the people of Koh Ta Meas engaged in rice-fish cultivation (Frelat and Souday 2013, pp. 5, 12). Isotopic and archaeological investigations have revealed that fish were the main source of protein in people's diets in this region (Ikehera-Quebral et al. 2017). The chronology of Koh Ta Meas is associated with the appearance of regional settlement hierarchies and emerging sociopolitical complexity in Mainland Southeast Asia (Ikehera-Quebral et al. 2017). It also corresponds with relatively warm East Asia conditions (~AD 1–300), followed by cooler conditions in the subsequent centuries until approximately AD 900, when the temperature increased (Zhang et al. 2018).

During the first millennium AD, highly urbanized temple cities with dense populations developed across the Greater Angkor region and, from the sixth century AD, aquacultural systems may have been widespread (Evans et al. 2013, p. 12597; Stark et al. 2015, pp. 1444, 1452). LiDAR imaging of this region has revealed an enormous, engineered landscape (over 1000 km^2) of hydraulic infrastructure, including artificial reservoirs, canals, ponds, and bunded rice fields (Fig. 7) (Evans et al. 2013, p. 12596; Klassen and Evans 2020; Fagan 2017, pp. 220–221; Hanus and Evans 2016). These sophisticated water management technologies would have stabilized food production and rice yields (Evans et al. 2013, p. 12599; Latinis et al. 2018). An intensive, state-level system of water management is particularly evident at Angkor Wat, where the major shrines lie at the center of a huge network of channels, embankments, and reservoirs that managed, stored, and dispersed water down through the city (Evans et al. 2013, p. 12596; Fagan 2017, p. 220).

Ponds were a permanent urban feature associated with village shrines and irregularly shaped mounds (Evans et al. 2013; Stark et al. 2015, pp. 1444, 1452). The building of these ponds was highly formalized during the 11th and 12th centuries AD (Evans et al. 2013, pp. 12,596–12,597), although their construction emerged at least by the sixth century AD (Stark et al. 2015, pp. 1444, 1452). It is thought that the purpose of these urban ponds was to provide access to freshwater for several households, particularly during the dry season (Stark et al. 2015, pp.

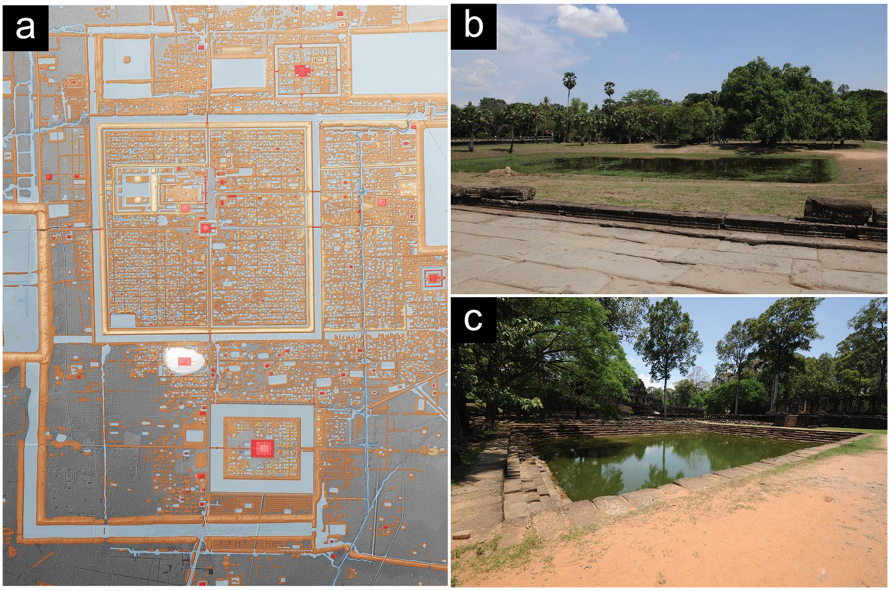

Fig. 7 Greater Angkor region earthworks and hydrological control features: **a** archaeological map of central Angkor over LiDAR terrain model (Image: Damian Evans, Christophe Pottier, and Pelle Wijker - Khmer Archaeological LiDAR Consortium); **b** reservoir at entrance to Angkor Wat (Image: Larry W. Mays; Mays 2015) **c** pond at Angkor Thom (Image: Larry W. Mays; Mays 2015).

1444, 1452). The mound-pond pattern changes near the major Angkor Wat shrine, where the raised mounds resemble "spirals" with water channels in between (Evans and Fletcher 2015, fig. 8). There are numerous hypotheses to explain the relationship between these unusual spiral mound ponds. One hypothesis suggests they constitute a raised field system in which the water channels provided lotus products for temple rituals and the mounds supported sandalwood trees (Evans and Fletcher 2015, p. 1414). Fish were culturally important in ancient Angkor, particularly snakehead murrel *(Channa striata*), where they were placed in ceramic pots used as mortuary offerings in burial contexts (e.g., Vat Komnou burials, Phum Snay burials) (Ikehera-Quebral et al. 2017; O'Reilly et al. 2006, p. 202).

The Angkor Borei site, located in the upper portion of the Mekong River delta, was also characterized by terraces, channels, and swamps. The residents of Angkor Borei supplemented these natural water features by constructing canals and reservoirs during the settlement's peak occupation (prior to 5th/6th century AD) (Bishop et al. 2003, p. 387; Ikehera-Quebral et al. 2017, p. 194). Fish remains at the site came from fresh- and brackish water drainages and ponds (Ikehera-Quebral et al. 2017, p. 194), and included snakehead murrel, climbing perch (*Anabas testudineus*), black skin catfish (*Clarias meladerma*), giant snakehead (*Channa micropelte*s), Asian red rail catfish (*Mystus nemurus*), and swamp eel (*Monopterus albus*) (Ikehera-Quebral et al. 2017, table 3). The numerous water features at Angkor Borei would have buffered the region's inhabitants from environmental instability by providing a reliable supply of water and fish (Ikehera-Quebral et al. 2017, pp. 226–227).

In the human-engineered agricultural and aquatic landscape of the Greater Angkor region, it is certainly possible that ponds in a raised field system were used to hold fish. Fagan (2017, p. 221) suggests that carp and catfish were trapped and netted at Angkor Wat and Angkor Thom and then fattened (domestication classification level 1). The enormous investment required to construct, maintain, and exploit the expansive hydraulic systems certainly evidences intensification, which would have greatly increased fish resource yield in the area.

Evidence of early fish farming in Vietnam has been hinted at by Mien and Ha (2009) who investigated the geoarchaeology of the northeast coastline of Vietnam. They describe small artificial hills in the tidal flats of Ha Long Bay that are several hundred square meters and about 2–4 m high that likely were used in cultivation and fish farming (i.e., earthen pond creation). They dated the feature using marine transgression records to the Ha Long period (3050–1050 BC). The extensive coastal intertidal flats in the Yen Mo and Thy Nguyen districts and also along the coast in Quang Yen, Hai Ninh, and Quang Ha would also have been advantageous areas for cultivation and fishpond farming (Mien and Ha 2009, p. 58). Further research is required to establish the use of these earthen ponds as aquaculture systems.

Between AD 1200 and 1400, fishermen in Island Southeast Asia (Indonesia, Malaysia), developed their own systems of aquaculture. Brackish-water fishponds are thought to have evolved naturally along with salt making in the coastal areas (Ling 1977, p. 7; Lovell 1989, p. 1; Schuster 1952; Nash 2011). Fish were caught and transferred to shallow earthen ponds (tambaks) around shorelines and estuaries. The tambaks were filled with sea water for salt production. However, during the rainy monsoon seasons they became natural ponds and were used to grow fish, especially milkfish (*Chanos chanos*), mullet (*Mugil cephalus*), and shrimp species (domestication classification level 1) (Brown and Prayito 1987; Liao 2000, p. 110; Ling 1977; Lovell 1989, p. 1; Nash 2011, pp. 29–33). In a law code from Java, Indonesia, named “Kutara Menawa,” dating to AD 1400, punitive measures were laid down against those who steal from a freshwater pond (siwakan) or a saltwater pond (tambak) (Brown and Prayito 1987; Schuster 1952). Farming of brackish water milkfish was introduced to the Philippines and Taiwan in AD 1500 (Liao 2000, p. 110).

Greece and Rome: Fishponds and Polyculture

Ephrem (2019) identifies early polyculture of freshwater fish in the Sacred Lake, Delos, Greece, around the second century BC. Delos, believed to the birthplace of the god Apollo and goddess Artemis, was an important religious center from Archaic times and housed one of the largest sanctuaries in Greece. The city of Delos was an independent city-state with thriving trading activities during Hellenistic times (314–167 BC), before becoming an Athenian colony (167–c. 90 BC) (Ephrem 2019).

The Sacred Lake (100 m × 70 m) was a rain-fed pond formed in a natural depression (1.5–2.5 m deep) that captured run-off water. During the Hellenistic period, the Delos inhabitants constructed an elliptical wall to enable the lake to contain 22,500 m^3 of freshwater and perhaps to develop an aquaculture system and fish breeding program (Ephrem 2019) (Supplemental file). Ephrem (2019; see also Molinier 1914, p. 103) reported fish breeding in the freshwater lake (7% salinity) that was supported by the archaeoichthyological assemblage. While the majority of the assemblage is made up of marine taxa available in the natural environment, 5.8% are freshwater fish despite Delos lacking a drainage network and natural freshwater ponds. The identified freshwater taxa are wels catfish (*Silurus glanis*), pikeperch (*Sander lucioperca*), and common roach (*Rutilus rutilus*) (Ephrem 2019). Given the non-native character of these freshwater fish and the ability of the Greeks to transport live freshwater fish in fish-well boats (Boetto, 2010, pp. 24–253), Ephrem (2019) suggests that the archaeologically identified freshwater taxa may have been transported for a breeding program in the Sacred Lake on Delos. Unlike marine fish, freshwater fish can survive transport in water as they better withstand changes in their environment (Berka 1986; Huss 1995).

The three fish taxa identified in the assemblages (roach, catfish, and pikeperch) are effective at adapting to low-salinity stagnant water and can be acclimatized together in the same pool (Ephrem 2019). This kind of polyculture has the advantage of using the various natural food resources in the basin as the combination of roach with predatory species (catfish and pikeperch) may be a means to feed the predatory fish and control fish populations in the limited-size breeding pond (i.e., trash fish). The selection of species, their transport to the island of Delos, and their acclimatization in the Sacred Lake all attest to a high proficiency in managing and perhaps breeding freshwater fish in a polycultural system in Hellenistic Greece. If indeed fish breeding was taking place, this would classify the Delos aquacultural system as domestication level 3, where the entire life cycle is closed in captivity (with wild inputs).

A similar polyculture system was practiced during the Roman Republic (c. 509 BC) and the later Roman Empire (27 BC), with the construction of fishponds first recorded by Pliny at Grotta Ferraia at approximately mid-second century BC (Kron 2014, pp. 6–7; Lambeck et al. 2018). Diodorus Siculus also recorded the building of fishponds for fish farming in Agrigentum, Sicily, during this time (Fagan 2017). Roman aquaculturists developed both marine and freshwater fishponds, cultivating eels (common, congar, and Mediterranean moray), mullets (red, gray), seabreams (gilthead, saddled), and sea bass in marine fishponds, and salmon, trout, common carp, common bream, perch, tench, and roach in freshwater fishponds (Balon 2004; Kron 2014). Control over the fish held in the ponds was absolute, where fish were separated by species and age and there were distinct tanks for breeding (domestication classification level 3) (Supplemental file) (Busana 2018; Kron 2014). The construction of fishponds during the Roman Empire is strongly associated with both local economies, where there were vast ponds for intensive, commercial aquaculture and with social stratification, where owning a fishpond was associated with luxury and allowed elites to display wealth in the competitive climates of the late Republic and early Empire (Kron 2014; Marzano and Brizzi 2009).

The appearance of aquaculture in Delos, Greece, and throughout Italy during the Roman Republic coincides with the Roman Climatic Optimum (200 BC–AD 150), associated with warmer, humid climates (Bini et al. 2020; also reported 300 BC–AD 300: Clauzel et al. 2020). This period is probably more regionally climatically complex than currently reported, with researchers highlighting the paucity of palaeoclimatic data from continental Italy (Bini et al. 2020).

Peter the Great Bay, Russia: Oyster Farming

Oyster (*Crassostrea gigas*) aquaculture, dating to the Neolithic period, has been identified by Rakov and Brodianski (2007, 2010) around Peter the Great Bay, southern Primorye, Russia. The Neolithic Boisman culture (4875–2520 BC) emerged during the Holocene Climatic Optimum of warmer, more humid conditions and sea level rise that caused the formation of extensive lagoons (Popov et al. 2014, pp. 248, 255). Neolithic populations in the Primorye area were supported by intensive hunting, fishing, and gathering, including intensive exploitation of seasonal salmon runs; they adopted agriculture later on a localized scale (Popov et al. 2014). Formalized mortuary practices were evident at the Boisman II site (4550–3879 BC), with skulls displaying intentional deformation, possibly linked to elite social status (Popov et al. 2014, pp. 257–258). Middens associated with the Boisman II burials are predominantly oysters, perhaps indicating ritualized food consumption or collective feasting (Tabarev 2007).

According to Rakov and Brodianski (2007), oyster aquaculture took place through habitat substrate construction, the collection of spat, seeding and transplanting, and also through population tending, including the removal of oyster predators (Rakov and Brodianski 2010; Tabarev 2007). These skills classify the oyster industry of southern Russia as domestication level 2, as part of the life cycle is controlled through collection and transplanting of spat into a managed environment. Both the Boisman and later Yankovsky (900–100 BC) culture shell middens show evidence of age sorting, with spat (juvenile oyster) and oysters below one year of age absent or present only in minor quantities. This differs greatly from modern oyster farming in Peter the Great Bay, where spat constitutes up to 60 % of the total number of mollusks present. Rakov and Brodianski (2007, pp. 39–41, 2010, p. 26) argue that spat was collected and seeded elsewhere. While the minor presence of spat in archaeological middens may simply represent size choice by foragers or be the result of taphonomic factors, Rakov and Brodianski (2007) presented additional evidence for anthropogenic oyster seeding. Large oyster middens are located near the Poronai River mouth despite the nearest living oyster ground located 320 km away (Busse Lagoon) and the northern border of natural oyster habitat situated 500 km to the south (Rakov and Brodianski 2007, p. 41). Additionally, cases of introduction and acclimatization of oyster have been recorded on Sakhalin Island (Lake Nevskoye and Terpeniya Bay), along the western coast of the Tartar Strait (Sovetskaya Gavan and Chikhachev Bays), and Vladimir Bay, where water current flows would have prevented natural larval access and cold temperatures would have prevented spawning and larval survival (Rakov and Brodianski 2007). The presence of these shell middens and oyster populations cannot be a natural phenomenon and can be explained only by anthropogenic introduction, where people seeded and subsequently managed new oyster populations (Rakov and Brodianski 2007, p. 41).

Beyond introduction, the Boisman and Yankovsky groups constructed artificial oyster reefs, or bioherms, where stones, sticks, and shells were placed on the ocean floor to serve as substrate (or collectors) for plankton larvae (Rakov and Brodianski 2007, p. 41, 2010, p. 27). Numerous contemporaneous artificial oyster reefs have been identified in Nayezdnik Lagoon, adjacent to a Yankovsky shell midden and in the Ryazanovka River, 170 m from the Boisman II site, where an oyster valve on the artificial reef was dated to 4150 BC (Mikishin et al. 2002; see also Rakov and Brodianski 2007, p. 41).

Oyster shells dominate the Peter the Great Bay shell mounds (98–99%) despite large colonies of other taxa present in the bay, including mussels (*Mytilus grayanus*), clams (*Spisula sachalinensis*), and scallops (*Spisula* spp.*, Polititapes* spp.) (Brodianski and Rakov 2007, pp. 39–40). The abundance of oysters in ancient middens is so great that the authors suggest that cultivation would have been the only means to produce such vast quantities (Rakov and Brodianski 2007, p. 41). For example, the average volume of shell middens on the coast of Peter the Great Bay is ~150,000 m^3, containing ~1.5–2 billion mature oysters. The total natural population of oysters in the bay does not exceed 5 million, and the annual oyster yield in the 1930s amounted to 50,000–60,000 oysters. Oyster cultivation increases yield from a 1-m^2 area from 2–3 kg of meat (uncultivated) to 25–30 kg of meat. However, given the well-documented historic decline in oyster populations (Reeder-Myer et al. 2022), parallels with contemporary oyster population demography are perhaps not meaningful comparisons.

Rakov and Brodianski also note morphological features that distinguish the Boisman and Yankovsky shell midden oysters from natural oyster populations. The archaeological oysters display indistinct or absent radial ribs, valves that lack spikes, and unscalloped edges (Rakov and Brodianski, 2007, pp. 40–41, 2010, p. 26). Unlike natural oyster populations, archaeological shells also lack evidence of epifauna (e.g., drilling by worms, shelters of polychaete worms and barnacles, colonies of bryozoans and sponges, etc.) on their valve surface. Notably, paleoenvironmental data suggest that sea level rise led to the formation of a marine lagoon near Boisman I and II at approximately 5000 BC (Popov et al. 2014, p. 253) that may have been less saline. Oyster populations would have been less likely to show evidence of parasitism growing under these less-saline conditions. The oyster farmers of the Boisman and Yankovsky cultures may also have protected oyster population through predator removal, as middens dating to the Zaisanovka culture contained the rapa whelk (*Rapana* sp.), a voracious consumer of oysters, which was absent from Boisman and Yankovsky period deposits (Rakov and Brodianski 2007, p. 42). Although, if the Boisman and Yankovsky aquaculturalists were removing the rapa whelk, it might be expected that the shell of this predator would be present in midden deposits, evidencing its removal.

Similar to the oyster cultivators at Shell Mound, Florida, oyster production around Peter the Great Bay and in the southern Primorye region evidences intensification. Oyster populations that were already being exploited were cultivated through the construction of artificial reefs (capital and skill input), requiring a labor investment.

The oyster growing range was also expanded into previously unpopulated areas. This expansion may in some cases be considered extensification. However, here, it is associated with intensification as it relied on the application of new technology and skills (spat collection and transport, artificial reef construction) and investment in landesque capital (artificial reef construction) on land previously less effectively used (Brookfield 2001, p. 200).

Hawaiian Islands: Fishponds

In Polynesia, ancient Hawaiians integrated fishpond aquaculture into an entire watershed management-food production system (*ahupua'a*), thoroughly documented by Costa-Pierce (1987, 2002). This complex subsistence system included agriculture, aquaculture, and animal rearing in a large-scale barter economy (Costa-Pierce 1987, p. 322). Four broad types of fishponds were constructed in the Hawaiian Islands and integrated to various degrees with taro (*Colocasia esculenta*) agriculture and other resource production (Supplemental file). These pond types included freshwater taro fishponds, other freshwater ponds, brackish water ponds, and seawater ponds (Fig. 8) (Costa-Pierce 1987, p. 325). Despite some early dates, researchers currently accept that fishponds were first in use approximately AD 1400 (Burney 2002; Carson 2018; Kikuchi 1976; Weisler and Kirch 1985), a few centuries after island colonization at approximately AD 1000–1100 (Dye and Pantaleo 2010, p. 113; Field and Graves 2008, p. 212; McElroy 2007, p. 143; Weisler et al. 2023). This period of fishpond construction corresponds with the transition from the Early Expansion Period (AD 1200–1400) to the Late Expansion Period (AD 1400–1650) and is characterized by significant wetland agriculture, exponential population increase, and the construction of dryland field systems in leeward zones (Kirch 2010). Prior to the Early Expansion Period, there was a period of cool and dry conditions (AD 900–1200), followed by relative stability (Cobb et al. 2003). Nunn et al. (2007, p. 390), however, contend that Hawai'i would have experienced the rapid cooling and sea level fall of the "AD 1300 Event." El Niño Southern Oscillation (ENSO) frequency increased between AD 1100–1400 (Cobb et al. 2003; Field and Lape 2010). According to Kirch (2010, pp. 127–128), during the Late Expansion Period key transformations from chiefship to kingship took place, including investment in monumental architecture. Chiefs had exclusive ownership of the land and its resources. They were responsible for directing the construction of the ponds and distributed the proceeds to enhance their status and as a symbol of the chiefly right to conspicuous consumption (Kikuchi 1976).

Of the pond types, the freshwater taro fishponds display the greatest integration of production systems. These ponds were developed inland to cultivate taro and grow a range of euryhaline and freshwater fish, such as mullet (*Mugil cephalus*), milkfish (*Chanos chanos*), silver perch (*Kuhlia sandwicensis*), and Hawaiian gobies (*Eleotris sandwicensis*, *E. fusca*), as well as freshwater prawns (*Macrobrachium* sp.) and green algae (*Spirogyra* sp., *Cladophora* sp.) (Supplemental file). Fish were able to enter the freshwater taro fishponds directly from the ocean through artificial estuaries. The integrated taro-fish system would have benefited both products:

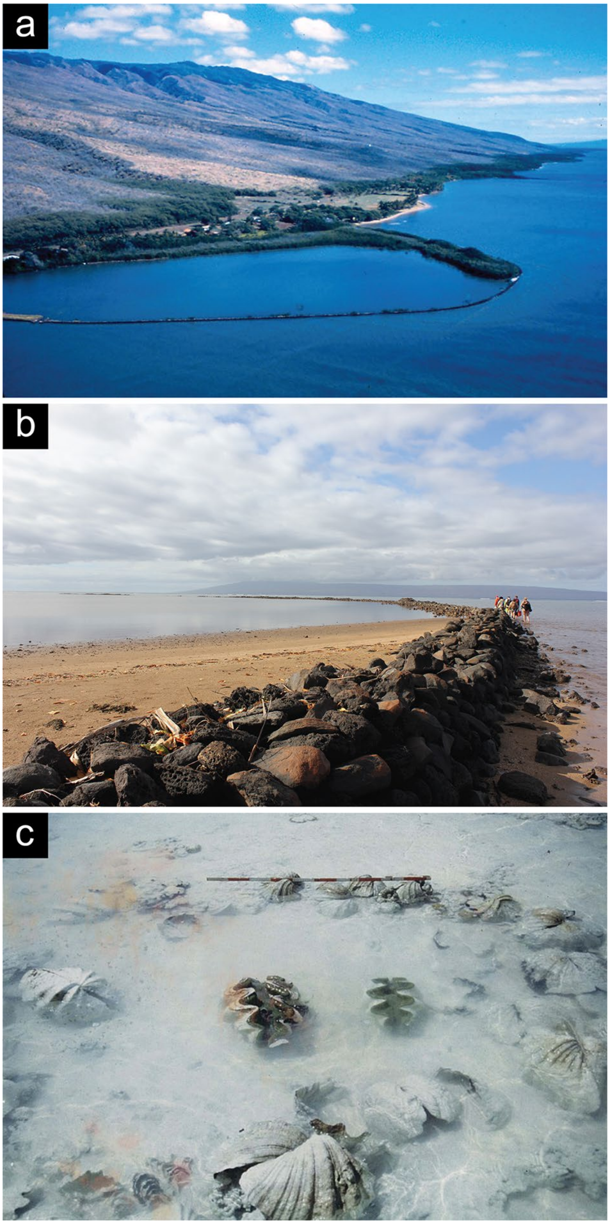

Fig. 8 Pacific Island aquaculture: **a** aerial view of Aliʻi (foreground) and Kānoa (background) fishponds, south shore of Molokaʻi, taken in 1980 (Image: Marshall Weisler; Weisler and Kirch 1985, fig. 3); **b** view south across Kānoa fishpond toward Lānaʻi, taken in 2018 (Image: Ashleigh Rogers); **c** giant clam garden, Abemama atoll, Kiribati (Image: Frank Thomas).

fish would have assisted taro growth through continual grazing and pruning activities and reduced pests, while mound-planted taro would have left channels for swimming fish to feed on the insects and ripe leaf stems (Costa-Pierce 1987, p. 325; Kamakau 1976). Hawaiian fishponds were not fertilized with manures or kitchen refuse (Costa-Pierce 1987, pp. 324–325; Kikuchi 1976) and were instead fed with grass and taro leaf from adjacent agricultural fields and mussels, clams, and seaweeds from natural ecosystems (Titcomb 1952; Wilder 1923). Surplus fish from the freshwater taro fishponds were moved into shallow ponds located close to the sea to maintain stock levels.

Other freshwater ponds and brackish water ponds produced similar resources to the freshwater taro fishponds (Costa-Pierce 1987, fig. 6). Seawater ponds, however, produced a number of euryhaline- and marine-based resources. These arc-shaped coastal ponds were formed by broad, semicircular walls of basalt blocks built on shallow reef flats out from the shore (e.g., Moloka‘i south shore fishponds) (Fagan 2017, pp. 96–97; Nash 2011, p. 34). They were often constructed around, or adjacent to, streams to increase productivity of the pond, as the freshwater input attracted and fed numerous taxa that thrive in brackish water (e.g., mullet, milkfish). These ponds were also constructed with sluice gates that allowed seawater to flow in and out but prevented larger fish from leaving. Seawater ponds are an excellent example of polyculture. In addition to mullet (*Mugil cephalus*) and milkfish (*Chanos chanos*), many small or juvenile marine fish, such as jacks (Carangidae), threadfin (Polynemidae), bonefish (Albulidae), and ten-pounders (Elopidae), could move in to feed and grow and were later harvested as adults as they tried to move back out to sea to spawn (domestication classification level 2) (Costa-Pierce 1987, fig. 6). Numerous reef fish taxa could also be held in these seawater ponds (e.g., parrotfish, wrasse, goatfish, unicornfish), as well as crabs (Costa-Pierce 1987, fig. 6). The Hawaiian fishponds represent incredible monumental architecture and intensification of production. Enormous investment in capital and skills (technology) took place to permanently improve an already exploited area of land that required intensive labor inputs to construct and maintain.

Federated States of Micronesia: Giant Clam Gardens

One of the most famous archaeological sites in the Pacific is the UNESCO World Heritage Site of Nan Madol, Pohnpei. Nan Madol was constructed in a lagoon and consists of 92 artificial islets built from basalt and coral boulders that stretch over 83 ha (Athens 1983; Dieudonne 2002, p. 9; McCoy et al. 2015, 2016). Construction of the city is attributed to the Saudeleur dynasty (AD 900–1600), and its function is thought to be ritual, mortuary, and administrative, with the remains of temples, burial vaults, elite residences, meeting houses, and public baths identified (Athens 1983, pp. 51–52, 2007; Comer et al. 2019; Dieudonne 2002, p. 9; McCoy et al. 2015). Using high-precision uranium series dating of coral from the tomb of the Saudeleur dynasty, McCoy et al. (2016) indicated that the beginning of monumental building and political control over the entire island was established by AD 1180–1200. This period coincides with the Pacific Medieval Warm Period (AD

800–1300) and an increasing ENSO frequency (AD 1100–1400; Cobb et al. 2003), followed by the cooling and drought of the Little Ice Age (AD 1400–1850) (Field and Lape 2010)

Residents of Nan Madol kept sacred animals in artificial basins, such as moray or saltwater eels and turtles, which held a highly significant position in ancient Pohnpeian society (Athens 1983, pp. 55–56, 2007; Hambruch 1936, p. 35; Hadley 1981, p. 115; Mauricio 1993, p. 157; Morgan 1988, p. 76). Moray eels, in particular, were a worshiped deity, and turtles and dogs were used as offerings to these deities (Kataoka 1996, pp. 250–251; Mauricio 1993, p. 469). The raising of turtles and eel for ritual purposes does not align with the interpretation of aquaculture used in this review. However, the oral histories also reference the housing of other marine creatures, and surveys of the site corroborate the existence of pools and stone pens to house fish and clams (McCoy et al. 2015; Dieudonne 2002, pp. 9–10).

Athens (1983) surveyed and mapped a number of islets on Nan Madol, including the islet of Dorong (or Darong; McCoy et al. 2015) that was constructed symmetrically around a natural reef pool (see Morgan 1988, pp. 66–67). This reef pool was used for keeping and raising clams (*Tridacna gigas*, *Anadara* spp.) for the chiefs, and numerous *Anadara* spp. clam shells and an unusually large number of *Conus* artifacts (beveled rings) were scattered on the islet surface (Athens 1983, pp. 56–67, 1984, pp. 139–141, 147; see also Hadley 1981, p. 101; Hambruch 1936, pp. 29-I; Morgan 1988, pp. 76–77). The use of the Dorong pool for raising clams is corroborated by McCoy et al. (2015; see also McCoy and Athens 2012, fig. 1), who report a relatively low retaining wall that formed a square around a large natural reef pool used for food production, including the raising and keeping of clams (Hambruch 1936, pp. 29-I; Hadley 1981, p. 101). Kataoka (1996, pp. 250–251; Hambruch 1936) similarly note that the subrectangular pool on Dorong was used for storing shellfish, fish, and potentially also turtle. *Anadara antiquata*, along with *Tridacna gigas* and *Tellina palatam*, was a favored shellfish and was likely the species cultivated in the Dorong pond (Kataoka 1996, p. 242); it was an important and preferred shellfish taxon at Nan Madol and more widely across Pohnpei. Dorong also provided coconuts, breadfruit, pandanus, and other fruits, possibly used as sacrificial offerings (Morgan 1988, pp. 76–77; see also Hambruch 1936).

The practice of ancient clam culture may have occurred more widely across Micronesia. According to Dieudonne (2002, p. 11), on Yap clams were gathered and brought into stone-walled fish traps for long-term containment. Giant clam (*Hippopus hippopus*, *Tridacna gigas*) gardens have also been identified in Kiribati, Micronesia (Fig. 8) (Thomas 2001, 2003, fig. 2). Small specimens (<40 cm) would have been gathered from the leeward reef and ocean reef flat and deposited in shallow lagoon reefs adjacent to settlements, where they were allowed to grow until ready for consumption (Thomas 2003, p. 248). Extant giant clam gardens may be demarcated by the presence of a circular coral enclosure, coral rubble, a fish trap, or may have no distinguishing features (Thomas 2001, 2003, p.248).

Micronesian clam gardens indicate a high level of control over clam life. Clams are gathered and held in a constructed pool where they are watched and tended as they grow. The raising of juvenile clams in a controlled environment is classified as domestication level 2 as part of the life cycle is controlled in captivity. This artificial ecosystem also enhances clam habitat in a way, as it protects them from a major destructive threat—tropical storms and powerful waves.

Discussion and Conclusion

A review of the archaeological literature on ancient aquaculture has illuminated three points: (1) ancient aquaculturalists were ecosystem engineers who domesticated landscapes; (2) past aquacultural systems emerged under similar environmental and social conditions; and (3) through historical ecology, similarities across systems may be pertinent to present-day aquaculture.

Domesticated Landscapes

In ecology, ecosystem engineers are organisms whose presence or activity alters their surroundings, thereby creating, maintaining, or modifying habitats, influencing all associated species, and directly or indirectly modulating the availability of resources (Crain and Bertness 2006; Gibson and Lewis 2017; Jones et al. 1994, pp. 373–374; Levis et al. 2017). For example, a beaver creates ponds and wetlands that may persist for centuries where previously there were running streams (Jones et al. 1994), and a tree will shade the understory and drop-leaf litter, thereby lowering soil temperatures, altering soil pH, and creating a physical barrier to seed emergence (Crain and Bertness 2006; see Jones et al. 1994, table 1). Important ecosystem engineers can expand distributional limits for numerous species, enhance biodiversity, and form the foundation for ecological community development and expansion (Bouma et al. 2009; Crain and Bertness 2006; see also Spengler 2021). The adaptive success of ecosystem engineering has been widely recognized since at least as early as Darwin (1859, 1881; Spengler 2021). Humans are ecosystem engineers "par excellence" (Jones et al. 1994, p. 373).

The ancient aquaculturists in all regions were acting as ecosystem engineers, creating constructed, cultural landscapes as food-producing systems that persisted for millennia (e.g., McNiven 2008). In many cases (e.g., Bolivia, Cambodia, Australia, Hawai'i) their activities brought about enormous physical state changes through extensive earthen and stone works that altered landscape usability and hydrology. Through these physical changes, producers created novel habitats for new taxa. For instance, the introduction of freshwater fish into the Sacred Lake on Delos, Greece, or the building of oyster reefs and expansion of oyster population range in Russia. Other peoples modified and extended existing ecosystems like the extension and maintenance of clam beds to increase clam productivity in the Pacific Northwest or the expansion of wetlands at Budj Bim Cultural Landscape, Australia. The activities of these early aquaculturists as ecosystem engineers certainly enhanced the availability of their target resources. However, it also influenced all associated species in the broader area. In Mexico, Belize, and Bolivia, the construction of raised field systems facilitated the existence of ecotones—transitional areas (i.e., marshland) where two ecological communities meet. In this case, aquatic meeting terrestrial attracted water birds, reptiles (turtles, crocodilians), and amphibians—all of which were further resources. In numerous other areas, habitat creation and expansion also increased the abundance of wild resources beyond the target aquacultural product (e.g., Australia, Hawai‘i). People exerted an enormous degree of control over the surrounding land- and seascapes and resources to turn food collection into regulated and managed production (eco)systems, even developing highly formalized integrated production systems (e.g., rice-fish farming in China, Japan, and Southeast Asia, taro-fish farming in Hawai‘i; Supplemental file).

Through action as ecosystem engineers, people came to domesticate their landscapes. At the beginning of this article, I argued that a morphological or genetic change in a target taxon was not a requirement for identifying ancient aquaculture. Instead, what we see (through ecosystem engineering) are morphological and genetic change in the landscape, which becomes a cultural construction. This change is morphological through the alteration and construction of landforms and hydrologies. It is genetic in the modification of biota, where floral and faunal species are moved from place to place, desirable taxa promoted, and unwanted taxa removed to create the ideal species composition (Terrell et al. 2003). This environmental manipulation was not casual. As with domesticated species, domesticated landscapes were heavily dependent on people and involved intensive and regular management activities (e.g., Lepofsky et al. 2015, p. 237). People were the key selective agent that transformed environments into domesticated, cultural landscapes that successfully produced aquatic resources for millennia.

The Emergence of Aquacultural Systems

Harlan (1992, p. 46) wrote: “people do similar things for entirely different reasons and they find very different solutions to the same problems.” While this is undoubtedly true, there are some striking social and environmental similarities associated with the emergence of ancient aquaculture across time and space.

The development of food-producing technologies has been broadly attributed to increasing human population and concomitant declines in natural resource availability (N. Smith et al. 2019). While there is likely truth to this statement, this review found that other factors were also strongly correlated with the appearance of past aquaculture. In each area, societies were described as having high population densities and/or had experienced a recent rapid increase in population. These societies were also sedentary. Even in Australia, where groups are generally considered to have been more mobile, the appearance of aquaculture occurred alongside permanent or semipermanent sedentism, for example, Budj Bim stone houses (Clark 1991) and increasing numbers of contemporaneous sites in southeast Queensland (McNiven 1999; Ulm and Hall 1996). Further, aquaculture tended to emerge during warm, wet climatic periods, such as the Early Holocene Optimum in China, the Roman Climatic Optimum in western Europe, and the Medieval

Warm Period in southern North America and Micronesia, usually following periods of climatic instability (cooling, drought), erratic sea levels, and higher levels of human mobility (e.g., Marquardt and Walker 2013; Sassaman et al 2016; Thompson et al. 2014, 2018). The increased precipitation associated with warm, wet climatic optimums resulted in inundation of low-lying areas (e.g., southern North America, Bolivia), lagoon expansion (e.g., Boisman Bay, Russia), and lake high stands (e.g., China).

Perhaps the appearance of these favorable conditions was the catalyst for coastal dwellers to expand into food production as, according to Schalk (1977, p. 228), specialization is favored in highly stable and productive environments. Or, perhaps, the change in environment simply made aquaculture a favorable option, and it was increased population and sedentism that truly prompted technological advancement. Specialization is considered the primary response to increased production requirements arising from these circumstances (Betts and Friesen 2004, p. 359), although population size alone cannot sufficiently explain cultural developments (Vaesen et al. 2016). Ancient aquaculture systems were also able to persist throughout climatic (cooling), sea level (lowering), and environmental (drying) shifts. For instance, aquacultural production at Mound Key continued from the Medieval Warm Period (AD 850–1200) into the Little Ice Age (AD 1200–1850) (Sassaman et al 2016; Thompson et al. 2014, 2018, 2020b). In many parts of the world, European invasion and colonization is likely what eventually resulted in the collapse of these food production systems through warfare, disease, and resource overexploitation (Castilla-Beltrána et al. 2020; Ferguson 1990; Reeder-Myers et al. 2022).

The appearance of aquaculture was not always associated with the appearance of favorable environments. In Hawai‘i, for example, fishponds emerged in AD 1400 during climatic instability associated with increased El Niño Southern Oscillation (ENSO) frequency and following the rapid cooling and sea level fall of the "AD 1300 Event" (Nunn et al. 2007). Similarly, oyster aquaculture in southeast Queensland, Australia, appeared at AD 750, following fluctuating sea levels and variable climatic and environmental conditions between 550 BC–AD 450. Unstable environments are usually associated with generalization, which occurs at the expense of efficiency but favors flexibility (Schalk 1977). Perhaps a case could be argued that aquaculture developed under unstable conditions as a means of reducing variance (risk) in unpredictable environments? Controlling the means of production in unstable environments may be viewed as a less risky, buffering strategy despite associated labor costs and loss of flexibility. In hunter-gatherer groups, environmental risk has been correlated with technological innovation and richness (Buchanan et al. 2015; Collard et al. 2013; Vaesen et al 2016). Although the technological developments attributed to these hunter-gatherer groups assist the generalist, aquaculture is most certainly a specialist activity. It has been argued that raised field systems in Llanos de Mojos, Bolivia, allowed pre-Columbian peoples to mitigate the risk of intense and frequent flooding events (Lombardo et al. 2011). The continued refinement of regional and local climate datasets could illuminate the influence of climate and changing environments more broadly.

Large populations and sedentism are strongly associated with the process through which aquaculture systems emerged: intensification. Intensification takes place when groups are constrained by dense human populations and/or environmental barriers (physical barriers, hostile neighbors), preventing them from expanding geographically. Instead, additional inputs (labor, capital, skills) are devoted to increasing the output of currently exploited resources within a given area of land to meet food requirements. In the regions described, populations were already exploiting aquatic zones and invested additional resources to increase productivity (a Blue Revolution) through (1) monumental works to create habitats and alter hydrologies; (2) skill and technology development to create and maintain systems; and (3) increased labor cost and restructuring to successfully construct, exploit, and maintain the aquaculture systems.

Intensification is central to many explanations for the appearance of sociocultural complexity (Carlson 1998; Fladmark 1975; but see Moss 2012; Rowley-Conwy 2001; Warren 2021). In archaeology, the term complexity is generally used to denote a society that exists of many interconnected or interwoven parts (Kantner 2002). Feinman (2012, p. 36) defines social complexity as "[t]he extent of functional differentiation among social units," which "may be vertical or horizontal. Vertical complexity is hierarchical governance with a degree of concentration in decision making and power. Horizontal complexity is the differentiation of a population into various roles or subgroups." Sociocultural complexity is often identified through traits, such as social stratification (hierarchy), status differentiation (e.g., hereditary inequality), regional social integration, political centralization or institutionalized leadership, and economic intensification (e.g., food production). Greater sociocultural complexity is seen as an increase in the quantity and elaboration of components (traits) and their relationships with one another (Kantner 2002). Here, I use the term "complexity" to indicate the presence of interconnected components (traits) in a society. Differences in the number and type of traits present in these societies is not indicative of greater "advancement." It is reflective of different cultural trajectories, how cooperation and institutions articulate with resources and practices (Thompson 2023), environmental requirements, and the likelihood of trait materialization to enter the archaeological record.

Sociocultural complexity is strongly linked with economic intensification through the production of surplus. Surplus is significant in complex societies. It guarantees food security to the population and legitimizes the social order, whether that social order is a ruling institution in a hierarchal society or group relations in a transegalitarian society (Richards 2011). In each of examples, the societies evidence traits associated with sociocultural complexity beyond economic intensification (aquaculture). In some cases, these groups may display numerous traits, such as the social stratification and political centralization evident in southern North America, Bolivia, the Hawaiian Islands, and Nan Madol. In other instances, sociocultural complex traits are more evident through economic components. In the Pacific Northwest, for example, clam garden construction and maintenance are thought to evidence reified systems of ownership and control (N. Smith et al. 2019, p. 14). Similarly, in Australia, eel aquaculture at Budj Bim supported a system of regional social integration that involved large, intergroup meetings and trade and exchange of eels as a valuable commodity (Rose et al. 2016, p. 592). Previously dismissed ethnohistorical accounts reported the existence of regional social stratification and hereditary chiefs in this area of Australia (Builth 2002; Richards 2013). Despite differences in the societies that constructed aquacultural systems, the food security (surplus) provided by these systems would have had the same affect: to legitimize the social order. Often the institutions being legitimized had a religious or symbolic aspect (e.g., divine kings in Hawaiʻi, priestly class in Nan Madol) or, as in the case of Budj Bim (A. Smith et al. 2019, p. 290), the aquaculture system may be tied to creation stories. This means that, beyond legitimizing the social order, the aquacultural system (through surplus) was legitimizing people's understanding of the world.

An interesting correlation may exist between the domestication classification level and the number of socioculturally complex traits. The examples that were classified as domestication level 3 came from China, Japan, western Europe (Greece, Rome), Bolivia, Mexico, and Belize (Fig. 2, Table 2). They displayed evidence of captive breeding within a constructed environment and intentional (not passive) interference in the breeding cycle. These societies are associated with many complex traits: social stratification, centralized leadership, and regional social integration (trade and exchange). But this does not appear to be a firm rule. Other areas, such as Hawaiʻi, Nan Madol, Mound Key (Florida), and the Greater Angkor region in Cambodia, are similarly characterized by these complex traits and yet were classified to domestication levels 1 or 2. It is also unlikely that domestication level reflects the degree of intensification and the limits to extensification (i.e., hostile neighbors, physical barriers). For example, Hawaiʻi and Nan Madol (being islands) are surely the most limited in their capacity to "extensify" and would need to intensify to increase food production. Yet their levels of domestication are classified as 2.

Environmental opportunities may be a driving factor in the degree of taxa domestication. If surplus food needs are met through enhancing ecosystems or stocking adults, there is no need to control breeding in a closed system. However, perhaps in some instances breeding in situ may constitute lower economic effort (and expense) than transporting adults. This may be the case in the Sacred Lake of Delos, Greece, or in Roman Republic cities and perhaps elsewhere too. Could the path of least resistance, therefore, explain why some societies attained particular taxa domestication levels?

Ancient aquaculture is a burgeoning field of archaeological research that requires greater research to disentangle the factors surrounding its global appearance. Here, it was broadly suggested that dense populations, sedentism, favorable warm-wet environments, and traits of sociocultural complexity are associated with its development. Was food production driven by resource shortages and/or high variance (risky) environments? Was sedentism and aquaculture the response to favorable environmental conditions? Did aquaculture emerge before or after socioculturally complex traits? How do levels of domestication relate to social and environmental factors? How did aquacultural systems respond to climate and environmental change through time (e.g., McCoy et al. 2017)?

Given the influence of environmental variation and cultural differences in ancient societies, a single broad narrative is unlikely (e.g., Moss 2012). Questions surrounding ancient aquaculture need to be incorporated into research designs globally to refine chronologies of the emergence of this system. Together with local climate chronologies, this would better describe the social (demography, sedentism, sociocultural complexity) and environmental drivers of aquaculture.

The archaeology of aquaculture requires the development of robust methodologies for identifying evidence of these systems (e.g., Nakajima et al. 2019), not just in the physical environment (e.g., domesticated landscapes) but also in the target population. These changes need not be the permanent physical and genetic changes of domestication and, instead, could represent a farmed population characterized by different population age and size structures (e.g., Nakajima et al. 2019; Prestes-Carneiro et al. 2019). In the case of shellfish, perhaps shell size and morphology reflects the farm location and associated environmental conditions (e.g., Rogers and Weisler 2020; Thompson et al. 2020a). The potential of this technique would be illuminated by the quantification of population age and size structures and individual body/shell morphology of modern farmed products. Population-specific criteria may be particularly important for demonstrating shellfish aquaculture, as it can be less archaeologically conspicuous than fish aquaculture that is frequently evidenced by extensive and enduring landscape modifications.

The archaeology of aquaculture also requires increased theorizing to understand how and why it came to be implemented and the subsequent society trajectory. Investigations into past aquaculture would be greatly improved by the contribution of First Nation and Traditional Owner communities, whose knowledge and histories have already greatly illuminated this topic (e.g., Deur et al. 2015; Lepofsky et al. 2015; McNiven et al. 2012, 2015; Ross et al. 2015; Ross with members of the Quandamooka Aboriginal Land Council 1996; A. Smith et al. 2019; N. Smith et al. 2019; Williams 2006).

Historical Ecology and Present-Day Aquaculture

The modern context surrounding aquaculture is strikingly similar to the ancient one: populations are incredibly dense, sedentary, and socioculturally complex, and the world is experiencing climate change and environmental instability. Aquaculture in the modern context also developed through the process of intensification when wild caught fisheries could no longer keep up with the rapid increase in fish consumption (Botta et al. 2020; Garlock et al. 2020; Hayashida 2005; Kobayashi et al. 2015; Troell et al. 2014).

But the outcomes of the past and present Blue Revolutions appear to be diverging. Ancient aquaculture (through ecosystem engineering) domesticated landscapes to produce a greater abundance of desirable resources within a functioning ecosystem. Much contemporary commercial aquaculture is practiced as large monocultures: intensive feedlots that generate releases of waste material to the environment from uneaten feed and excreta, producing enormous nutrient concentrations. This nutrification can result in various negative local environmental effects such as eutrophication, oxygen depletion, biodiversity modifications, and pollution of the surrounding waters (Troell et al. 2003, p. 72). Modern offshore salmon farms in New Zealand, Scotland, Scandinavia, and particularly Australia have been described as "battery-hen farming of the sea," with producers accused of maximizing production at the expense of being careful environmentally (Ding 2021). Criticisms include environmental devastation, pollution, spread of disease and pests to wild stocks, mass capture of fish for salmon feed, and the genetic introgression of farmed salmon in wild populations (Crawford 2003; Crosbie et al. 2005; Taranger et al. 2015). The excessive nutrient input from salmon farms, combined with warming water, is also thought to be increasing jellyfish blooms around the globe (Bingham 2021). Jellyfish swarms dominate entire ecosystems and, in their ideal reproductive conditions, could result in entire ecosystem phase shifts. In Northern Ireland, jellyfish blooms (mauve stinger, *Pelagia noctiluca*) have resulted in catastrophic mass death at salmon farms (BBC News 2014; McDonald 2007). These monoculture aquacultural systems lack resilience. In many aspects of modern life, we have become extreme specialists and socially and economically have lost the ability to be flexible in the face of change.

Conversely, ancient aquacultural systems may have been highly resilient. They operated sustainably through the successful long-term production of food for millennia, without wider natural resource depletion. Some systems even continue to operate in a similar form today (e.g., rice-fish cultivation in China, chinampas field systems in Mexico). Given the success of past systems and the current difficulties faced by the industry today, can the ancient Blue Revolution provide insight into future aquaculture directions?

Historical ecology has emerged as an important transdisciplinary approach for investigating the influence of people as keystone species and natural climatic change on ecosystems over long timescales (Braje et al. 2009; Rick 2013). The application of this deep-time perspective, derived from archaeology, ecology, and paleobiology, provides context for understanding the structure and response of ecological communities, as well as management and restoration of contemporary ecosystems (Braje 2010; Braje et al. 2009; Egan and Howell 2001; Jackson et al. 2001; Lyman 2006; Rick and Erlandson 2008). It allows us to evaluate how we arrived at the present and project possible future outcomes based on long-term ecological and cultural data (Foster et al. 2016). As LeFebvre et al. (2022, p.1) stated "In the uncertain futures of the Anthropocene, such historical baselines will contribute significantly to scientific approaches for building more resilient and sustainable societies."

There appear to be two major deviations between ancient and present-day aquaculture systems. First, ancient systems focused on incredibly resilient species, taxa that could survive in a range of salinities (marine, brackish, lentic) and temporary, very low oxygen water bodies (even out of water in buried channels in moist soil; Blatrix et al. 2018; Lulewicz 2020, pp. 139–140; Prestes-Carneiro et al. 2019). It is no coincidence that, in the ancient world, the most commonly farmed fish were carp, tilapia, catfish, mullet, toadfish, lungfish, and eels, all species that thrive in a diverse range of habitats. In terms of mollusks, oysters were also the farmed product of choice. Despite being ubiquitous with a (nearly) global distribution, oysters are also highly resilient and can withstand varying salinity and turbidity in their habitat. In many parts of the world today, resilient species such as carp, tilapia, catfish are farmed (De Silva and Phuong 2011). However, in other parts of the world these taxa are not viewed as desirable for consumption, and farming focuses on commercially valuable fish species, such as salmon. This is also the case for wild caught fisheries. In North America, toadfish (consumed and farmed prehistorically at Mound Key) are very rarely targeted by modern fisheries as their appearance and mucus secretion on their skin makes them an unappealing catch (Kritzer and Hughes 2010; Lulewicz 2020, pp. 139–140).

The farming of more adaptive taxa may be beneficial. These resilient species (e.g., carp) can be highly invasive when introduced to new, non-native environments (Koehn 2004). It is not being suggested that they specifically be farmed around the world, rather that resilient native species be considered as viable aquaculture products. A similar recommendation has been made for the value of locally native plants in North American and Australian agriculture (Ahmed and Johnson 2000; Shelef et al. 2017).

In the past, system resilience was further increased by farming a diversity of products across different trophic levels. This leads into the second major deviation between ancient and modern aquaculture systems: much contemporary commercial aquaculture is practiced as large monocultures, while ancient systems were essentially farmed ecosystems. These past systems were integrated polycultures with interdependent, interrelated, and interlocking parts that maximized the utilization of nutrients and minimized negative effects on the wider environment (Edwards 2015). Across all regions, numerous aquatic products (fish, mollusks, aquatic plants) were farmed and, in some cases, terrestrial crops were also incorporated (e.g., China, Mexico, Cambodia). Like natural ecosystems, parts of the aquacultural system (e.g., waste) fed and/or contributed to the growth and survivability of others (energy transfer) resulting in a holistic agroecosystem (Crain and Bertness 2006). Integration may have been in the form of “trash fish” (e.g., China, Greece, Rome) or perhaps in the incorporation of “extractive species” (mollusks, aquatic plants, e.g., Hawai‘i, Bolivia) that utilized organic detritus, plankton, or dissolved nutrients in the water column (Edwards 2015, p. 3). Integrated systems can synergistically increase total output, and the co-cultured species can each yield valuable commercial crops, even if some produce less than they would, short term, in a monoculture (Chopin 2006; Neori et al. 2004). Overall, ancient systems are characterized by resilient taxa and the integration of products (resources) across trophic levels in an agroecosystem.

But what is the future of aquaculture? According to Costa-Pierce (2002, 2010; see also Edwards 2015, p. 6), the Blue Revolution needs to become greener, perhaps a Turquoise Revolution (Chopin 2013, p. 19) by incorporating ecological principles into an alternative aquaculture development model: ecological aquaculture. Ecological aquaculture not only deals with the technical aspects of ecosystem design and ecological principle, but also integrates social ecology, community development planning, and concerns for the wider social, economic, and environmental contexts of aquaculture to better plan for sustainable working waterfronts (Costa-Pierce 2010, p. 90, fig. 1). The concept of ecological aquaculture is not new and closely resembles traditional integrated aquacultural systems. Much like the examples from the past, traditional and low-technology farming approaches contain lessons learned over many generations, which should be regarded as valuable instructive bases for modern aquaculture development. Typically, however, these more natural systems are not attractive to farmers due to limited input of external nutrients, resulting in lower productivity. Traditional integrated agro-aqua systems primarily satisfy a complex of environmental (e.g., maximizing resource use) and social aims rather than only being concerned with maximizing short-term profit (Ruddle and Zhong 1988; Troell et al. 2003). Fisheries scientists are now proposing that future aquacultural technologies could attain sustainability by integrating waste generating (fed) and cleaning (extractive) organisms in each farm, mimicking natural ecosystem cycling (Boyd et al. 2020; Edwards 2004; Troell et al. 2003, pp. 70–71). One emerging approach—integrated multitrophic aquaculture—may find a balance between productivity and environmental sustainability by attempting just that. This method integrates pellet-fed finfish culture with inorganic extractive seaweeds and organic extractive mollusks and benthic detritivores such as sea cucumber (Chopin 2013; Chopin et al. 2001; Edwards 2015, p. 7).

The possible future direction of sustainable aquaculture strongly resembles that of ancient aquacultural systems, where there is an integration of diverse taxa (as outputs) to create a living system or the "aquaculture ecosystems" created by ecological aquaculture (Costa-Pierce 2010, p. 90). Further similarities between past aquacultural systems and future directions would involve the consideration of local, resilient taxa as aquacultural products, integration of more terrestrial and/or aquatic crops within systems, or the incorporation of natural/wild environments with food production to increase habitat for nontarget species (e.g., birds, reptiles, amphibians, mammals) and create a larger, more holistic food-producing ecosystem (Costa-Pierce 2010, fig. 1). While these thoughts (from an archaeologist, not a fisheries scientist) may be unattainable, there is certainly important knowledge that can be gleaned from aquaculture systems that functioned sustainably for thousands of years.

The trajectory of human food systems has been well described by Brummett et al. (2013, p. 319), who stated "the world is rapidly moving toward a wholesale transformation from a wild landscape with pockets of human population and industry, to one of a managed landscape with pockets of wild places." This transition was begun thousands of years ago by human producers acting as ecosystem engineers. Today, almost all habitable places on earth have experienced transformations, with the goal in food security becoming sustainable intensification of those areas already developed for human use. Perhaps knowledge from the past, in this instance, can contribute to the development of sustainable aquaculture practice into the future.

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