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Amazonian Wetland Domestication: A Spatial Analysis of Pre-Columbian Fish Weirs in Lowland Bolivia

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AMAZONIAN WETLAND DOMESTICATION: A SPATIAL ANALYSIS OF PRE-COLUMBIAN FISH WEIRS IN LOWLAND BOLIVIA

by

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B.A. University of Central Florida, 2021

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ABSTRACT

Recent archaeological studies show that pre-Columbian communities began modifying Southwestern Amazonia approximately 3,500 years ago. In lowland Bolivia, a recently mapped network of fish weirs in West Central Llanos de Mojos (WCM) demonstrates how ancient *Mojeño* groups built artificial earthworks to harness seasonal flooding and catch fish. In the eastern region of Baures, a similar complex of fish weirs has been studied since the 1990s, generating questions about how this system may function in a different hydrological and anthropogenic setting. Similarly, previous research within WCM has focused on the fields and forest islands that pre-Columbian populations built to elevate themselves and their crops from the floodwaters that consume the landscape. However, water is still a necessity for communities, and the dry season beginning in early summer can leave the landscape in a state of drought. This begs the question, were inhabitants also participating in large-scale environmental transformations to domesticate wetlands and increase their duration and scale? This proceeds from the assumption that weirs were not only interacting with water to catch fish but controlling its flow and accumulation to expand wetland habitats and resources more broadly. Using a combination of spatial data and statistical analysis, this study defines potential wetlands within the region, distinguished by two unique patterns of fish weirs, stacks and networks. Results indicate that these wetlands have the capacity to affect water flow and accumulation for over 600 m^2 of land but maintain differences in their sizes and relationships to major bodies of water and nearby anthropogenic features.

To my two orange pumpkins, Pancake and Benedict.

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Also, to Dr. Neil Duncan, though my thesis has nothing to do with phytoliths, I am grateful for my brief time as a PEAL laboratory assistant. It helped inspire a new passion for botany, which I hope to incorporate into my future research.

I would also like to acknowledge the many ProSIGAB volunteers who have helped digitize tens of thousands of earthworks across the region, especially Stephanie Boothby, Thomas Lee, Jackie Beery, and Dorian Vlasov whose efforts were of specific use in this study. I would also like to thank Drs. Neil Duncan, Scott Branting, Gabriela Prestes-Carneiro, and Donovan Adams for being part of my committee and lending their valuable and diverse expertise to my research project.

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CHAPTER ONE: INTRODUCTION

In 2019, a new distribution of pre-Columbian earthworks was detected in the wetland savanna region of Llanos de Mojos (Figures 1 and 2). The first of these features was found lying beside a forest island in West Central Mojos (WCM), composed of mounded earth that changed directions multiple times at sharp angles in a zigzag pattern (Figure 3). Further investigation by volunteers of the Proyecto Sistemas Informáticos Geográficos y Arqueológicos del Beni (ProSIGAB) on satellite imagery revealed many more of these features. At present, the dataset is distributed across 11,500 km^2 of savanna and contains almost 750 km of digitized earthworks (Figure 2).

In contrast to the striking linearity of causeways and the standardized rectangular shape of raised fields (Lee and Walker 2022; Walker and Erickson 2009), these earthworks differ from previously mapped feature datasets in their seemingly non-artificial shape, possibly illustrating why they lay undetected for so long. In fact, the first published image of these features almost a decade earlier described the adjacent canals, ponds, raised fields, and forest islands, yet not the zigzagging lines jutting out from them (see Figure 13 in Lombardo 2010). Available satellite imagery has also greatly improved since this time, making the features more visible. After comparison to a similar set of earthworks in the far eastern province of Baures, ProSIGAB classified the features as fish weirs—linear earthworks built in rivers or floodplains, designed to trap fish by exploiting seasonal flood waters. Both complexes present structures that zigzag across low-lying seasonally submerged savannas, often connecting adjacent forest islands. They are also commonly found in association with artificial ponds (Blatrix et al. 2018; Erickson 2000; McKey et al. 2016). However, as updated satellite imagery reveals more and more of these fish weirs, it has become clear that the WCM dataset represents a diverse array of physical structures, spatial patterns, and unique associations with earthworks that diverge from the precedent established in the Baures hydraulic complex (Robinson 2021). Additionally, by situating these recently mapped features within previous ethnohistoric and archaeological literature of the region, this project finds these features may have had a much larger role in wetland domestication than their name implies (Duncan et al. 2021; Erickson 2000; Métraux 1948; Prestes-Carneiro et al. 2019, 2021).

With this in mind, this thesis analyzes how the distribution of pre-Columbian fish weirs across West Central Mojos domesticated wetland environments by building on natural cycles of flooding. Special attention is paid to the amount of land that these earthworks affect as they manipulate the range and seasonality of water. This project analyzes these variables with respect to different mapped clusters of fish weirs within WCM, which demonstrate unique spatial patterns as well as relationships with large bodies of water and other anthropogenic features. Hypothesis testing permits the identification of statistically significant differences in spatial data between differently patterned clusters of fish weirs, referred to as potential wetlands. Additionally, correlation tests identify whether variables are related. Finally, prior research will inform what ecological and cultural implications networks of fish weirs might have for WCM, especially for populations that occupied forest islands and farmed raised fields. What do potential wetlands afford these communities?

These goals are addressed from the research paradigm of historical ecology, in which landscape arises as the product of a dialectical relationship between nature and culture as they interact in a geographically defined space and historically specific period of time (Balée 2006; Crumley 1994). Further, as many indigenous ontologies do not recognize a distinction between themselves and their environment, this analysis incorporates the definition of landscape forward by Descola (2016): landscape as transfiguration. Under this perspective, landscapes are not built into existence by humans; rather nature is physically and perceptually re-represented at a different scale. Lastly, because life in Mojos is defined by the existence and lack of water, this author uses the term "waterscape" as an alternative to "landscape" (Prestes-Carneiro et al. 2021).

CHAPTER TWO: NATURE & CULTURE IN AMAZONIA

Amazonia has long been recognized for its biological diversity (Plotkin 2020:9). Images of lush, green tropical forests dominate the public's perception of life in the South American river basin. Similarly, the history of anthropological and archaeological research in the region has been characterized by its environmental approach. Early on, Julian Steward (Steward 1946, 1955) examined how ecology might influence cultures as well as how the impacts might be detected archaeologically through the "cultural core", a "constellation of features which are most closely related to subsistence activities and economic arrangements" (Steward 1955:37). Moreover, archaeological cultures that demonstrated cross-cultural regularities in their ecological adaptations and maintained similar levels of sociocultural arrangements would represent a "cultural type". This approach came to be known as cultural ecology.

In South American archaeology, the approach of classifying cultures through environmental zones became the guiding schema for writing about the pronounced linguistic and cultural diversity of the continent early on (Silverman and Isbell 2011:8). The most apparent example comes from the *Handbook of South American Indians* (Steward 1946-1959), which was published by the Smithsonian Bureau of American Ethnology as part of a series that documented the cultural, physical, and historical geography of the western hemisphere. Steward (1946:4) adapted a pre-existing culture area scheme and organized ethnological and archaeological research according to four cultural cores, *Vol. I, The Marginal Tribes* (1946)*, Vol. II, The Andean Civilizations* (1946)*, Vol. III, The Tropical Forest Tribes* (1948)*,* and *Vol. IV, The Circum-Caribbean Tribes* (1948). Within these, indigenous cultural traditions were classified according to their geographic location and conceptualized as products of their distinctive regions. In Volume III, for instance, the tropical forest and savanna tribes of the Amazon were brought together under their limitations and adaptations to dense forest and extreme hydrology, as hunter-gatherers and moderate horticulturalists of bitter manioc who lacked architectural and metallurgical refinements but were skilled at navigating rivers and making pottery (Lowie 1948:1).

Cultural ecology led to the adoption of ecological and evolutionary principles from the fields of natural science. This was the approach taken by South American archaeologist Betty J. Meggers (1954, 1960, 1971, 2001) who understood the small populations of contemporary indigenous groups in the Amazon as representative of the groups that inhabited it 2,000 years earlier. In exploring the interactions between cultures and the tropical lowland environment, she found that the subsistence practices, social organization, and belief systems of several tribes in the *terra firme* (forest uplands) and *várzea* (river floodplains) were cultural adaptations to the differential resource availability of the two areas (Meggers 1971). Since then, low population density, early warfare, swidden horticulture, and food taboos have all been evaluated as human responses to natural resource scarcity in the Amazon (Lathrap 1968; Rival 2006; Ross et al. 1978).

Similarly, Meggers (1960:306–307) argued that a key variable in the growth of cultural complexity was the agricultural potential of the surrounding environment due to its effect on subsistence. She drew on Leslie White's (1949) thermodynamic law of evolution, which states that the cultural output of any group is equal to the interaction between energy and technology. As such, in a Type 1 environment, which Meggers defines as having little to no agricultural potential, a society whose technological reservoir is limited to that which human bodies can accomplish (i.e., no domesticated work animals) will be severely limited and constrained to a small-scale hunter-gatherer lifestyle such as those identified in the Amazon. Under this perception, the environment determines cultural output because its agricultural potential controls how much energy a population has access to. This would also explain the apparent lack of monumental architecture and other evidence for complex societies in the Amazon during the period Meggers worked.

Environmental determinism was also compounded by Western biases. In contrast to European researchers who were studying their own prehistoric ancestors, interpretations of pre-Columbian groups in America were heavily impacted by native stereotypes (Trigger 1980). At its core, these stereotypes represent an "idealized European vision" of New World peoples and frame them as innocent and timeless, ecologically noble savages (Redford 1991:1). They assume that either groups could not or would not progress out of traditional lifeways. Sustainability and preservation of the natural environment came before individual needs, and communities would rather live a marginal existence than "improve" their lives by exploiting natural resources (i.e., mining, logging, and hunting) and manipulating their surroundings. This is the corollary to the ecologically noble savage, the belief that when Europeans arrived, the western hemisphere was a pristine wilderness, untouched by humans. In contrast to these Western ideas, indigenous peoples were not limited in size and complexity by their environments nor striving for their preservation (Denevan 1992).

Across Amazonia, a now large body of archaeological and environmental research reveals the magnitude and diversity with which people engaged with and transformed their surroundings. Evidence for large built environments, intensive agriculture, the creation and management of agroforests, as well as the control of water, comes from all areas of the basin, largely from riverine and seasonally flooded savannas like Mojos, the Upper Xingu, and Marajó Island but also from *terra firme* forests (Balee 2013; Duncan et al. 2021; Heckenberger et al. 2003; Khan et al. 2017; Levis et al. 2017; Neves et al. 2004; Piperno et al. 2015; Posey 1984; Prestes-Carneiro et al. 2021; Roosevelt 1991; Whitney et al. 2014). Aside from conducting archaeological surveys and excavations, which can detect the presence of Amazonian Dark Earths (ADEs)—fertile black or brown, anthropogenic soils containing charcoal and ceramics—these studies have made use of ecological inventories and ethnobotanical studies in order to understand the use and distribution of economically valuable species by indigenous groups as well as remote sensing technologies like LiDAR, which can detect differences in forest composition and anthropogenic structures by collecting topographic data (Odonne and Molino 2021).

Many of these studies fall under the interdisciplinary research paradigm known as historical ecology (HE), which explores human-environment relationships as they are expressed across different spatial scales and temporal dimensions. Its characterization as interdisciplinary is fundamental because the ways in which human behavior can manifest within the environment are incredibly varied. The research program makes use of anthropology, geography, plant genetics, integrative biology, and general ecology (Balée 2006; Erickson and Balée 2006). Additionally, Crumley (1994:9) writes that among humans, “practices are maintained or modified, decisions are made, and ideas are given shape; a landscape retains the physical evidence of these mental activities”. In this way, the landscape becomes the primary unit of analysis, and humans are understood as a primary mechanism for change. Thus, as opposed to environmental determinism, HE depicts humans as creative agents that are capable of creating, shaping, and maintaining landscapes to suit their needs. Unlike cultural ecology, cultures are not limited by their ability to adapt their technologies and populations to their surroundings. Furthermore, historically modified landscapes become the background upon which new generations are born and come to develop their worldviews and practices, which will, in time, come to define the landscape, demonstrating a dialectical relationship between nature and culture but also the past and present.

Furthermore, recent engagement with the theoretical perspective of landscape within the wider field of anthropology encourages archaeologists to focus on the exploration of this phenomena as it may be perceived in more traditional, indigenous ontologies. Descola (2013, 2016) reminds researchers that Western society is unique in dividing the domains of nature and culture and that most groups prior to scientific thought conceptualized themselves and their actions as part of the broader natural world. In his ethnographic research with the Amazonian Achuar of the Ecuadorian rainforest, for instance, Descola (2016:5) defines landscape as a process of transfiguration, which induces a "deliberate change of appearance at the end of which this site becomes the global sign of something other than what it was globally before it was transfigured". Hence, when the Achuar build a house garden, they are not constructing a space that is divorced from the nearby tropical forest—they are merely transfiguring how the forest appears in that portion of the environment through a specific selection and arrangement of plants. Their dwelling and associated tasks do not constitute a purely cultural realm that is dichotomized from the space in which they work because they are one and the same.

Within West Central Mojos, sprawling anthropogenic landscapes can only be understood as the result of a long-term dialectical relationship between the Mojeño communities and the ecology of the floodplains. Over the course of numerous generations, the accumulation of earth in novel ways transfigured the original or "pristine" environment into a physically and perceptually new cultural realm that provided spaces in which to live, farm, and fish yet was still fundamentally dependent on natural seasonal cycles. As opposed to claims of earlier Amazonianists, pre-Columbian communities were not limited by soil infertility or seasonal flooding. In fact, they were drawing on and expanding the latter's impact for their own needs. Especially in the context of the newly identified fish weirs within WCM, this project will argue that local groups were recreating the larger wetland environment in which they lived. Instead of a *land*scape, however, this kind of hydrological transfiguration manifests a waterscape, which emphasizes the connection between nature and society in an aquatic place (Swyngedouw 1999). Prestes-Carneiro and others (2021) are the first to apply this concept in the Amazon. They coopt the application of waterscape in political ecology and to local ontologies to emphasize how places are created by the often-uneven distribution of water and access to it (Gagné and Rasmussen 2017; Strang 2005; Swyngedouw 1999). Further, these features provide a framework from which to explore the variety of ways people know and interact with water in different waterscapes. In particular, the authors use "waterscape domestication" to understand "how humans and animals have interacted throughout history in the many aquatic environments in Amazonia" (Prestes-Carneiro et al. 2021:92). The application of waterscape and domestication here does not emphasize ethnozoology and domestication of aquatic species to the same extent.

Instead, landscape is approximated by waterscape; this allows it to retain the same theoretical meaning under historical ecology yet emphasizes the importance of water in Mojeño life.

CHAPTER THREE: BACKGROUND

Physical Context

Llanos de Mojos is a wetland savanna spanning approximately 110,000 km^2 in the northern geopolitical department of Beni, Bolivia (Figure 1). This region sits between the Andes mountains and the uplands of the Brazilian Shield and is characterized by a hot and humid climate as well as strong, predictable cycles of drought and flooding (Walker 2008a:927). It is also distinguished by its location at the southern end of the Amazon River basin. From here, the Río Madeira contributes 19.1% of the Amazon's annual volume, and its Mamoré tributary, the central river in Mojos, contributes 4% (Amazon Waters Initiative 2023). Consequently, the environment within the Madeira River basin is characterized by its avulsion-prone fluvial network, an amalgamation of small river channels whose courses readily change and leave lakes, swamps, and paleochannels in their wake. Elevations on the alluvial plain only vary between 150 and 170 m above sea level (Walker 2008a:928), permitting even small rivers to routinely overflow, change course, and deposit sediments known as crevasse splays (Lombardo 2016). Mojos also experiences extreme seasonal changes in precipitation. Droughts persist from May to September when winter weather dries many of the shallower fluvial channels. However, beginning in November, heavy rains fill the tributaries of the Mamoré with 1,500 to 1,800 mm of precipitation, causing downstream rivers to back up and inundate the surrounding landscape. Additionally, poorly draining clay loam soils and minor topographic relief result in standing water for five to ten months of the year (Denevan 1966:9–13). This unique combination of topography and hydrology leads local inhabitants to describe the wet season as a mixture of “water from above”, in the form of rain, and “water from below”, in the form of flooding (Walker 2018:117).

The intense, annual flooding and constantly evolving fluvial network have important effects on the topography and ecology of the region. As a result, environments in Mojos are distinguished (1) by their susceptibility to flooding, and (2) by the vegetation that tolerates the amount of available water. These present as a mosaic of wet and dry savannas and forests (Denevan 1966:15–18). Wet savannas are the most abundant type of environment and are characterized by their relatively low elevation and poorly draining soils, which leave them submerged for half of the year. As a result, they produce grassland, or *pampa*, vegetation as few tree species can tolerate the extremes of flooding and drought. Elevated and well-drained areas are more susceptible to fires. Lowland savanna can also burn at the height of the dry season when small rivers evaporate, and grasses dry out. Wet forests are found along the sloping banks of rivers in *galerías*. These areas are the first to see inundation in November and contain many economically useful trees such as Brazil-nut (*Bertholletia excelsa*), wild rubber (*Hevea brasiliensis*), and the fast-growing *balsa* (*Ochroma*), which is noted for its soft wood. Dry savannas and forests are characterized by well-drained and elevated soils, often located on river levees, and in forest “islands” along smaller rivers and abandoned fluvial channels. Other kinds of local categories denote transitional environments. An *arboleda,* for instance, is an area of open scrub that is only briefly flooded. In western Mojos, many *arboledas* feature termite mounds and agricultural earthworks that support the growth of drought-tolerant trees and palms.

These marked differences in vegetation and water levels have important implications for the modern and pre-Columbian inhabitants of Mojos. For them, arguably the most important component of this complex landscape are the islands of dry forest, which are easily recognized on satellite imagery as dense concentrations of trees in an otherwise open landscape (Figure 4). These *islas*, which total several thousand in WCM alone and average 7 ha, have provided refuge and resources to inhabitants since Mojos was first occupied more than 10,400 years ago (Lombardo et al. 2020). Their elevation offers dry land for settlement and agriculture; forests provide shade, wood, and other useful/edible plants; and wildlife offers opportunities for hunting (Walker 2018:41–42). Nearby bodies of water keep locals hydrated and provide resources like fish. Langstroth (1996:6–8) finds that the islands are formed by multiple natural and artificial processes. Natural forest islands are commonly identified by sandy soils and their arrangement "in chain-like patterns", a product of their origin in the eroding banks of river levees. In contrast, anthropogenic islands are characterized by the clayey subsoil of their adjacent wetlands, which ancient inhabitants built up into artificial mounds (Langstroth 1996:xv–14). More recently, researchers have identified forest islands of shell-midden on both sides of the Mamoré, which were made by the mobile hunting and gathering groups of the early and middle Holocene (Lombardo et al. 2013). This generates questions about the extent to which early inhabitants created or transformed their surroundings.

Irrespective of their origins, a series of reconnaissance studies by Walker (2018:41–43) demonstrates that the islands were frequently inhabited. Nearly 75% of the islands surveyed show evidence of permanent pre-Columbian habitation, demonstrated by thick layers of anthropogenic soils and ceramic deposits. Based on these findings, seasonal flooding has implications for the cultural context within Mojos, and populations living in this wetland savanna for thousands of years were likely active participants in the environment.

Social & Historical Context

The earliest accounts of the indigenous populations in Mojos were authored by Spanish explorers, soldiers, and missionaries, beginning in the mid-sixteenth century. Interest in the Bolivian Amazon initially developed because of a desire to locate the legendary city of gold known as the “Realm of the Gran Mojos or Paititi”, a rumor that was founded on anecdotes of the Inca Empire in the Andes (Métraux 1943:3). However, these early expeditions were quickly abandoned in the swampy and mosquito-ridden conditions of the savanna. By the 1540s, the only significant discovery was that Mojos was heavily populated by a number of ‘savage Indian chiefdoms’ (Denevan 1966:1, 29). These were the multiethnic and multilingual groups whose distinct social structures and lifeways were of interest to Spanish missionaries.

Eventually, the exploitation and conversion of these groups became the focus of Spanish involvement in the region. This was initially carried out in the form of slave raids from Santa Cruz. Block (1994:31) notes that these incursions, which at times took more than 300 prisoners, significantly contributed to the disruption of life on the savanna, impacting productive capacities and social structures in villages. For missionaries, fear of being enslaved was the largest obstacle in converting inhabitants to Christianity. Even when the region fell under the administration of the Jesuit Order in 1668, it took an additional 16 years to establish Loreto, the first Spanish settlement in Mojos (Denevan 1966:29–31). Following this, priests marshaled what was left of the dispersed villages and established 21 missions where native cultures were repressed and replaced with dominant languages, new political and settlement patterns, new crops, new crafts, and new traditions (Block 1994). This process, along with the epidemics brought by Europeans, contributed to a major depopulation of the savanna as well as to the destruction of cultural entities that had complex but productive relationships with their surroundings (Métraux 1943:1–2).

Early ethnohistoric accounts from missionaries are among the most descriptive of the cultural and linguistic diversity that was present in the region before it was broken down by Spanish influence. In his review of these accounts, Denevan (1966:40–53) identifies six main linguistic groups that occupied the savanna: the *Mojo*, *Baure*, *Cayuvava*, *Movima*, *Itonama*, and *Canichana*. These groups were among the largest and most politically influential in the savanna. There were also numerous "marginal tribes", which were distinguished by their smaller size and unique languages. Similar to the Canichana, they were described as occupying the edges of the region on forest islands and *gallerías*, subsisting off of hunting and fishing. Detailed reports were reserved for the "socially stratified agricultural people with large populations and large villages", namely the Mojo, Baure, and Cayuvava whose relatively "civilized" appearance intrigued the Spanish (Denevan 1966:43). Sources document well-made plazas and streets with inhabitants who wore clothes and participated in skilled crafts such as weaving and pottery making. Communities were presided over by local headmen, and often by a single chief at the larger scale. In addition to their long-distance trade relations, these villages were distinguished by their exceptional agricultural capacities, and surpluses of maize, manioc, and peanuts were frequently traded for stone grinders, salt, and knives. Descriptions of these groups heavily contrasted those of the Movima and Itonama, who displayed evidence of large villages and sophisticated craft but less reliance on agriculture and village governance, often referred to as “naked barbarians…living in misery…with bestial customs” (Denevan 1966:53).

In addition to their diversity, Europeans noted during contact that these groups were remarkably well-adapted to the complex, semiaquatic environment they lived in. Agricultural efficiency and success in hunting and fishing were supported by in-depth knowledge of the surrounding floodplains. During the wet season, for instance, inhabitants traveled in canoes, built raised barbeque pits, and slept in hammocks hung above the floodwaters (Block 1994:23). The hallmark of these groups and their predecessors was their participation in major community drainage projects that made settlement, agriculture, transportation, and water management possible within the seasonally flooding savanna (Denevan 1966:45). This resulted in the creation of permanent earthworks across the extent of the floodplains. However, ethnohistoric accounts are limited in that they cannot describe the pre-Columbian peoples of Mojos, or *Mojeño,* that occupied the region for thousands of years prior to the arrival of the Spanish (Walker 2018:2). Explorers and Jesuits do not mention savanna farming or the construction of earthworks in their accounts (Denevan 1966:95). As a result, interpretation of these features requires archaeological research.

Archaeological Research in Mojos

Archaeological research on the pre-Columbian landscapes of Mojos began in the early twentieth century with Erland Nordenskiöld (1913), who produced detailed reports on the cultural material of several large residential mounds outside Trinidad. More recently, archaeological work in southeastern Mojos has sought to understand the nature of pre-Columbian habitation by collecting data on pottery, subsistence, mortuary practices, and residential mound construction. A combination of remote sensing and field survey revealed 189 of these monumental sites, or *lomas*, over 200 smaller sites, and approximately 1,000 km of causeways and canals (Lombardo and Prümers 2010; Prümers and Jaimes Betancourt 2014). Excavations at Loma Mendoza by Prümers (2012), for instance, documented periodic remodeling events of a 1,000-year occupation, which started with the construction of a platform around 400 AD and was followed by a truncated pyramid and additional lower house platforms. They conclude that these sites were not uninhabited ceremonial centers but instead permanently occupied by agriculturalists who cultivated a diversity of crops (Dickau et al. 2012; Whitney et al. 2013). Additionally, ceramic studies contribute to the formation of a regional chronology. By comparing sequences between habitation sites, researchers have been able to demonstrate contemporaneous occupations for Lomas Alta de Casarabe, Mendoza, and Salvatierra (Jaimes Betancourt 2012; Prümers 2012). Current research in the area now employs LiDAR to specify the extent and size of these Casarabe-culture sites. Prümers and others (2022) define a four-tiered hierarchical classification of sites based on platform dimension, architecture, total area enclosed, and number and scale of additional earthworks. They find that the two largest sites, Cotoca and Landívar, represent the first case of "tropical agrarian low-density urbanism" identified in the tropical lowlands of South America, refuting the age-old claim that Amazonia was occupied by small populations that did not take part in monumental architecture or craft specialization (Prümers et al. 2022:325).

Anthropogenic transformations of the landscape extend far beyond the confines of the residential mound or forest island "site", however, and these settlement investigations represent only a small portion of the archaeological research being conducted in the region. Duncan and others (2021) find that climate change in the early Holocene is unable to account for the large-scale hydrological and vegetative changes that began in West Central Mojos around 3,500 ya. Instead, paleoenvironmental and archaeological evidence demonstrates that pre-Columbian communities were involved in the historical creation and maintenance of engineered landscapes that utilized hydrology, fire regimes, and agroforestry to increase the productivity of their environment.

Further, regional patterns of artificial earthworks, consisting of raised, mounded, and ditched agricultural fields, causeways, canals, ring ditches, and fish weirs, demonstrate that Mojeño groups were not limited by seasonal flooding or soil infertility. The first of these studies was conducted by William Denevan (1966) who synthesized the early sporadic surveys by archaeologists and Spanish accounts in order to paint a regional picture of pre-Columbian Mojos. This book profoundly impacted the kind of research being performed in Mojos by drawing attention to the role of artificial earthworks in pre-Columbian life. As a result, many recent archaeological studies have focused on the shape, purpose, extent, and patterning of these earthworks (Blatrix et al. 2018; Denevan 2001; Dougherty and Calandra 1981; Erickson 1980, 1995, 2000, 2006, 2010a, 2010b; Erickson and Balée 2006; Langstroth 1996; Lee and Walker 2022; Lombardo 2010; Lombardo et al. 2011, 2020; Lombardo and Prümers 2010; Martin 2018; Mckey et al. 2014; McKey et al. 2022, 2016; Prestes-Carneiro et al. 2019; Prümers 2012; Prümers et al. 2022; Prümers and Jaimes Betancourt 2014; Robinson 2021; Walker 2001, 2004, 2008a, 2008b, 2011a, 2011b, 2018; Walker and Erickson 2009; Whitney et al. 2013, 2014).

Within WCM, the landscape has been the focal point of archaeological research into the lives of its past inhabitants since the 1990s and earlier. First under the guise of Proyecto Agro-

Arqueológico del Beni (PAAB) but now managed as the Proyecto Sistemas Informaticas Geograficas y Arqueologicas del Beni (ProSIGAB), one archaeological project has been conducting survey and excavation along the Iruyañez and Yacuma River systems. Here, habitation sites on forest islands tend to be associated with pre-Columbian landscapes such as those containing raised fields. Raised fields are part of an agricultural technique that utilizes rectangular platforms of earth accompanied by adjacent canals in order to elevate crops above seasonal floodwaters (Martin 2018). The documentation of these earthworks by Denevan (1966) garnered the attention of Andeanist scholars like Clark Erickson who were studying the remnants of agricultural earthworks in the *altiplano* (Erickson 1980). Not only have these platforms been found to prevent cultigens like squash and root crops from rotting in floodwaters, but experimental projects demonstrate that they also yield more annually than modern swidden agriculture. This was likely achieved by farmers applying canal sediment, or "green manure", as fertilizer (Stab and Arce 2000).

Later research conducted by John Walker (2004) sought to understand why raised field systems were eventually abandoned, leading to greater knowledge about pre-Columbian settlement in WCM. Site data from the intensive excavation and survey of chiefly two forest islands, El Cerro and San Juan, was combined with remote sensing data of raised fields. The addition of chronological data from radiocarbon dates and historic documents identified changes in population density, agricultural intensity, and social organization through the pre-Columbian, protohistoric, and historic periods.

Evidence of significant anthrosoils (containing Amazonian Dark Earths, charcoal, ceramics, and burned clay) were recorded alongside a high number of nearby fields, suggesting that El Cerro could have possibly supported around 2,000 individuals during the pre-Columbian period around the 6th century (Walker 2004:121, 2011a, 2018:52–56). Radiocarbon dates pulled from contexts containing ceramics estimate occupation at San Juan from 400 to 700 CE cal (Walker 2018:48-50). Here, the recovery of large rim sherds (~1 m in diameter) in association with raised fields has been connected to large feasting events, likely to feed the work parties who were building and maintaining the earthworks. Additionally, the ceramic assemblages recovered from this site are among the first to be associated with raised fields, prompting researchers to investigate how these sites relate to other sequences in and outside of the region (Walker 2011). For example, compared to the wares documented by Jaimes Betancourt (2012) at Loma Salvatierra, the ceremonial center was making use of a much wider cultural inventory of design elements, fields, paint colors, and sculptural techniques than San Juan. Domestic and ritual practices are not necessarily shared across a similar floodplain environment. Given that the San Juan occupation exists toward the beginning of the 1,000-year occupation at Salvatierra, time could be playing a significant role. Additionally, Walker (2011) notes that the limited variation in San Juan wares could indicate a specifc use-context, in which only the serving vessels of a cultural assemblage are represented.

Archaeological evidence like ceramics and raised fields are significant indicators of cultural lifeways and population densities. Walker (2004) finds that while European diseases did reduce the overall population within the region over time, Contact alone is not an adequate reason for the abandonment of raised fields because this kind of agriculture would have been a familiar and realistic option for survivors, especially given the small number of individuals required to construct the platforms. Similarly, given the ability of WCM communities to raise the agricultural capacity of their surrounding environment, climate change (such as ENSO events) would not have posed a significant threat to this way of life. There is also insufficient data to suggest that these climate events were even affecting pre-Columbian settlements. Finally, while Jesuits did introduce metal tools and cattle, there is no evidence of raised field agriculture within Missions, and thus, no evidence that Jesuits attempted to change agricultural practices (Walker 2004:121-125).

More recently, a common finding by many studies is that different types of earthworks are often found associated with one another across the savanna. Walker (2018:123–126) identifies seven regional patterns of these unique cultural landscapes and finds that they were produced under different local histories and ecologies and permitted different kinds of community tasks. For instance, in southwestern Mojos, raised fields, causeways, and canals form a larger network of earthen structures that spans over 50,000 km^2 of savanna along the Río Apere (Erickson 1980, 2006; Walker 2011b, 2018; Walker and Erickson 2009). In addition to the subsistence tasks afforded by fields, the construction of canals near mound or forest island settlements permitted water management and the transportation of goods and people via canoe. Despite dominating canoe transportation, waterways were likely difficult to navigate during drier parts of the year when water levels were low and aquatic vegetation grew thick. During these times, associated causeways, or ancient roadways, provided another means of passage over land, connecting important locations more than 10 km apart (Denevan 1966:89).

Thus, in WCM the movement of earth by past local groups transformed the savanna into a multifaceted, productive landscape that fostered agriculture and efficient transportation. Additionally, because these anthropogenic environments vary across Mojos, the types of features and the advantages they afford vary as well. For instance, the mound fields currently being mapped in western Mojos differ drastically from raised fields in their spherical shape, raising questions about their use in agriculture (Figure 5). In Baures and WCM, forest island ring ditches have been debated as serving defensive functions, given the way they encircle village sites (Erickson 2006). More recent research reveals their possible connection to the cultivation of house gardens and the prevalence of ADEs and agroforestry, more broadly (Robinson et al. 2023; Walker 2008b, 2011c). In particular, this study concerns the last of these earthworks, fish weirs. Prior to this, fish weirs had only ever been mapped in the Baures hydraulic complex to the far east of Mojos. Since their identification in WCM, they have been found associated with forest islands, raised and mounded fields, and artificial ponds. The widespread distribution of fish weirs across the savanna, however, raises questions about their potential role in water management and the creation of semi-permanent wetlands, which likely had significant implications for the rest of the cultural landscape as well as the ecology of the environment.

Fisheries in Mojos

> Fishing was one of the most rewarding activities. Annually, the receding floods left millions of fish stranded on the land or concentrated in small pools were [*sic*] the Indians killed them at leisure with cudgels and spears. More commonly, fish were shot with bows and arrows…The Mojo also built weirs across the outlets of lagoons and placed a fish trap in each opening of the weir [Metraux 1948:414].

Ethnohistorical and Zooarchaeological Evidence

Aquatic resources abound in the interfluvial environment of Mojos, making them key components in indigenous economies of the pre-Columbian period and those of the modern day.

Of the six main linguistic groups that occupied the savanna when the Spanish arrived, each was skilled at navigating dugout canoes and employed numerous fishing strategies, depending on the catch, season of year, water levels, and even time of day. Knowledge of these practices is limited to a few sentences in most Jesuit sources; however, they are supplemented by a growing body of zooarchaeological research (Prestes-Carneiro et al. 2019; Prestes-Carneiro and Béarez 2017:387). Through several investigations east of the Mamoré River, Prestes-Carneiro has sought to evaluate the role of fishing in Mojeño economies and Amazonian societies more broadly. Especially as landscape patterns differ across the region, so too will fishing environments and the specific cultural technologies used to take advantage of aquatic resources. These include both tool-based strategies as well as landscape modifications that controlled water.

Throughout the year, indigenous groups made creative use of clubs, spears, bows and arrows, poison, and traps. Calm waters were ideal for the application of plant-based fish poisons, commonly known as *barbasco* (i.e., *Paullinia pinnata*, *Hura crepitans*, and others), which would anesthetize or kill large quantities of fish. At night, fishers would attract their catch using torchlight. Other techniques made use of bottomless baskets and bushels of reeds to manually trap fish in shallow waters or force them toward the shore where they could be easily speared or clubbed. Fishhooks and nets were introduced by the Spanish missions but were not commonly used until the first half of the twentieth century because they risked snagging on branches and other debris in swampy environments (Denevan 1966:109; Métraux 1948:414; Prestes-Carneiro and Béarez 2017).

By far the most efficient strategy recorded during contact relied on the seasonal cycle of flooding. As water levels retreated through April, May, and June, they stranded fish in small muddy pools of lowland savanna where they were easily killed and collected. Given the availability of and ease with which fish were caught, these practices were more important for obtaining protein among the Mojo, Baure, and Canichana than hunting (Métraux 1948:408–425). In fact, fish represent approximately 40% of the total faunal remains recovered at Loma Salvatierra, providing evidence that aquatic resources occupied a more important role in the pre-Columbian diet than terrestrial species such as cervids, birds, and rodents like agouti and nutria (Prestes-Carneiro et al. 2019). These findings are significant in light of earlier claims that lowland Amazonian societies were limited in size and complexity by a dearth of available protein (Lathrap 1968; Lowie 1948; Ross et al. 1978).

Along with caiman, turtles, and freshwater snails, historic and archaeological sources identify several commonly eaten species of fish among groups before and during contact. This includes those found in clear running waters of lakes and rivers such as *surubí* (*Psuedoplatystoma* spp.), *tucunare* (*Cichla* sp.), and *dorado* (*Salminus* spp.) as well as several species that thrive in shallow and stagnant floodwaters such as armored catfish (*Hoplosternum littorale*), tiger fish (*Hoplias malabaricus*), *serepapas* (*Cichlidae* spp.), pirañas or *palometas* (*Serrasalmus* spp.), and *anguila* (*Synbranchus* spp. eels and *Lepidosiren paradoxa* lungfish). Interestingly, out of 36 taxonomically identified species, fish in this second group are overrepresented in the archaeological record at Loma Salvatierra (Prestes-Carneiro et al. 2019). Ninety-eight percent of the study's MNI is accounted for swamp eels, armored catfish, and lungfish which are facultative air-breathers and can survive in shallow, poorly oxygenated waters or muddy channels that are left behind at the height of the dry season. Their recovery from artificial ponds and canals implies the intentional use of landscape modifications by inhabitants to extend their exploitation of fish as a protein resource well into the driest season of the year. Receding floodwaters will naturally funnel fish to the lowest point in the landscape; this includes paleochannels and swamps but also anthropogenic ditches. Additionally, as ponds create unstable environmental conditions, only fish adapted to these circumstances would survive. Thus, the archaeological communities at Loma Salvatierra could (1) catch larger, open-water species as flooding reached its largest extent and (2) harvest as needed from a stable store of drought-tolerant fish the other half of the year.

Baures Hydraulic Complex

Archaeological knowledge of pre-Columbian fishing activities in Mojos is further augmented by examining the presence and use of fish weirs in the region. Employed by indigenous communities throughout time and all over the world, fish weirs represent a diverse category of traps and structures that are built into bodies of water and designed to drive fish into an enclosure where they can be easily caught and collected. Each build is influenced by local hydrology, geography, and topography but can also be determined by the available construction materials (Connaway 2007:5). However, the ability of a fish weir to function as intended hinges on indigenous knowledge, which local communities develop through long histories of interaction with their land and nearby water sources. As a result, they create valuable pieces of infrastructure capable of providing a stable source of dietary protein (Connaway 2007; Erickson 2000; Huchzermeyer 2012; McKey et al. 2016).

First studied by Clark Erickson (2000), the Baures hydraulic complex represents one of the several identified landscape patterns in Mojos but was the first documented to contain fish weirs, which are found associated with artificial ponds, canals, causeways, forest islands, and ring ditches (Figure 6). Erickson's identification of these hydraulic features is predicated on "form, orientation, location, association with other hydraulic works and ethnographic analogy" (Erickson 2000:190). He notes that the non-linear mounds (1-2 m wide and 20-50 cm tall) are made from compacted earth and zigzag across the savanna for distances of up to 3.5 km, often reaching the edge of forest islands. The key aspect of these earthworks, however, is the presence of funnel-like openings at each angle of the zigzag. These occur every 50-200 m and are approximately 3 m long and 1-2 m wide (see Figures 3 and 5 in Erickson 2000).

Due to the absence of agricultural fields and a design that is inefficient for transportation, Erickson contends that the earthworks were suited for managing and harvesting fish, especially when understood in the ecology and hydrology of the Baure environment. As waters increase during in the wet season, fish have considerable mobility over the terrain, but as flooding declines from April to July, they become trapped behind the earthen barriers and funneled toward the ends of the zigzags where nets or baskets collect the catch. Additionally, the associated nearby ponds (10-30 m in diameter) retain water all year round and could keep fish alive until needed. Further, by enclosing anywhere from 10 to 80 ha of savanna, this cultivated wetland environment would support the cultivation of other species such as freshwater snails (*Pomacea*), reptiles, and birds, which were eaten by inhabitants, as well as palms (*Mauritia flexuosa*), whose fibers were of great utility for weaving mats, basketry, hammocks, bowstrings, and thatching roofs. Ethnographic accounts and radiocarbon dates of charcoal from an associated causeway suggest that this enhancement and management of seasonal aquatic resources was built and maintained by small kin groups and communities prior to the arrival of the Spanish around AD 1700 (Erickson 2000).

Several recent studies support and build upon Erickson's assessment of the Baures landscape. McKey and others (2016) identify cultural and ecological parallels between Mojos and a modern-day hydraulic complex in the Bangweulu floodplains of Zambia (see Figure S3 in McKey et al. 2016). Not only do the fisheries share a similar construction in similar environments, but according to the ethnographic analog, the Baures complex would have been a highly productive and sustainable form of aquaculture. Huchzermyer (2012) finds that because larger adult fish favor deeper water, they leave the shallow spawning area provided by the weirs before water levels drop below the earthworks. Additionally, most juveniles targeted by the weirs do not survive the competition and predation of their first dry season. Thus, the fisheries have no negative effect on the population and Zambian fishers can catch an annual yield of 35.5 kg of fresh fish per hectare of enclosed floodplain. If systematic excavations and zooarchaeological studies can confirm that this analogy is correct, the Baures fisheries would represent valuable community infrastructure that could be maintained for generations after the initial investment of labor. McKey and others also draw inferences from Zambia about the social organization that might have predicated construction, maintenance, and use of the weirs. Bangweulu fishing chiefs known as *chipupila* serve political and spiritual positions in fishing communities. They decide access rights to individual weirs and mediate conflicts between fishermen. Additionally, weir construction and maintenance are collective activities. As a result, the fishing economy forms a central part of community life by balancing individual privileges and social responsibilities.

The most recent study of the Baures hydraulic complex by Blatrix and others (2018) analyzes the spatial organization of the weir zigzags, or V-shapes, in relation to the flow of water and placement of artificial ponds. Working in a separate study area from Erickson (2000), they record a new kind of weir with significantly larger V-shapes (~30 m long and 39 m wide), 90% of which lacked the funnel-like opening at each end. Instead, these earthworks contain centrally located ponds, which the authors argue would function to trap bottom-hugging fish as water levels depleted in the dry season. This would negate the need for inhabitants to manually collect fish in baskets to be moved and stored in ponds farther away. Sample excavations also located a live *Synbranchus* swamp eel within the moist sediment of a pond during the dry season, supporting the authors' conclusion that the design of the structures targeted different fish (Blatrix et al. 2018:10). Funnel-like openings for use with baskets catch the out-migrating, open-water fish that recently finished their reproductive season in the shallow waters. These are the same kinds of species found by McKey and others (2016) in the Zambian analog and by Prestes-Carneiro and colleagues (2019) at the archaeological site of Loma Salvatierra (i.e., *surubí*, *dorado*, *serepapas)*. The nested ponds, however, target the facultative species such as eels and armored catfish that thrive in murky, stagnant floodwaters. Importantly, no zooarchaeological study has yet been conducted on the Baures or WCM fish weirs, but such data will be crucial to verify how these features operate.

Collectively, these case studies illustrate how different Mojeño communities made productive use of the ecological niche that is seasonal flooding by exploiting similar species of fish with similar technologies. While Loma Salvatierra does not yield evidence of fish weirs, pre-Columbian inhabitants were capitalizing on the natural processes of inundation and desiccation to catch and store fish year-round. Moreover, the use of ponds in each location is intriguing. While never found alone, these key pieces of infrastructure supplement the use of canals and fish weirs by providing depressions that trap fish as flooding recedes. This practice also harkens back to ethnohistoric sources, which document linguistic groups walking around the draining savanna and bringing home baskets of fish (Métraux 1948:414). The only difference is that archaeological populations were engineering waterscapes that would guarantee large, sustainable quantities of food within accessible distances from their villages.

Along with zooarchaeological evidence, fish weirs provide the strongest evidence that indigenous communities in Mojos were intentionally modifying their surroundings to expand an ecological niche. If not for the fish remains at Loma Salvatierra, ponds and canals might only be associated with water management in order to provide crop irrigation and maintain a source of fresh drinking water for inhabitants. Thus, in Baures, the presence of the features is important, especially given that no systematic excavations have occurred in the vicinity of the fish weirs and no zooarchaeological studies have been carried out (Beveridge and Little 2002; Prestes-Carneiro et al. 2019).

Weirs in Water Management

The objective of this project is to better understand the functioning of the archaeological features defined as fish weirs in WCM. Previous research within the region has focused on the fields and forest islands that pre-Columbian populations built to elevate themselves and their crops from the floodwaters that consume the landscape. However, water is still a necessity for communities, and the dry season beginning in early summer can leave the landscape in a state of drought. This begs the question, were inhabitants also participating in large-scale environmental transformations to domesticate wetlands and extend their range and seasonality? This proceeds from the assumption that weirs were not only interacting with water to catch fish but controlling its flow and accumulation for broader purposes.

Non-fishing weirs play a critical role in water management. Unlike dams, weirs do not function to fully stop the flow of water unless levels are very low. Instead, the goal of these systems is to impede and slow water as it moves quickly through different elevations and threatens nearby infrastructure with flooding. Recent research has also found that these features can influence concentrations of nutrients, increasing oxygen levels via water turbation and decreasing downstream eutrophication by storing excess nitrogen and phosphorous. In slower and shallower waters that are characteristic of freshwater wetlands, weirs can foster healthy aquatic ecosystems that feature an abundance of fish, mollusks, plants, and algae (Cisowska and Hutchins 2016; Flora and Kröger 2014).

Because weirs keep water within defined zones and therefore in larger volumes, they increase the amount of time it takes water levels to peak and recede after flooding events. Even low-grade weirs (20-50 cm) located within drainage ditches work to increase water volumes and slow their evaporation and drainage, especially when vegetation is present. This also has a positive effect on local habitats by maintaining a stable water depth for flora and fauna (Kröger et al. 2008; Prince Czarnecki et al. 2014). In some cases, long-term use of weirs can result in the permanent retention of water within the surrounding environment. After the construction of sixteen weirs within four of South Korea’s main rivers, Im and colleagues (2020) reported a significant decrease in the size and number of seasonally flooded and non-flooded habitats while areas with permanent flooding significantly increased. Within contemporary WCM, the strategic placement of a small barrier within the channel of a seasonal stream near the town of Santa Ana del Yacuma resulted in the creation of a new lake in 2017 (Figure 7). These observations and studies, therefore, demonstrate the tremendous impact that can be made with the construction of comparably small weirs.

CHAPTER FOUR: MATERIALS AND METHODS

Given the above information, this project takes an exploratory approach to investigate the functioning and hydrological impact of the WCM fish weirs. This is accomplished through a three-part analysis that collects and interprets spatial data using maps as well as descriptive and inferential statistics. During the first part of the analysis, distance and spatial patterning between fish weirs serve as a means for grouping them into two kinds of potential wetlands. These units provide an estimate for how much land is affected by these weirs in comparison to the amount of earth moved in their constructions; thus, groups can be tested for statistically significant differences in size as well as distance to other features. Additionally, potential wetlands displaying different spatial patterns may also show patterned differences in their relationships to other hydrological and anthropogenic variables. This latter data is collected in the second and third parts of the analysis. In the second, relationships are defined between the defined clusters of fish weirs and large rivers or bodies of water within WCM. In addition to rain, rivers would act as sources of water for fish weirs to manipulate, making distance an important variable. The third part defines relationships between weir clusters and other anthropogenic features in the landscape. Where do weirs fall in relation to forest island settlements and different types of agricultural fields? Tests of association are used to quantify how variables change together.

Mapping Fish Weirs with GIS

The focus of this analysis is the fish weir dataset, an ArcGIS feature layer consisting of almost 1,700 polylines spread across 11,500 km^2 of savanna on the western side of the Mamoré

River in Llanos de Mojos (Figure 2). The polylines represent fish weirs that were digitized using aerial imagery. From above, these archaeological features appear as narrow causeways of packed earth that change directions multiple times at sharp angles, creating zigzags or V-shapes (Figure 8). On the ground, they are obscured visually by tall grasses but can be detected due to an absence of water when traversed (Figure 9). By navigating the GPS coordinates of several of these features, limited archaeological survey has documented stretches of firm, dry ground in otherwise marshy pampa (Walker et al. 2019).

When the dataset was created in 2019, it was originally hosted on ArcGIS Online where volunteers of the Proyecto Sistemas Informaticas Geograficas y Arqueologicas del Beni (ProSIGAB) could collaboratively examine and map large datasets of archaeological features at a more efficient pace. In order to minimize inconsistencies and ensure that no natural landforms or modern features (i.e., cattle trails, roads, fence lines) were included in the dataset, the author verified each individual polyline (Robinson 2021). Now that the dataset contains almost 2,000 entries, however, digitization of this feature class is no longer crowdsourced through an online service but conducted locally on ArcGIS Pro due to the advances in user interface as well as feature editing and management capabilities.

Despite the changes in platforms and number of digitizers, the features have been continuously digitized against the World Imagery basemap, an ESRI-managed map service that provides high-resolution satellite and aerial imagery of the Earth’s surface in the form of a raster tile layer (ESRI 2023b). This service is available for both visualization and analysis, and features DigitalGlobe Maxar imagery with resolutions down to 0.3 m in certain parts of the world such as large metropolitan areas in North America. Even within remote areas such as the Bolivian

Amazon, the coverage is impressive. Several tiles are now beginning to display resolutions down to half a meter, revealing the extent and diversity of anthropogenic landscapes and permitting increasingly precise mapping.

As of May 2023, there are still several caveats in using this service to map. Tiles within the basemap represent mosaics of high-quality satellite imagery. Each piece is selected based on cloud cover and color and then stitched together, but the process is not seamless (ESRI 2023b). Basemap-quality imagery is available at different points in time and seasonal flooding produces a constantly changing environment, meaning that the Mojos landscape varies from patch to patch of the World Imagery "quilt". A tile depicting dry savanna grasses in September might be merged with a tile depicting a saturated wetland from April (Figure 4). Similarly, the features that run between these tiles will vary in appearance based on the time of year. Thus, familiarity with the range in variation is necessary to accurately detect and map these features.

The identification of fish weirs is facilitated through use of the World Imagery Wayback, a digital archive that holds every version of the basemap as it has changed over the past six years and across different regions (Szukalski 2022). The majority of the West Central Mojos dataset was mapped on versions dating to October 2016, but some additions to the basemap appear as recently as July 2022. These tiles were assembled with Maxar Worldview-02 imagery captured in 2015-2016. The imagery's source, satellite information, and the date of capture along with its resolution and accuracy are revealed by selecting any area of the map. The most useful tools available are the Swipe and Animate modes, which display different years of imagery at a scale of the user's choice in a split screen or automatically cycle through several at a time in a GIF format. These tools clearly illustrate the changes in physical appearance for each feature over time and at different seasons of the year, permitting more precise mapping and a stronger determination of its identity as an archaeological earthwork. While constant updates to the basemap make systematic mapping of the region difficult, the publicly available database of legacy imagery suggests that this may be possible at some point in the future when years of half-meter resolution tiles show the full extent of anthropogenic landscapes.

Along with these technical disadvantages, there are a few inevitable limitations that accompany remote mapping projects. First, no matter how high the resolution is, imagery cannot capture every detail of the landscape. Where fieldwork is not part of the research design, there will be a disconnect between what is seen on the imagery and what exists down on the ground. This has been the case while digitizing the novel features of West Central Mojos. The savanna terrain is complex, and it can be difficult to distinguish where a linear feature ends, especially if erosion has affected the structural integrity of the earthwork since its construction and maintenance during the pre-Columbian period. For these features which are non-linear and seemingly no more than a meter wide, this resolution puts them at a higher risk of being digitized incorrectly. Because of this, this project does not investigate questions that cannot be reliably answered based on the available imagery. This includes topics which require precise feature dimensions as well as those that investigate physical aspects of the earthworks such as materials and methods of construction.

Variation in the West Central Mojos Dataset

WCM fish weirs are characterized by significant variations in physical appearance, distribution, and organization. This contrasts with other feature datasets that have been previously mapped in WCM such as the raised fields, which can be easily identified by their consistent and artificial rectangular shape (Lee 2017; Lee and Walker 2022; Lombardo 2010). They have also been distinguished from the more perfectly straight causeways that span savannas in the southeast (Walker and Erickson 2009). Several characteristics, however, indicate their artificial nature: zigzags (or V-shapes); patterned relationships with other features; and, a propensity to cluster in groups.

The first fish weir identified within the Quinato Wetland greatly resembled the fish weirs mapped by Erickson (2000) as well as Blatrix and colleagues (2018) in Baures (Figures 1 and 6). In both regions, fish weirs cross low-lying savanna that is inundated during the wet season and drained in the dry season. They are not found at higher elevations in river *galerías* or on forest islands and often end right at the edges of lowland depressions. Their designs are distinctly non-linear. Terms such as "zigzag" and "V-shape" describe the sharp angles that interrupt the lengths of the weirs, yet, while they are not causeways, they often do connect nearby forest islands that hold evidence of pre-Columbian habitation (Figure 4). Earthworks can also be found associated with shallow, round ponds, many of which are used today as watering holes for cattle (Figure 5).

However, the two complexes are located over 200 km away from one another on opposite sides of the Bolivian floodplain and, therefore, cannot be directly associated. Consequently, even if they were both primarily used to catch fish, this analysis does not assume that the earthworks will share similar appearances or spatial organizations, especially since the West Central Mojos features cover a much larger area than the Baures weirs. For instance, Erickson's study blocks cover only 524 km^2, but the features themselves run for ~1,000 km^2. Additionally, fish weirs in WCM are associated with other types of anthropogenic structures aside from artificial ponds and forest islands. Raised fields are found along the edges of seasonal streams and swamps, often coming into contact with the edges of fish weirs (Figure 10). These fields are only found around the northeastern half of the feature distribution. In a paleochannel to the southwest, fish weirs are associated with the circular mound fields discussed by Denevan (1966:89; Figure 5).

As a result of these prominent differences between the Baures and WCM complexes, search parameters for digitizing features were intentionally non-specific. The task was to map noticeably non-linear features (with discrete zigzags if present) that were distinct from other archaeological earthworks in the area. Because of this, the physical range in this dataset is impressive, even if most objects tend to resemble the Baures weirs in key ways such as their zigzag shape and common arrangement intersecting forest islands. Not only do these features vary in shape because of the wide search parameters but elevation, moisture, vegetation, and soil color are also constantly changing as one moves across the landscape. Thus, it is difficult to give a comprehensive report on the dataset's variation (see Figures 3-5, 8, and 10-11 for examples of dissimilarity).

In terms of spatial organization, features are found both as individual occurrences and in clusters. For example, the feature shown in Figure 12 is the only one of its kind mapped for 5 kilometers. There are no nearby forest islands or other features such as agricultural earthworks, but it is near a river channel. It is also possible that there are more features in this area but are not visible in this image. Conversely, those features in clusters fall into one of three unique patterns, referred to as stacks, networks, and grids. A stack consists of at least two, roughly parallel weirs, often found in a river channel or low-lying area (Figures 4 and 13). This is the most common expression of weir clustering in WCM. Only two weirs are needed in sequence to be stacked, but there is no limit to how many can be in the sequence. If there are more than two, the stack should display regular spacing, and weirs should be roughly equidistant from any weir lying between them. Additionally, because drainage areas often follow meandering routes, a weir is also stacked if it and another weir are positioned radially around a bend such as an oxbow. In contrast, a network of weirs describes an abstract pattern of intersecting features. While stacked weirs run parallel to one another, weirs in a network merge and cross over one another, creating spaces that are partially or fully enclosed (Figure 14). This web-like pattern can be found in several areas of WCM. Similar to a network, a grid is defined as a group of fish weirs that intersect one another, however, the junctions created are perpendicular (Figure 15). This creates a roughly shaped grid of weirs that meet at approximately ninety-degree angles. Because networks and grids are both comprised of intersecting features, they fall under the same category. Networks are also far more common than grids with only one instance of the latter being documented thus far.

These different kinds of clusters are key to this analysis because they represent consistent and identifiable patterns of fish weirs with unique spatial relationships. Furthermore, the orientation and organization of fish weirs have implications for the flow and accumulation of water within clusters, which in turn influences the weir's use, productivity, and seasonality. For example, a stack of weirs in a river channel can significantly slow the flow and drainage of water to other areas. This can retain water for use, encourage the growth of useful habitats of aquatic plants and insects, and provide multiple barriers to trap fish when water levels fall below the weirs. Additionally, local hydrology would have a variable impact on this process, based on the amount and speed of water moving through an area as well as its likelihood to accumulate. Thus, it is hypothesized that patterns of weirs were purposely constructed according to local hydrology with the intention of manipulating it to create landscapes conducive to aquaculture.

Spatial Data

1. *Defining Potential Wetlands*

The basis of this analysis is the potential wetland unit, which consists of a cluster of fish weirs and the area of associated land they impact by controlling the accumulation and flow of water. Clusters were created in GIS by merging weirs that sat within a specified distance of one another into a larger polygon. This methodology aimed to approximate clusters of weirs that would have interacted cohesively, compounding the effects each individual feature would have on water and creating a potential wetland whose range and seasonality was modified by human intervention. For each weir, flat buffers of 500 m were generated on both sides. Additionally, because weirs are built perpendicularly to impact the flow of water and generally do not extend past the width of channels, each buffer was cut off at the two endpoints of each feature (Figure 16).

The buffer distance of 500 m was informed by the contemporary example of a weir referenced in Figure 7, which impedes water within an area the width of the stream channel and an upstream distance of around 1,500 m. In ideal circumstances, detailed topographic data would be used to model a watershed for WCM, more accurately estimating how much water each weir could impede based on its specific position in the terrain and, thus, how far a neighboring weir could be before they no longer shared the same body of impounded water. However, such data is not yet as readily available as satellite imagery, making this project exploratory in its approximation of the size of potential wetlands. Further, in order to generate a series of meaningful units that inform archaeological interpretations of the WCM fish weirs and the people who built them, a balance must be struck between larger and smaller buffer sizes. A buffer of 1,500 m that follows the contemporary example risks subsuming the majority of the dataset under one large potential wetland. In this case, the only fish weirs that would stand apart are those at the edges of the study area where volunteers spent less time. However, a buffer that is too small risks subdividing spatially patterned clusters of fish weirs that are noticeably associated or working together. As a result, 500 m was selected as an arbitrary, yet conservative estimate given the available information.

Aggregation of the fish weirs into their respective polygons resulted in the creation of 149 potential wetlands that represent clusters of associated weirs and an uninterrupted accumulation of water. Note that this number is likely to change in the future as more fish weirs are mapped and distances between potential wetlands shorten. Finally, the polygons were smoothed to eliminate any sharp edges and the forest islands were clipped out (Figure 17). This is because forest islands have high elevations compared to fish weirs and are rarely breached by water flows.

Several variables were collected for each potential wetland, including the total length of fish weirs in the polygon; number of fish weirs within the polygon; area of land affected by water; and, the cluster's spatial pattern, which could be classified as a stack, network (including grid), or neither. The option for neither category arises from potential wetlands that feature only one fish weir or those with few, distantly spaced weirs, which do not display a pattern (Figure

18). Again, while there are likely more features in the vicinity of single weirs, they were either not visible or their identification as a fish weir could not be verified at the time of mapping. As a result, these polygons were excluded from the statistical tests because they do not represent the fully domesticated spaces that this analysis explores. There is a relationship between the number of fish weirs present and their cumulative impact on local hydrology, but a fish weir with no upstream or downstream neighbors will be limited in the amount of water it can impede and accumulate.

2. *Hydrological Relationships*

For each potential wetland, the next stage of the analysis collected data on the nearest large body of water in WCM. Large water bodies consist of both main rivers, including the Mamoré, Iruyañez, Omi, Yacuma, Rapulo, and Apere as well as the centrally located Quinato Wetland (Figure 19). For this study, rivers represent a significant source of water for fish weirs during the wet season. In contrast, the Quinato has been hypothesized by Duncan and colleagues (2021) to be artificial wetland, potentially an example of the kind of wetland domestication that this analysis seeks to define. Several fish weirs are visible along the edges of the Quinato, but given its permanent state of inundation, most are submerged and therefore unable to be mapped and included in this analysis. Each large body of water was digitized by volunteers of ProSIGAB, Stephanie Boothby and Jackie Beery, and were available for analysis with slight adjustments to the boundaries. Distance of the closest body of water and type was calculated for each potential wetland via using the *Near* function within ArcGIS Pro. In measuring distance relationships, those features displaying a value of 0 are located directly within or intersecting the polygon of each potential wetland.

3. Anthropogenic Relationships

Finally, data were collected on the closest anthropogenic features to each potential wetlands, thereby revealing potential patterns in relationships between forest islands, fields, and fish weirs. Both the forest islands and two types of agricultural fields, raised and mounded, were mapped and organized by previous volunteers of ProSIGAB, primarily Dorian Vlasov and Thomas Lee (2017, 2020; Lee and Walker 2022; Figures 20 and 21). In addition to the distance of each closest feature, the area of the closest forest island was calculated with the *Near* tool in ArcGIS Pro. To understand the density surrounding each potential wetland, the number of islands located within 1 km and 5 km was also obtained via the *Summarize Nearby* tool. For agricultural fields, data of interest included the distance of the closest feature and its type as either a circular or rectangular field system. The same geoprocessing functions were used for both anthropogenic features.

Statistical Analysis

Statistical tests were performed within RStudio (R software version 4.2.3) after R-ArcGIS Support was enabled within the Geoprocessing Options pane of ArcGIS Pro. This downloaded the R package *arcgisbinding,* through which the attribute table containing the variables calculated for each potential wetland could be accessed (ESRI 2023a). All functions were conducted using the *base* R package unless specified otherwise.

Hypothesis Testing

Two-tailed hypothesis testing sought to identify statistically significant differences between potential wetlands with different spatial patterns. These included differences in the size of potential wetlands (part one) and their nearby hydrological and anthropogenic features (parts two and three). By identifying significant or recurring differences between potential wetlands, this project aims to identify how certain variables may be related to the functionality of the weirs whose spatial patterns change across the landscape. Mann-Whitney U tests ($p = 0.05$) were performed on each continuous variable as they did not meet the parametric assumptions for normality even after the data underwent logarithmic shape transformations. This was likely due to the presence of several outliers, and was confirmed by the D'Agostino Omnibus (R package: *fbasics*), Anderson-Darling (*nortest*), and Shapiro-Wilks tests (Gross and Ligges 2015; Wuertz et al. 2022). Use of the Levene's test (*car*) demonstrates that many variables also did not meet the parametric assumption of variance homogeneity, reinforcing the choice of hypothesis test (Fox and Weisberg 2019). Following this, a Kendall's tau-b effect size (*effsize*) was calculated to evaluate the size of the difference in means between data of potential wetlands presenting stacks and networks (ESRI 2023a). Lastly, a power test (*pwr*) was conducted to determine whether a significant difference would be correctly detected and that the null hypothesis would be correctly rejected (Champely 2020). For the purposes of this study, this is determined by subtracting the type II error from a probability of one (1-ß). A powerful test will be greater than or equal to 0.8. Because multiple tests were run for the same hypothesis, each *p*-value was alpha corrected using the Hochberg's adjustment. This method is especially effective at decreasing the false discovery rate, thereby lowering the total error.

Pooled & Grouped Correlation Tests

The second test utilized in this analysis sought to identify associations between variables in the pooled and grouped samples of potential wetlands. This would reveal how variables are related, whether they are present/change together at the level of the whole dataset or within potential wetland groups that demonstrate different spatial patterns. For instance, if distance to the nearest forest island or the size of the nearest forest island correlated with another variable such as the size of the potential wetland, it would represent a consist pattern related to the functionality of a potential wetland. Chi-square tests estimated the likelihood that certain outcomes would occur between categorical variables. Following this, Spearman's rank and point-biserial tests were used to calculate correlation coefficients between continuous pairs and continuous-categorical pairs, respectively. Pearson correlation tests were not employed because of the non-parametric nature of each continuous variable.

CHAPTER FIVE: RESULTS

Summarized below are the descriptive statistics and test results for each part of the spatial analysis. First, fish weir length and density are reviewed for the pooled dataset. Frequencies for each categorical variable are expressed using barplots. Measures of central tendency, spread, and shape for pooled and grouped datasets can be found in Tables 1-3 (see Appendix B). These are followed by boxplots for continuous variables and results of the Mann-Whitney hypothesis tests (Table 4). Next are correlations coefficients between variables, explained at the pooled and grouped levels (Tables 5-10). Scatterplots are provided for significantly correlated variables. The three extreme outliers visible in Figure 22 are described last. While these extremes are not included in boxplots or scatterplots for the sake of presentation, they are included in the statistical results.

Fish Weir Length & Density

For each individual fish weir in the pooled dataset (n = 1,672), length in meters was calculated to examine how the earthworks vary in size across WCM (Figure 23). The average length for a fish weir is about 444 m, but this must be considered alongside a relatively high standard deviation (s = 375.3). Exactly 1,555 fish weirs, or 93% of the dataset, are shorter than 1,000 m; however, several exceptionally long features positively skew the distribution. The shortest weir is than 10 m in length while the longest documented is 3801 m, almost four kilometers. As a result, feature length ranges tremendously within the dataset. Twenty-five percent of the dataset falls below 194 m while about half of all fish weirs are less than or equal to 341 m. Around 75% measure at or under a half a kilometer, or 568 m.

Figure 24 also illustrates that the density of features across the savanna is not constant. Cumulatively, there are 742 km of fish weirs covering an area of roughly 11,500 km^2 in WCM. Points on the map marked in red, orange, and yellow denote areas where fish weirs reach their highest concentration per square kilometer. These contrast the cooler toned areas where large clusters are not found.

Potential Wetlands

The schema used to define potential wetlands produced 149 polygons around distinct clusters of fish weirs (Figure 25). Figure 26 shows the frequency with which the clusters fall into a particular spatial arrangement. Potential wetlands with only one feature or those not presenting a clear spatial pattern represent the majority (n = 58). When these are removed, potential wetlands containing stacked fish weirs (n = 46) made up 50.5% of the dataset, followed closely by those with networks of fish weirs (n = 45) at 49.5%. Both categories of spatial patterns are mutually exclusive.

Figures 27-29 present boxplots of each size-related variable collected for potential wetlands. Within each graph, potential wetlands with networks consistently affect more land than potential wetlands with stacks. Respectively, the medians for each group are 3.73 km^2 and 1.53 km^2, a difference of more than 2 km^2 (Tables 2 and 3). Equally compared with stacks, networks contain more fish weirs (median: 12 and ~4) and have higher total lengths (median: 4.54 km and 1.42 km). These differences are reflected in the results of the two-tailed hypothesis (Table 4).

There are statistically significant differences in the size of potential wetlands with networks and stacks ($p < 0.001$). Additionally, with Kendall tau-b effect sizes of 0.491 to 0.461, the difference borders on being large. Given the results of the two-tailed power test (1-ß = 0.050), however, these results must be taken with caution.

Tables 5-7 show the Spearman's rho correlation coefficients produced for each pair of continuous variables for the pooled and grouped datasets. Within every potential wetland, area of affected land has a strong positive correlation with total length ($\rho = 0.946$) and number of fish weirs ($\rho = 0.884$). Total length is also correlated with the number of fish weirs in each wetland ($\rho = 0.847$). Interestingly, among the grouped correlation results, the coefficient for number of weirs drops to 0.738 and 0.628 for affected area and total length. Scatterplots visualize these relationships for each spatial pattern without extreme outliers (Figures 30-32).

Hydrological Relationships

The map in Figure 19 illustrates the major bodies of water in connection with the WCM fish weir dataset. Eighty seven percent of all potential wetlands can be found lying between the Omi, Iruyañez, and Yacuma Rivers. Additionally, the barplot in Figure 33 shows that few potential wetlands are found as far east as the Mamoré or as far south as the Rapulo and Apere Rivers to be considered nearest to them, the latter of which has no close potential wetlands. In contrast, the Quinato Wetland is the nearest body of water to 29 potential wetlands, almost a third of the dataset. Both spatial patterns are similar in their frequencies to each body of water; however, networks are slightly more common near the Iruyañez and Omi (n = 12 and 13) while stacks are more common around the Yacuma and Quinato (n = 7 and 16).

A key component of hydrological relationships is the amount of distance between potential wetlands and their closest large body of water. One quarter of all potential wetlands can be found within 304.43 m of a large body of water. Half are located within 1.76 km, and three-quarters are within 3.93 km (Table 1). The box plots in Figure 34 demonstrate that while both spatial patterns commonly intersect bodies of water at 0 m, stacks are found at shorter distances. Twenty five percent are found within 144.53 m and half are found within 1.48 km. The same statistics for networks are 514.94 m and 2.00 km, respectively (Tables 2 and 3). The results of the hypothesis testing do not show a statistically significant difference between both groups, however ($p = 0.766$). While the test does meet the power threshold of 0.80, the effect size ($\tau_b = 0.080$) is negligible (Table 4).

Results of several correlation tests expressed moderate correlation coefficients for variables related to field systems; however, none demonstrated a high correlation ($\rho \geq 0.60$). For example, Spearman's tests demonstrated a moderate relationship ($\rho = 0.502$) between distance to water body and distance to fields at the pooled level (Table 5). Pointbiserial tests also showed a moderate relationship ($\rho = -0.513$) between field type and distance to nearest water body in reference to potential wetlands with stacks (Table 9). The presence of mound fields near a potential wetland is moderately correlated with decreasing distance to a water body. Conversely, raised fields are moderately correlated with increasing distance to a water body.

Anthropogenic Relationships

Fields

The distribution of fish weirs in WCM extends across both types of field systems, mounded and raised (Figure 20). Based on their current mapped extents, raised fields are the most common agricultural earthwork in association with potential wetlands (n =59) in contrast to mound fields (n = 32; Figure 35). Additionally, spatial patterns are not uniformly distributed among the fields. According to the Chi-square tests, networks are one and a half times as likely to be adjacent to raised fields compared to stacks (OR = 1.514). However, this association is not statistically significant ($p = 0.339$). Further, results of the pointbiserial tests show that no numeric variable significantly correlates with the type of nearest field at the pooled or grouped level (Tables 8-10).

The median distance from a potential wetland to an agricultural earthwork is 0 m (Table 1; Figure 36). Additionally, for each spatial pattern, over half of the grouped datasets intersect directly with a neighborhood of fields or lies within 10 m of one (Tables 2 and 3). There is a noticeable difference in the third quartile statistics. Seventy-five percent of potential wetlands with stacks can be found within 551.85 m of a field, but this distance jumps to over a kilometer for networks. Again, however, the hypothesis testing finds that the size of the difference is negligible ($\tau_b = -0.032$) and that it is not statistically significant ($p = 0.766$; Table 4). There are also no significant correlations between distance to nearest field and any of the other size or relationship variables (Tables 5-7).

Forest Islands

Figure 21 shows the distribution of forest islands within WCM compared to potential wetlands. Many of the largest forest islands can be seen heavily concentrated around the main river stems while smaller islands tend to fill the space between bodies of water. Similar to their relationships with fields, 25% of all potential wetlands directly intersect forest islands (Table 1). Among networks, distance to the nearest island is 0 m for half of the group. In contrast, 50% of wetlands with stacks of fish weirs are found within 250 m. This difference is exacerbated in the third quartile of each group. Three-quarters of fish weirs in networks are within 200 m of the nearest island while those in stacks are within 850 m (Tables 2 and 3; Figure 37). The size of these differences is small (τ_b = -0.191), per the hypothesis test. They are also not statistically significant (p = 0.282), but the results must be taken with caution because the power threshold was not met (1-β = 0.265; Table 4).

The size of islands in close association with potential wetlands ranges from less than 0.001 km^2 to 1.31 km^2 (Table 1). There were also no statistically significant differences between groups for this variable (p = 0.766, τ_b = -0.115, 1-β = 0.951). Although, this does not mean that slight differences do not exist. Statistics for each quartile show that stacks are consistently closest to islands larger than those near networks. The difference starts at less than 0.001 km^2 for the first quartile but gradually increases to almost one tenth of a square kilometer in the third quartile (Tables 2 and 3; Figure 38).

Finally, the last two variables address the number of forest islands located within one and five kilometers of potential wetlands (Figures 39 and 40). Within 1 km of every wetland in the pooled dataset, there was a minimum of 0 islands and a maximum of 132. Within 5 km, the minimum number of islands was still 0 but the maximum jumped to 231 (Table 1). These statistics are influenced by extreme outliers, however. Most of the pooled dataset falls below 12 or 90 forest islands for each respective buffer. Hypothesis testing did show a statistically significant difference between groups for the former variable ($p = 0.019$, $\tau_b = 0.311$, $1\text{-}\beta = 0.051$). For each quartile, networks had around double the number of islands within 1 km than stacks (Tables 2 and 3). Interestingly, this statistical significance did not extend to the 5 km buffer where the p-value was larger than 0.05. The effect size for this test was small as well ($\tau_b = 0.226$; Table 4).

The pooled and grouped pointbiserial tests did not find any significant correlations between the forest island variables and nearest field type (Tables 8-10). Spearman's tests identified three significant negative correlations between the distance to a forest islands and number of forest islands within 1 and 5 km. However, it is expected that the number of islands within a certain radius will decrease as distance to the nearest island increases. Beyond this, several pairs of variables demonstrated moderate correlations ($\rho < 0.06$). For each variable related to the size of a potential wetland (area, total length, and number of fish weirs), distance to an island as well as the number of forest islands within 1 and 5 km changed accordingly. Naturally, the bigger a wetland is, the more land it will occupy and the shorter the distance will be to an island. Lastly, there were positive correlations between the distance to a forest island, water body, and field. As one increased, the others did so as well (Tables 5-7).

Extreme Outliers

The methods used to group fish weirs into potential wetlands also resulted in the creation of three distinctive cases that are defined by their large size relative to the rest of the pooled dataset (Figure 22). These extreme outliers (referred to as O1, O2, and O3) are differentiated from other outliers by their impact on distribution of the data, which prevented the use of parametric tests during analysis. Yet, they also pose as case studies where interactions between variables can be explored and combined with the results of the statistical analysis.

Each extreme outlier was classified as a network based on their high percentage of perpendicularly intersecting features. To the northwest of the study area, the smallest of these potential wetlands, O3, occupies 47.5 km^2 in the corner of land between the Iruyañez and Omi Rivers (Figure 41). It consists of 110 weirs, adding up to 63.7 km in total length. The only forest islands located within the wetland itself are small circular islands that are intersected directly by the network of fish weirs. Neighborhoods of raised fields border the gallery forests next to the rivers but do not sit in the space between weirs.

To the southwest are the second and first largest potential wetlands, O2 and O1. O2 lies north of the Omi River within open savanna (Figure 42). It is 57.3 km^2 in size and contains 117 weirs, totaling 73.3 km in length. Although, this area of WCM is defined by neighborhoods of mound fields, this wetland mirrors O3 in the strategic placement of the fields around the border of the wetland. Similarly, the forest islands directly associated with this network are small, circular features located well within the boundaries of the wetland.

O1 sits between the Omi and Yacuma Rivers within a paleochannel to the south of O2 (Figure 43). It possesses the greatest area of land potentially affected by fish weirs at 92.9 km^2

and consists of 327 individual features, cumulatively spanning a distance of 147 km. O1 is also unique because it can be subdivided into several clusters of fish weirs with different spatial patterns. Neat stacks of weirs fill the channel immediately beneath the river while a dense, unbroken network of features runs southwest. Forest islands associated with the stacked weirs are much larger and more organically shaped than the islands seen in O2 and O3. Fish weirs end as they reach the bank of the channel and do not continue on the other side of the islands. Mound fields do occupy the interior of the wetland polygon, but only on the edges of the channel where they intersect with fish weirs. The small network southwest in O1 also depicts fields within the boundaries of the wetlands lining the edge of a wide low drainage area. A few small forest islands sit on either side of the area. Interestingly, O1 and O2 are only separated by a distance of three kilometers and at least a third of that space is occupied by a small potential wetland containing only four weirs. This suggests the possibility that two may represent two halves of an ever bigger domesticated space if more features are identified between them.

CHAPTER SIX: DISCUSSION

The results of this analysis show that there are statistically significant differences in the size of potential wetlands that express different spatial patterns. On average, networks contain higher numbers of fish weirs and reach longer total lengths than stacks do. They are also more likely to affect the flow and accumulation of water onto larger areas of land. This implies that there is a direct relationship between the organization of fish weirs and the size of a domesticated wetland, suggesting that approaches to mound building may have changed depending on the area under focus. Further, the case studies presented by the extreme outliers highlight two kinds of environments, broad expanses of low savanna (O1, O2, and O3) and narrow channels dedicated to seasonal streams (O1). As fish weirs in networks intersect with one another in low savanna, they create fully or partially enclosed spaces and larger stretches of earth to impede the flow of water. This lies in contrast to stacks, which stretch across pre-defined channels of smaller sizes.

Although the results of the hypothesis tests were not statistically significant, there were differences between spatial patterns in the distance from a body of water. Stacks of fish weirs were closer to large rivers and the Quinato Wetland than networks. This makes sense given that seasonal streams are directly connected to main river streams. While O1 was technically classified as a network, the paleochannel containing the stacked portion emerged from the Omi River. In contrast, networks cover large areas of land between bodies of water. O3, for instance, was located 2 km inland from both the Iruyañez and Omi Rivers.

Relationships to anthropogenic features reflected a similar division as well between stacks and networks. Fields were found in closer association to stacks compared to networks.

This is likely a result of the differences in elevation between channels and broad areas of low savanna. The distinctive banks offered by seasonal streams put more distance between crops and floodwaters compared to cases such as O3. Only near the elevated gallery forests were raised fields located. Networks also demonstrated closer associations with forest islands and were often closest to islands of smaller size. This was also confirmed by the extreme outliers, and raises questions about the purpose of the small, round forest islands that frequently appear alongside fish weirs in networks. These artificial mounds are less than 500 m^2 in size, making it unlikely that they were once sites of permanent settlement. Instead, they may have played a seasonal role, providing temporary shelter from the elements during maintenance or use of the fish weir networks.

Agreement between the case studies and descriptive statistics provides an understanding of the physical differences between fish weirs in stacks and networks, but what does this reveal about the pre-Columbian wetland domestication in WCM? First, regardless of the spatial pattern being employed, this study finds that potential wetlands have the capacity to affect water flow and accumulation for over 600 km^2 of land in WCM. The number of single-weir polygons that were formed during the methodology also illustrates that there are many more clusters of fish weirs to be mapped as the World Imagery basemap is updated. Further, ecological research and the modern Mojo weir demonstrate the impact that low weirs can have on the duration and timing of flooding within a region. Larger, defined pools of water created by the strategic construction of fish weirs will evaporate more slowly, over time resulting in permanent changes to the local ecology and hydrology. Given the number of potential wetlands located in and around the Quinato Wetland, it is likely that the permanent swamp is the result of such a long-term process. Wetlands are economically valuable ecosystems, containing not only fresh water for inhabitants and crops but also many species of open-water and bottom-dwelling fish, mollusks, snails, and amphibians. Additionally, wetlands serve as vital nutrient reservoirs, which could be utilized to the benefit of nearby agricultural systems, such as the raised and mounded fields that sit at the edges of water channels and wet savannas.

Evidence for the creation of domesticated wetlands in WCM contributes to the now considerable body of research that is reshaping public perceptions of the Amazon. Communities such as the Mojeño drew on extensive knowledge of the environment and climate to reproduce, domesticate, or transfigure wetlands within the lens of their own culture, increasing their productivity by transforming the extent and duration of seasonal flooding (Baleé 2006; Descola 2016). If the natural cycle could trap hundreds of fish within small muddy pools as water levels begin to decline, so could they. Except these pools could be constructed closer to home, store fish until needed, and serve a variety of other purposes.

Thus, the WCM fish weirs add a new dimension to the scale of environmental transformations that have taking place within Llanos de Mojos, allowing archaeological communities to sustain dense populations by domesticating not only a landscape but a waterscape as well.

APPENDIX A: FIGURES

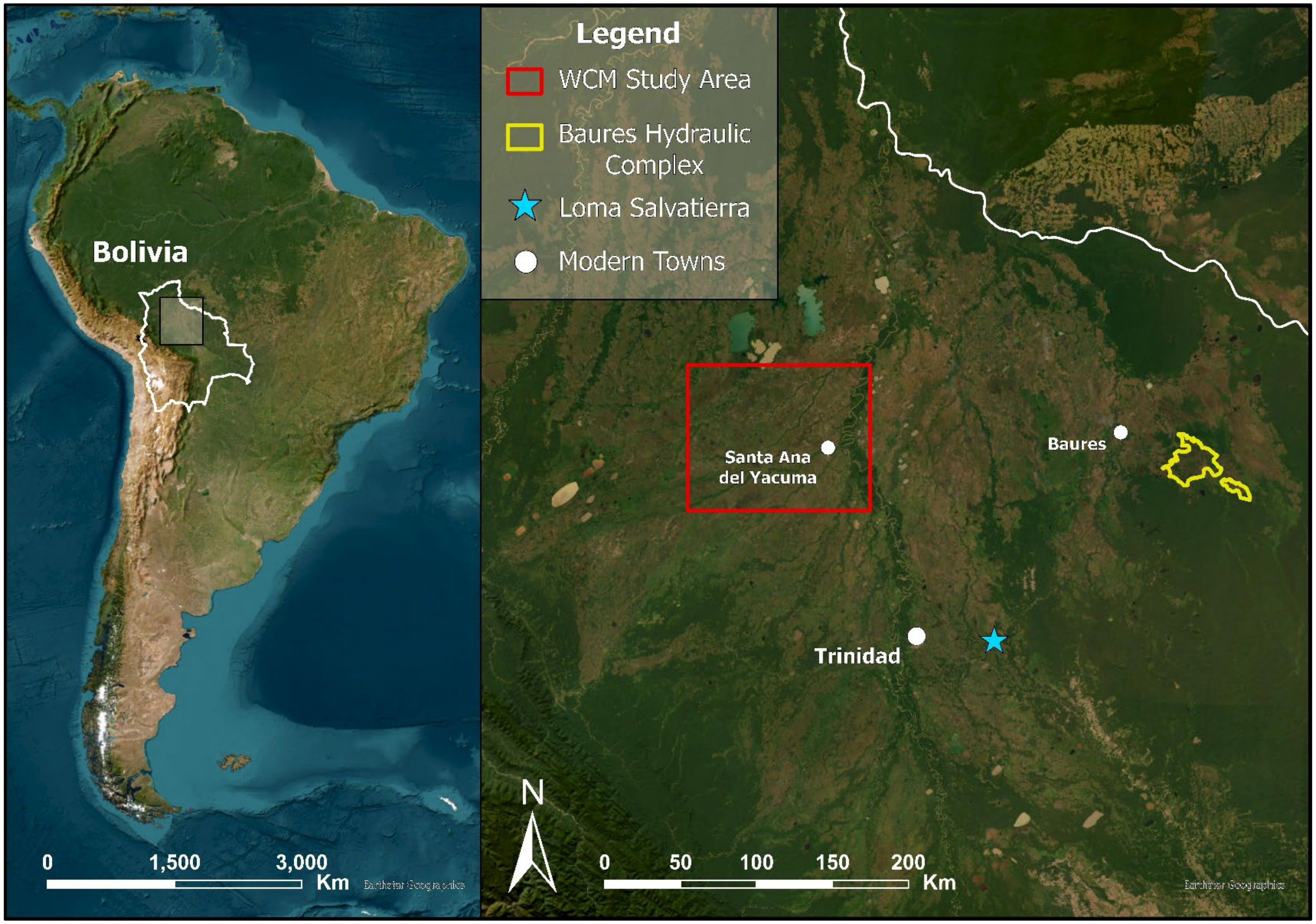


Figure 1. Map of South America (left) showing Bolivia and the location of the inset of Llanos de Mojos (right). Within the inset, the WCM study area is demarcated in red while the Baures hydraulic complex is outlined in yellow. These areas contain the only identified fish weirs within Mojos. The blue star marks the archaeological site of Loma Salvatierra where zooarchaeological research has been conducted on artificial ponds.

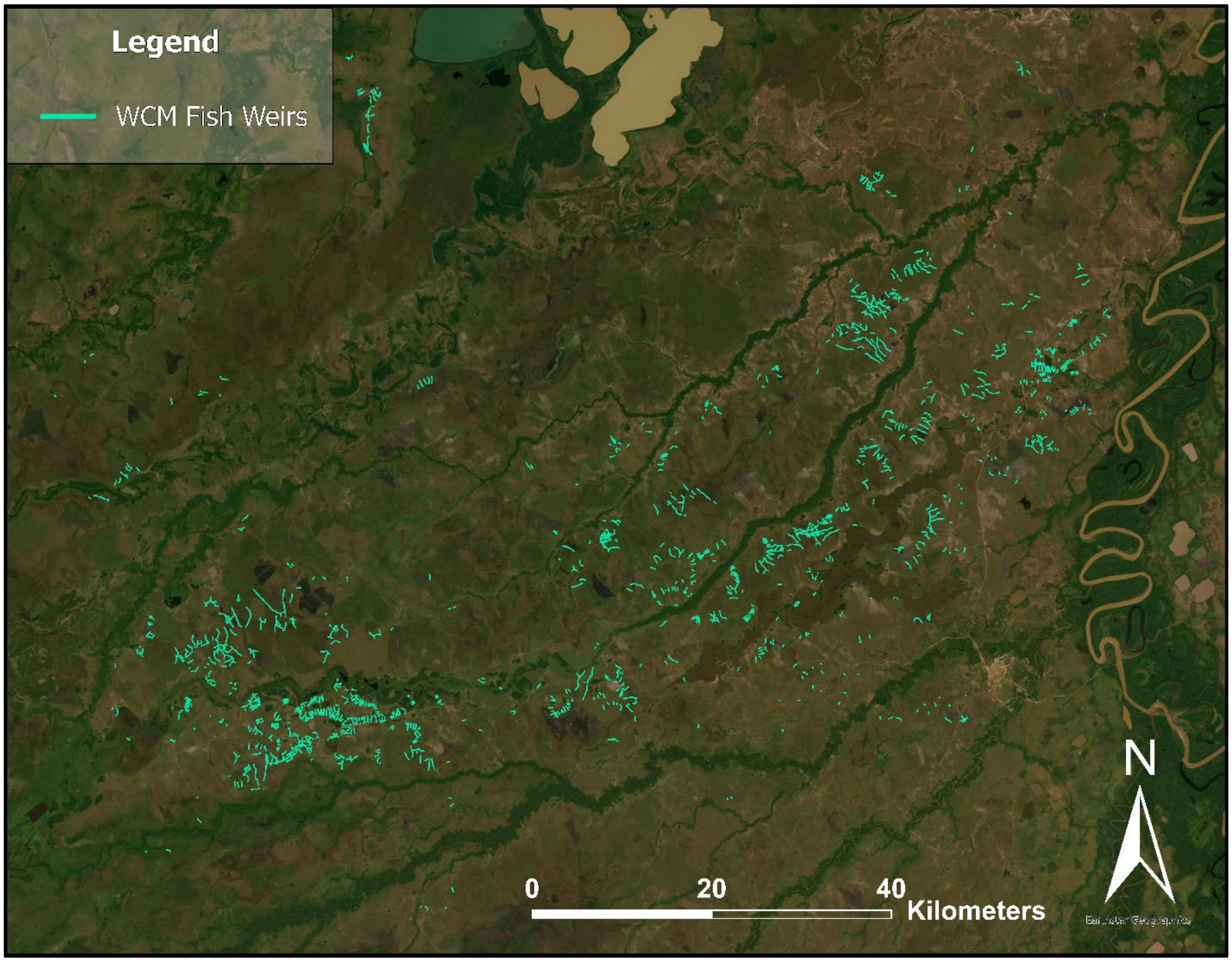


Figure 2. A composite satellite image of the West Central Mojos fish weir dataset. At present, the dataset is distributed across 11,500 km^2 of savanna and contains almost 750 km of digitized earthworks.

Figure 3. The first zigzag feature that was identified in WCM using satellite imagery. Located next to the forest island Miraflores in the Quinato Wetland.

Figure 4. Bright green forest island lining the bank of a water channel. Non-delineated fish weirs intersect the edges of the channel and the islands as they run parallel to one another. A marked change in the environment can be seen left of the image's center. This represents the point where different sets of imagery were "stitched" together to create a basemap with minimal cloud cover. Although fish weirs extend across this boundary, they are almost invisible on the lighter half, demonstrating how seasonal changes in the environment pose challenges for identifying and mapping features.

Source: Esri, DigitalGlobe, Earthstar Geographics, CNES/Airbus DS, USDA FSA, USGS, Aerogrid, IGN, IGP, and the GIS User Community, Esri Community Maps Contributors, Esri, HERE, Garmin, Foursquare, METI/NASA, USGS, US Census Bureau, Maxar

Figure 5. Dense grids of mound fields crowd the top right corner. These circular features were studied by Denevan (1966:89) and are currently being mapped by ProSIGAB volunteers. Three fish weirs can be seen extending from the cow pond to the mound fields at the edge of the water channel. Their lightly colored outline contrasts the dark, saturated environment, representing one of the many physical instances fish weirs are found in. Many modern cow ponds are artifacts from the pre-Columbian period. Their sheer frequency across the landscape and capacity to hold water make them valuable infrastructure for ranches. They appear commonly among fish weirs in both WCM and Baures.

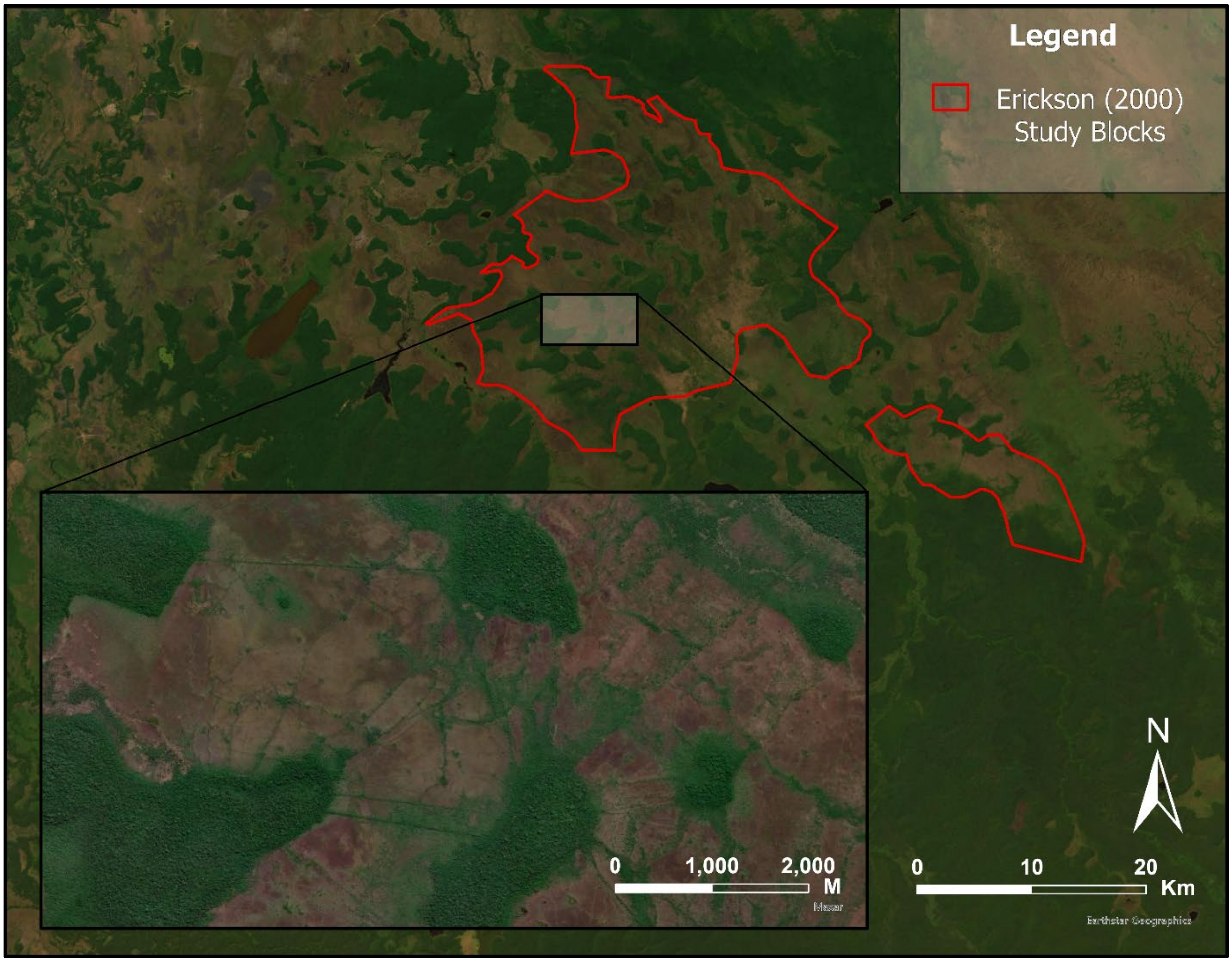


Figure 6. The Baures hydraulic complex located on the far eastern side of Mojos. Outlined in red are the two study blocks defined by Erickson (2000). Fish weirs, causeways, and forest islands are visible within the map inset.

Figure 7. The location of the artificial lake north of Santa Ana del Yacuma, in 2013 (left) and in 2017 (right) after the strategic construction of a low dam or weir within the channel of a seasonal stream. This demonstrates how the flow and accumulation of water can be impacted by relatively small, linear features. Imagery from 2014-2016 was not available for preview in the World Imagery Wayback archive.

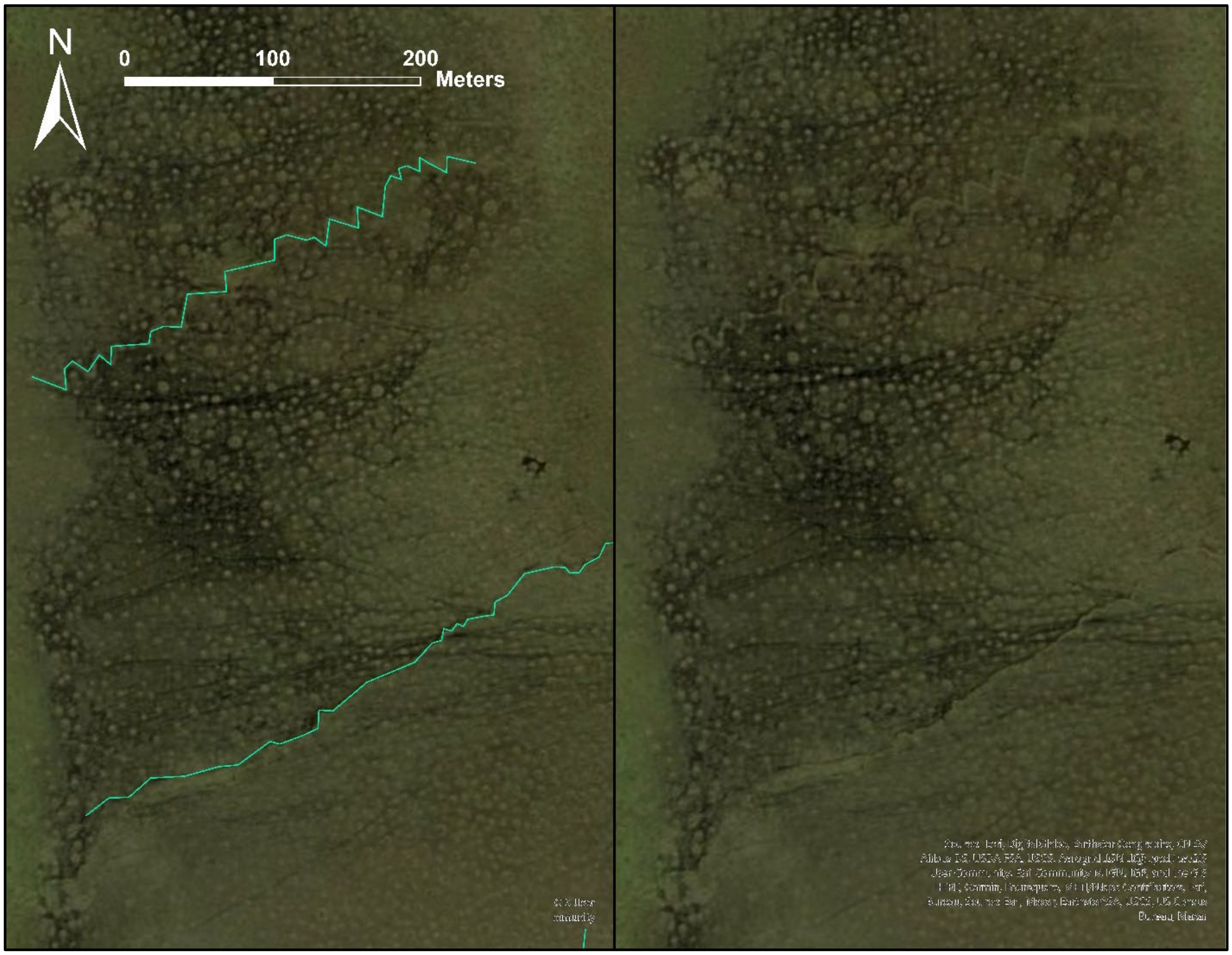


Figure 8. Two fish weirs from the edge of the Quinato Wetland. All mapped features present sharp changes in direction, known as zigzags or V-shapes, permitting their identification as fish weirs (Erickson 2000; Blatrix et al. 2018). Note the differences in the size, frequency, and shape of the zigzags between both features despite their proximity.

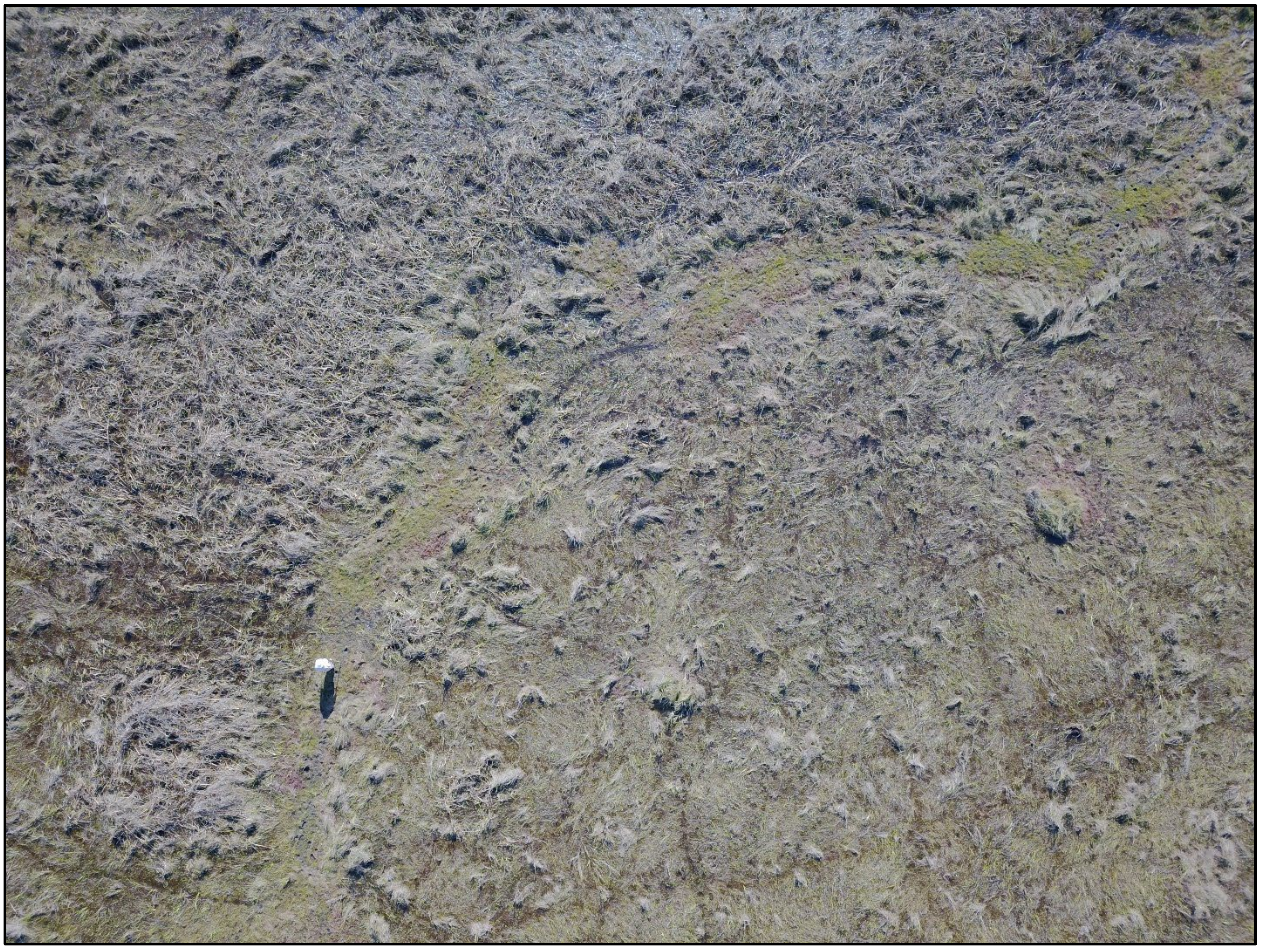


Figure 9. Aerial of a fish weir taken by a drone. The earthwork is represented by a slightly raised pathway absent of tall grass and water. Person for scale.

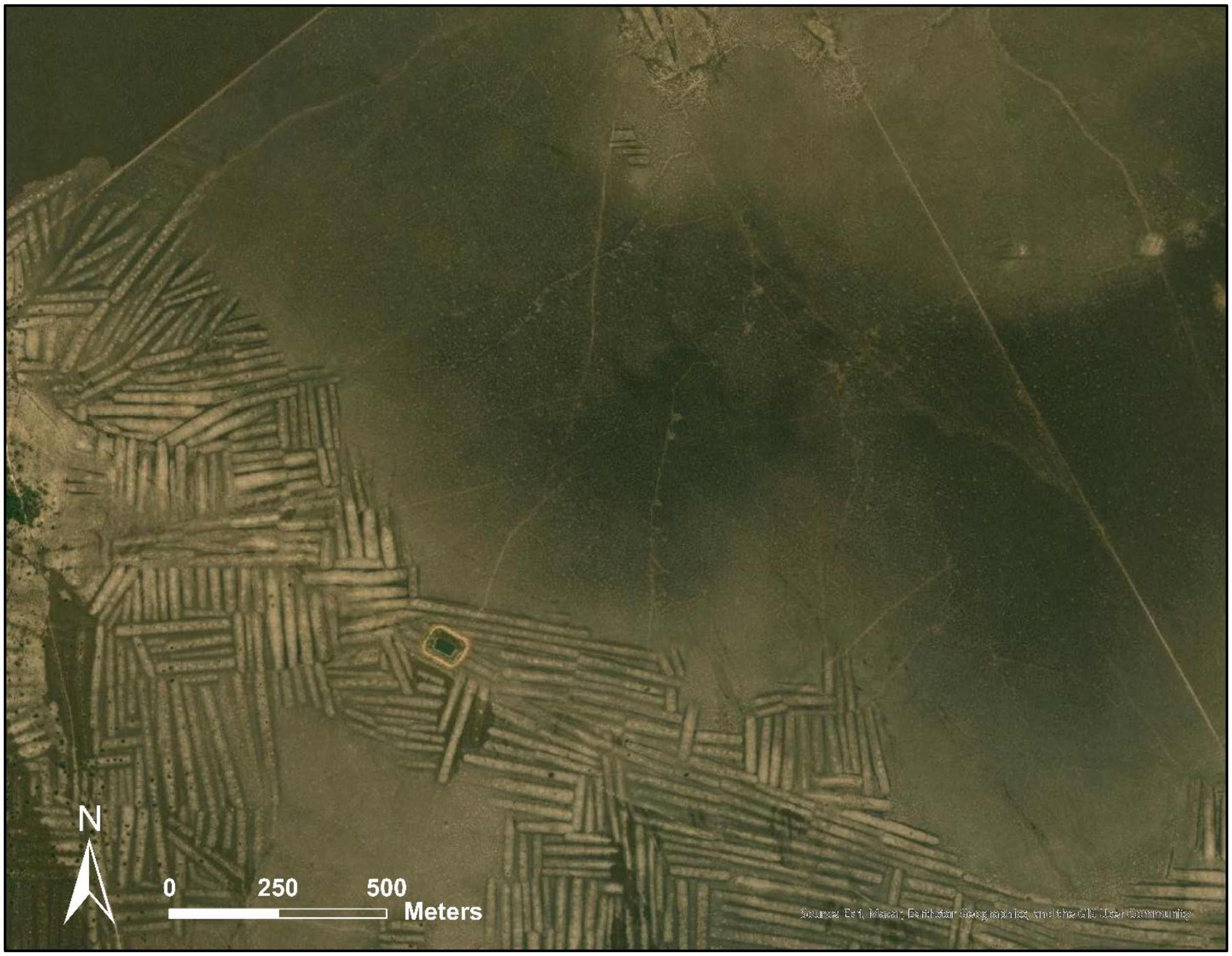


Figure 10. Fish weirs stretching across an area of low elevation, connecting areas of higher ground and the raised fields on them.

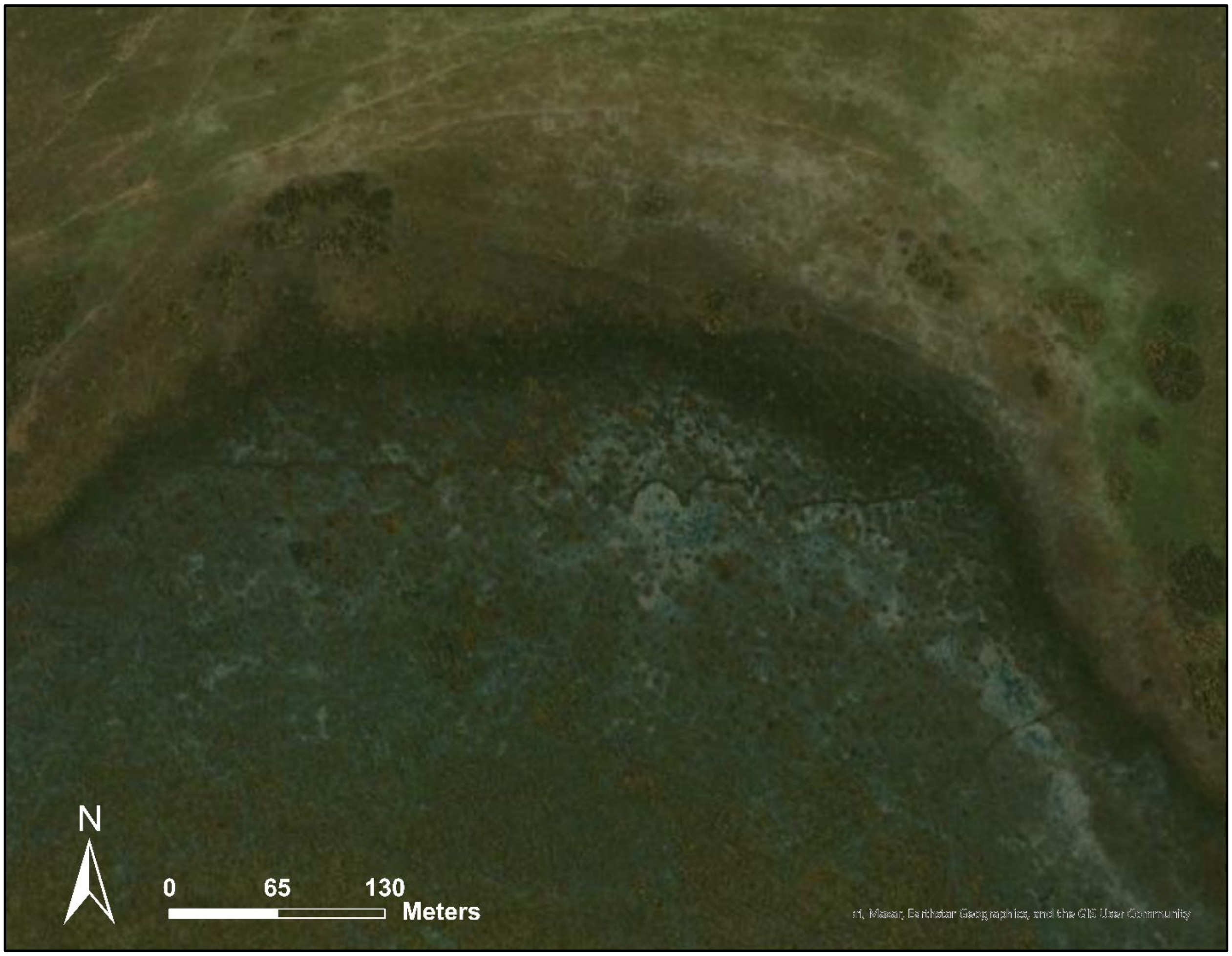


Figure 11. An edge of the Quinato Swamp, darkened by the presence of water. A similarly dark fish weir can be seen running left to right, demonstrating the diversity with which these features appear on satellite imagery.

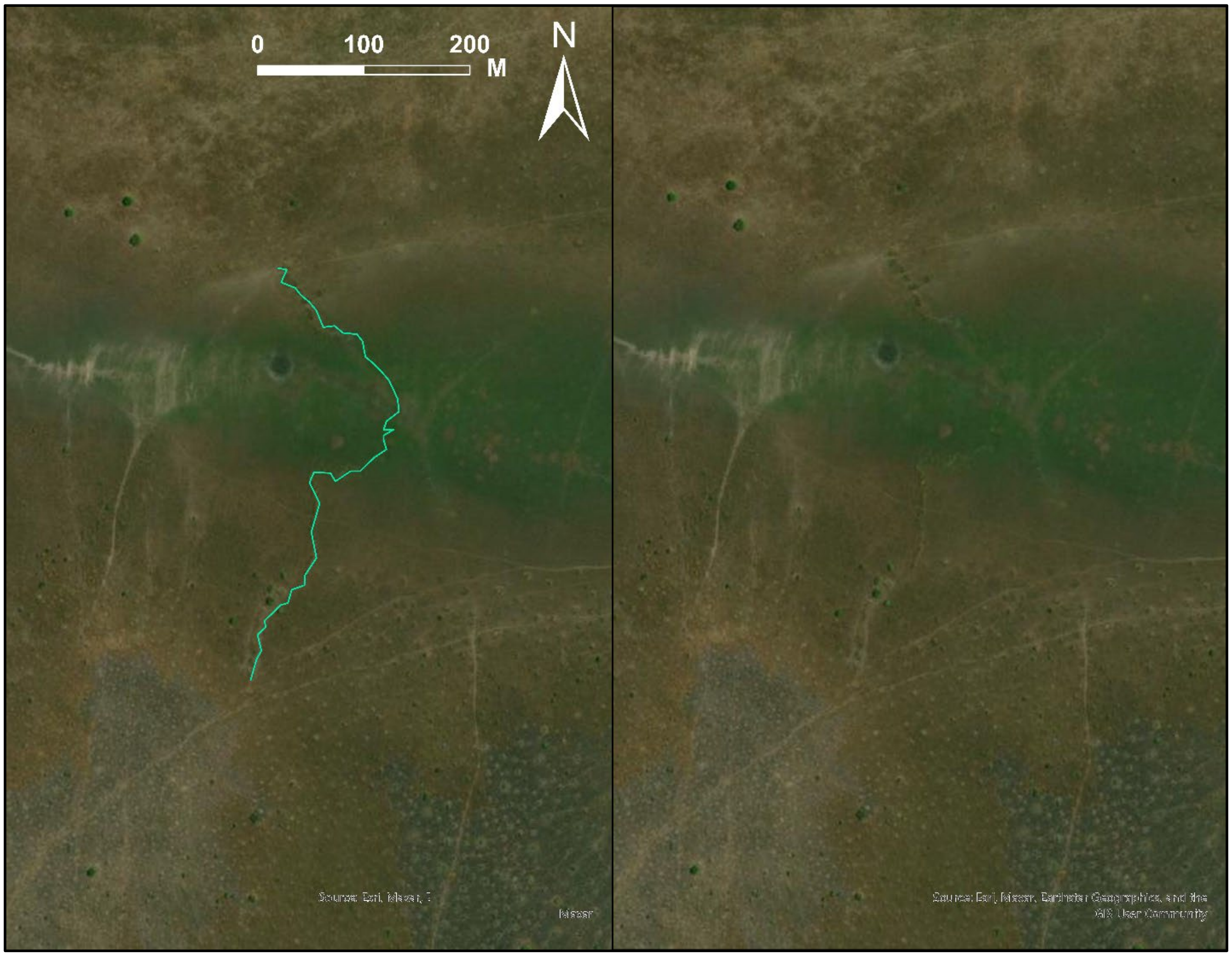


Figure 12. A lone fish weir stretches across a stream. There are no other mapped weirs within 5 km of this area, possibly because they are not visible in the current satellite imagery. The crossing lines visible below the feature are cattle trails, which are distinguished from the fish weirs by the lack of vegetation growing on them. They are also not beveled.

Figure 13. A stack of fish weirs running parallel to one another across a seasonal stream. Weirs in this spatial pattern rarely intersect one another.

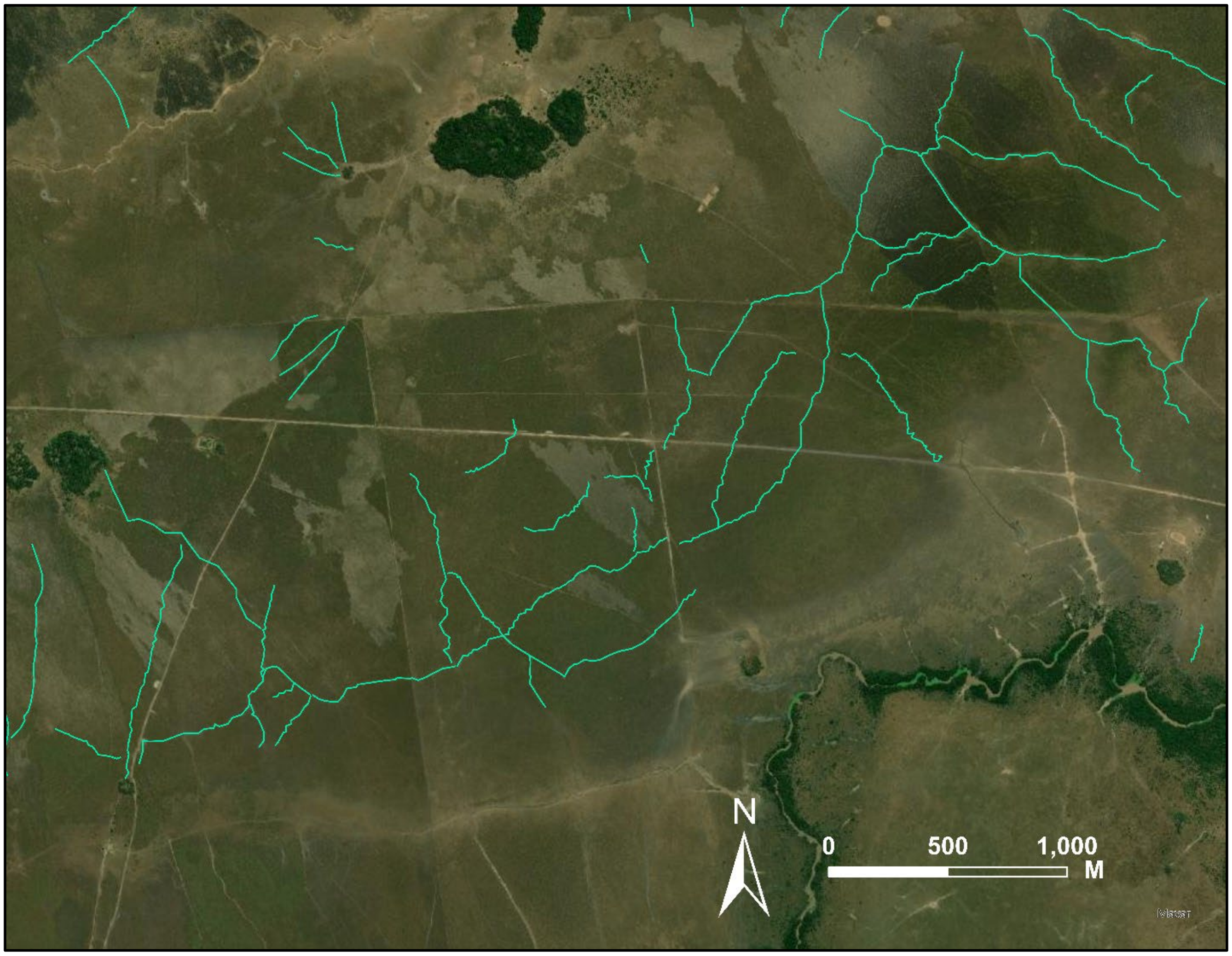


Figure 14. A web-like network of fish weirs. Weirs in this spatial pattern create partially or fully enclosed spaces by intersecting with one another. These clusters contrast the stacks of weirs that run parallel to one another visible directly to the north of the network.

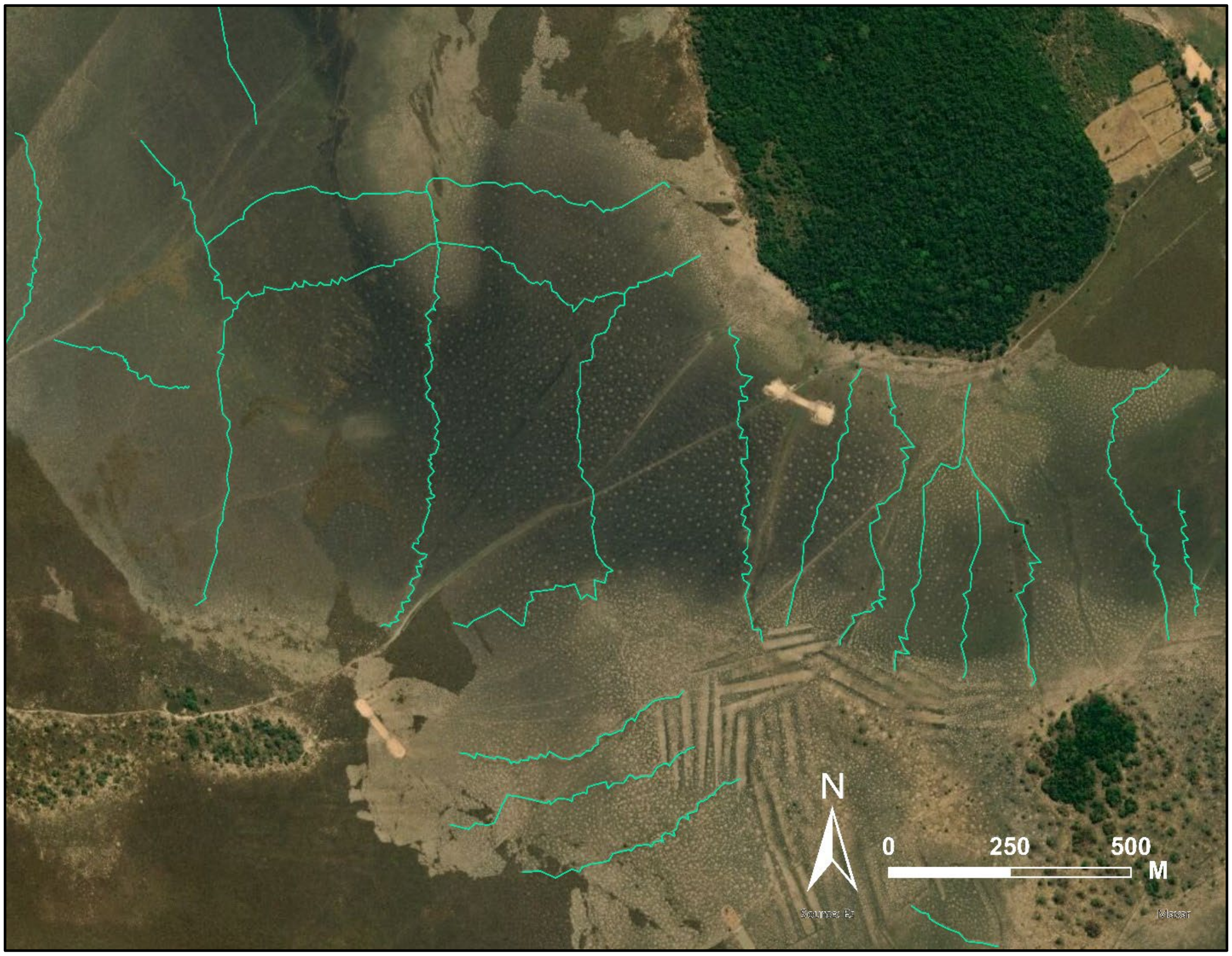


Figure 15. A grid of fish weirs (left) within the channel of a seasonal stream. This kind of pattern is classified as a network given the number of times weirs intersect one another. Stacked weirs can be seen to the right and south of the grid, intersecting with a forest island and raised fields.

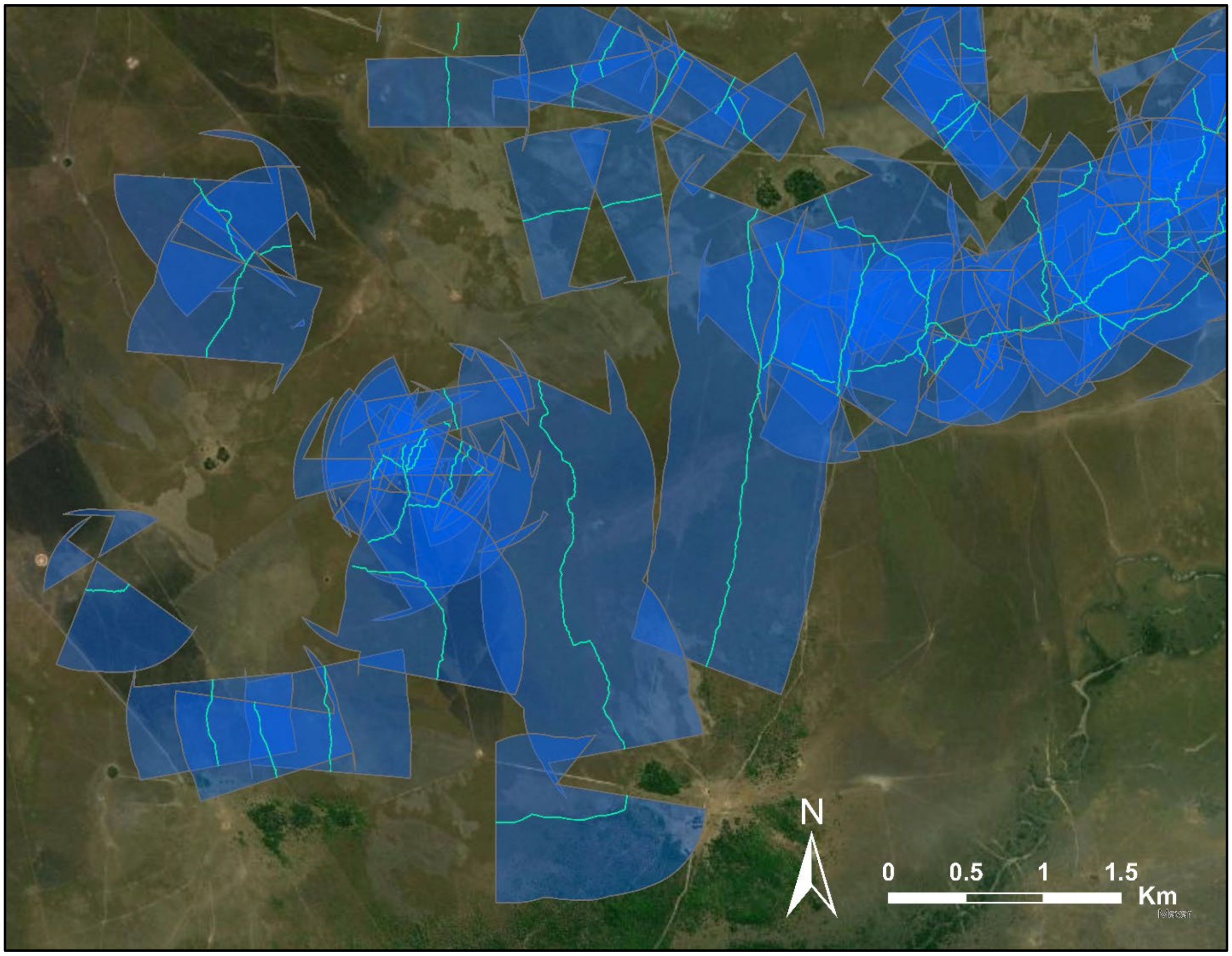


Figure 16. Fish weirs with 500 m flat buffers. Weirs with overlapping buffers were merged into polygons that represented potential wetlands.

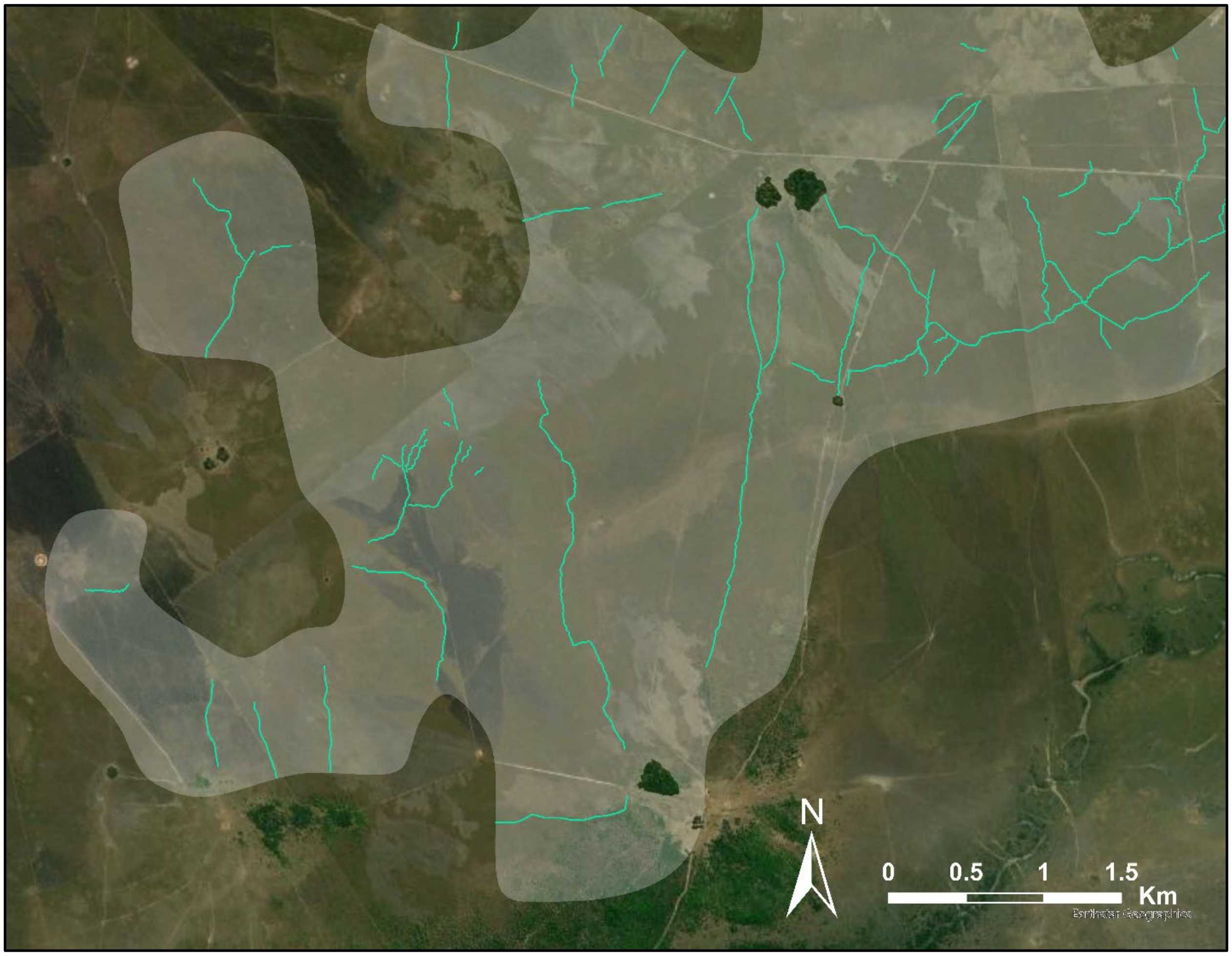


Figure 17. The potential wetland created from the buffers in Figure 16.

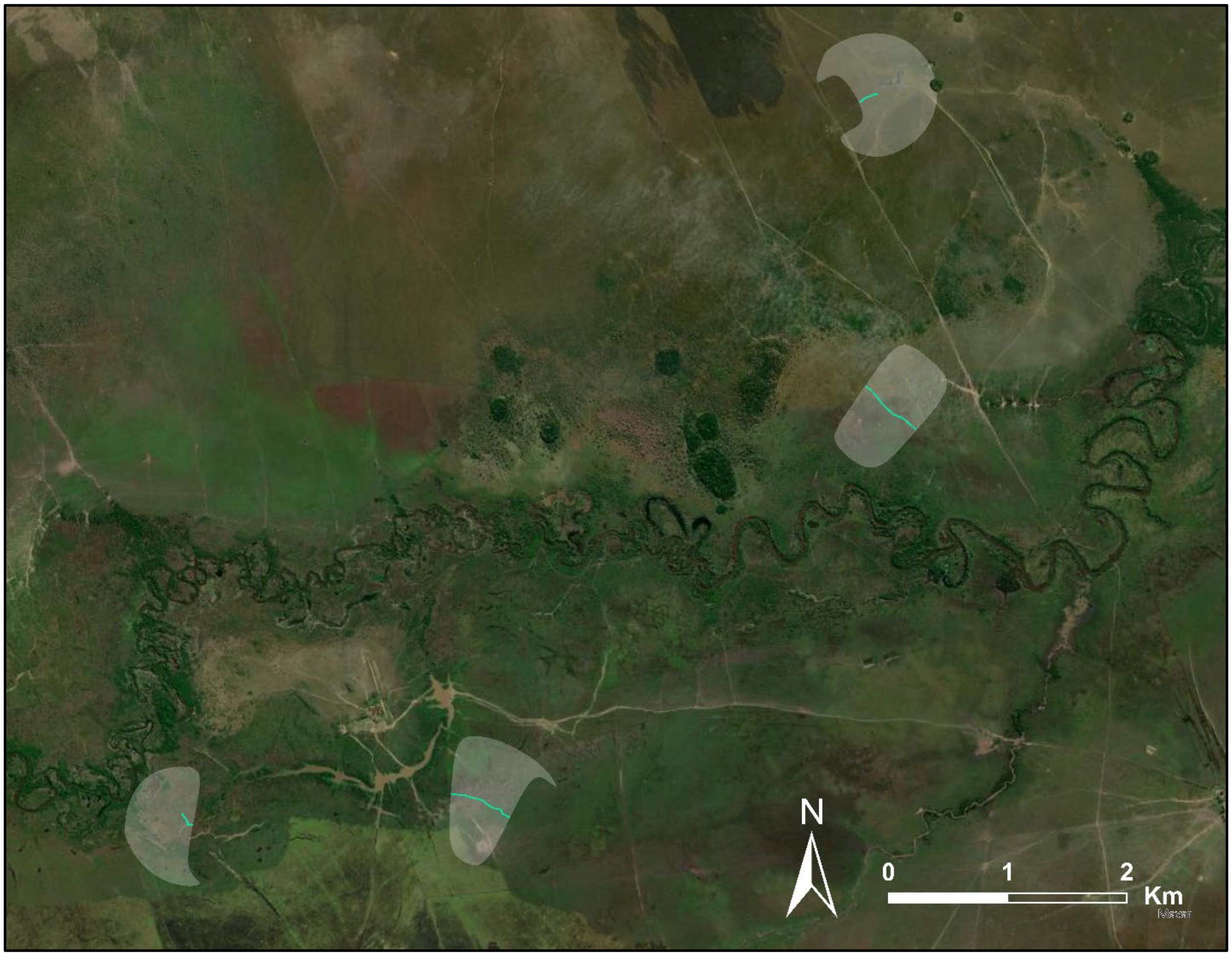


Figure 18. Potential wetlands classified as neither stacks or networks. These fish weirs lie on the margins of the WCM study area where volunteers spent less time. Additionally, weirs are more difficult to identify in some satellite imagery such as heavily vegetated areas. These potential wetlands were removed from the statistical analysis.

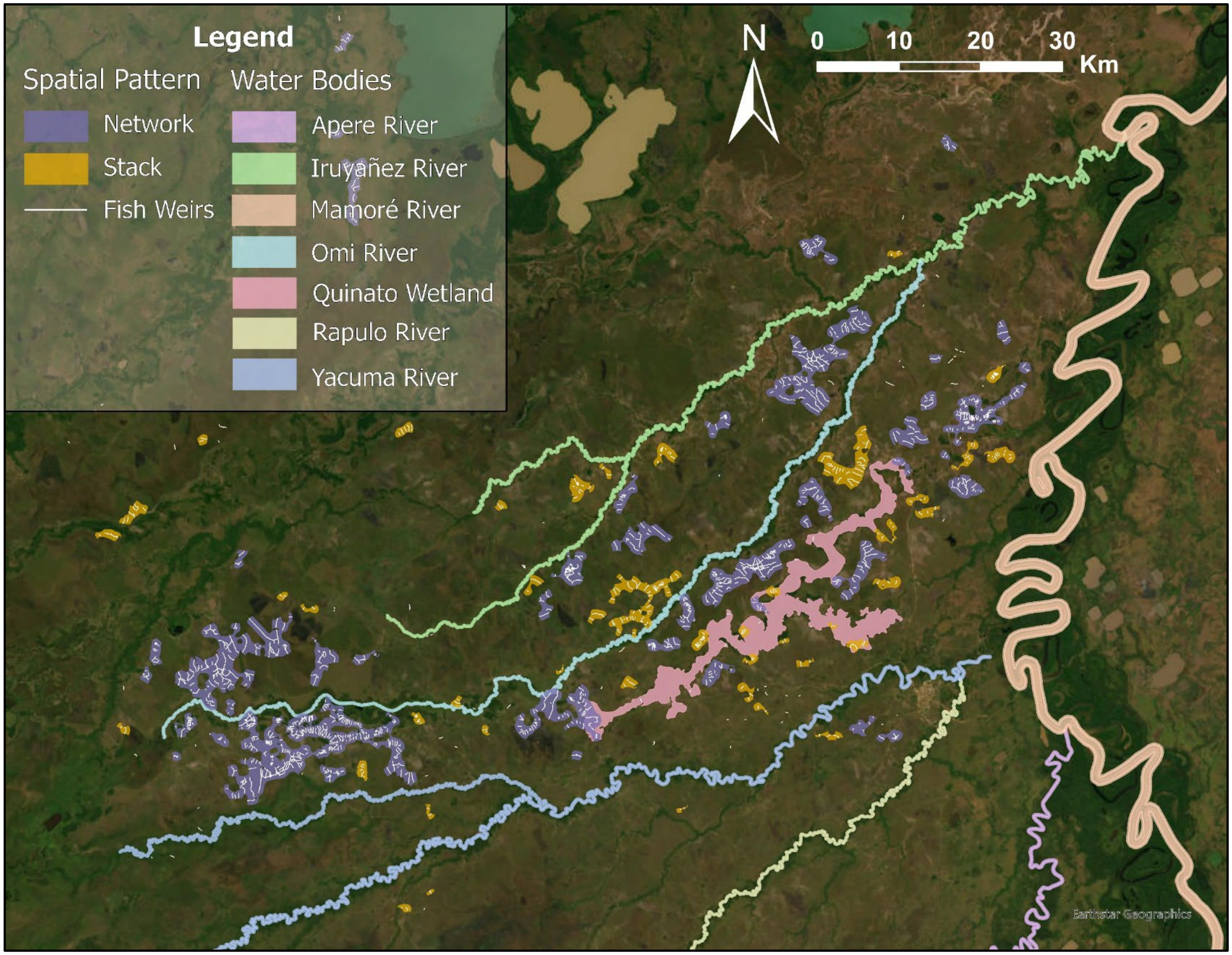


Figure 19. Map of the major bodies of water in the WCM study area, including the centrally located Mamoré as well as five tributaries and the Quinato Wetland.

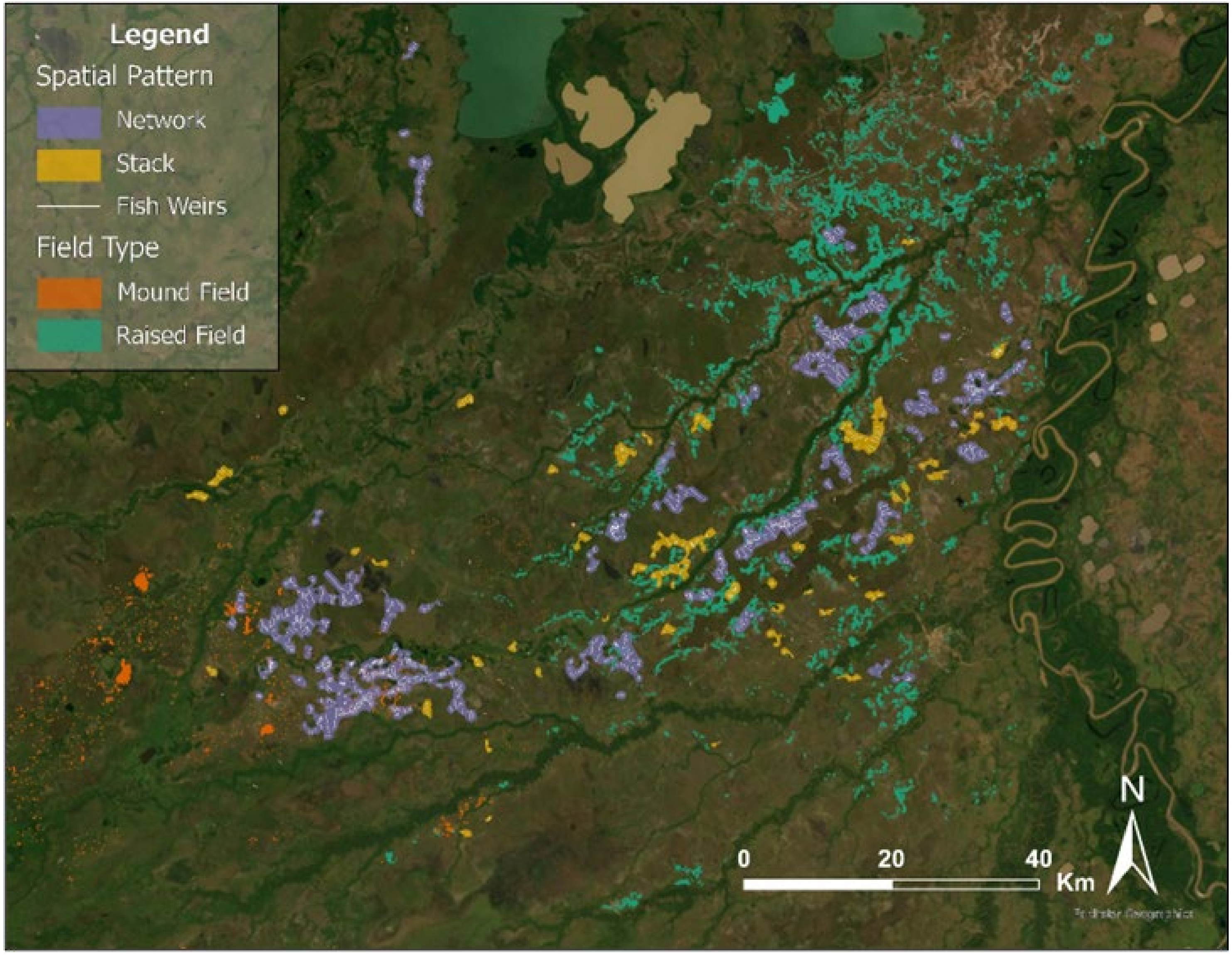


Figure 20. Map of the mounded and raised field dataset in relation to the potential wetlands representing stacks and networks,

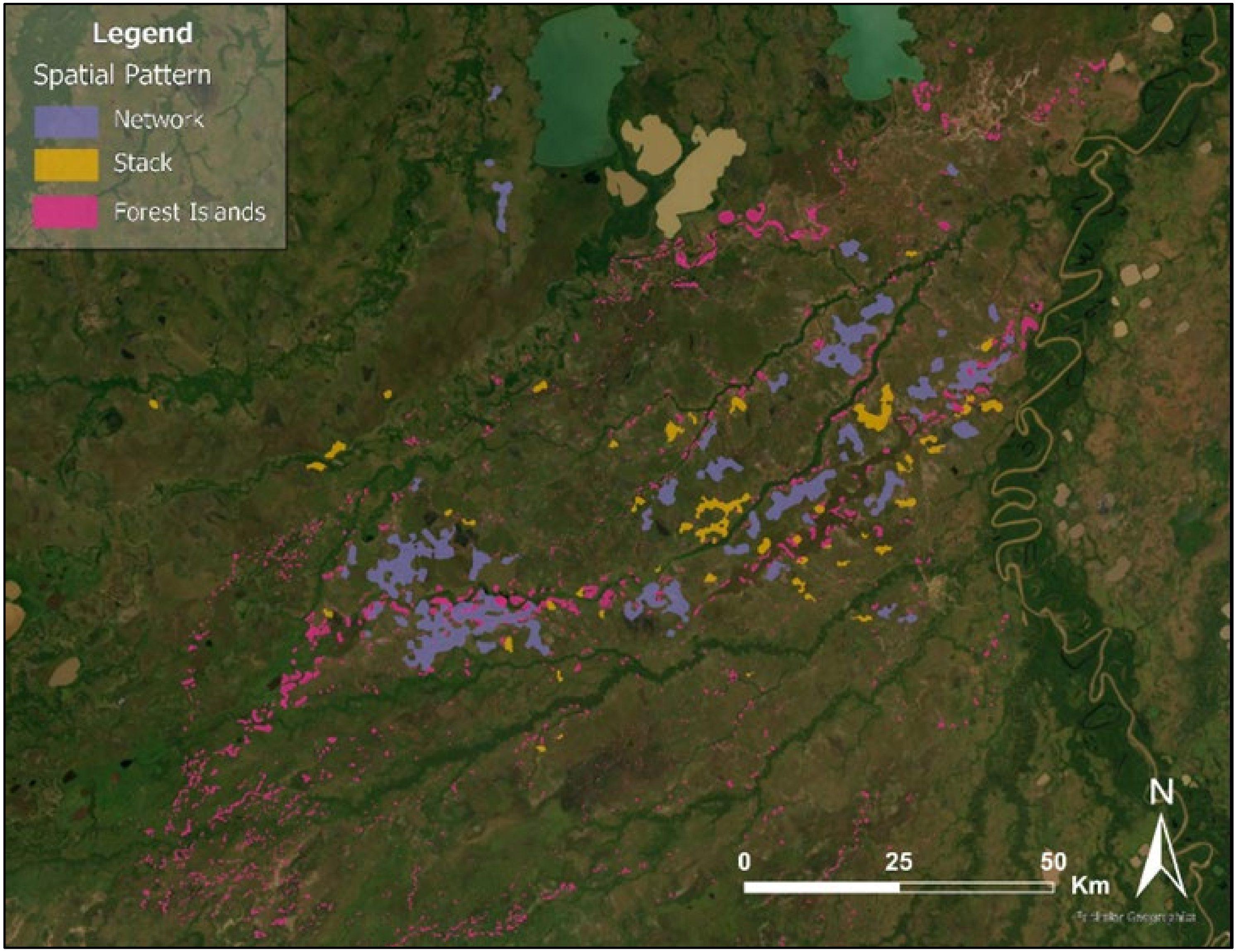


Figure 21. Map of the distribution of forest islands in the WCM study area in relation to potential wetlands representing stacks and networks.

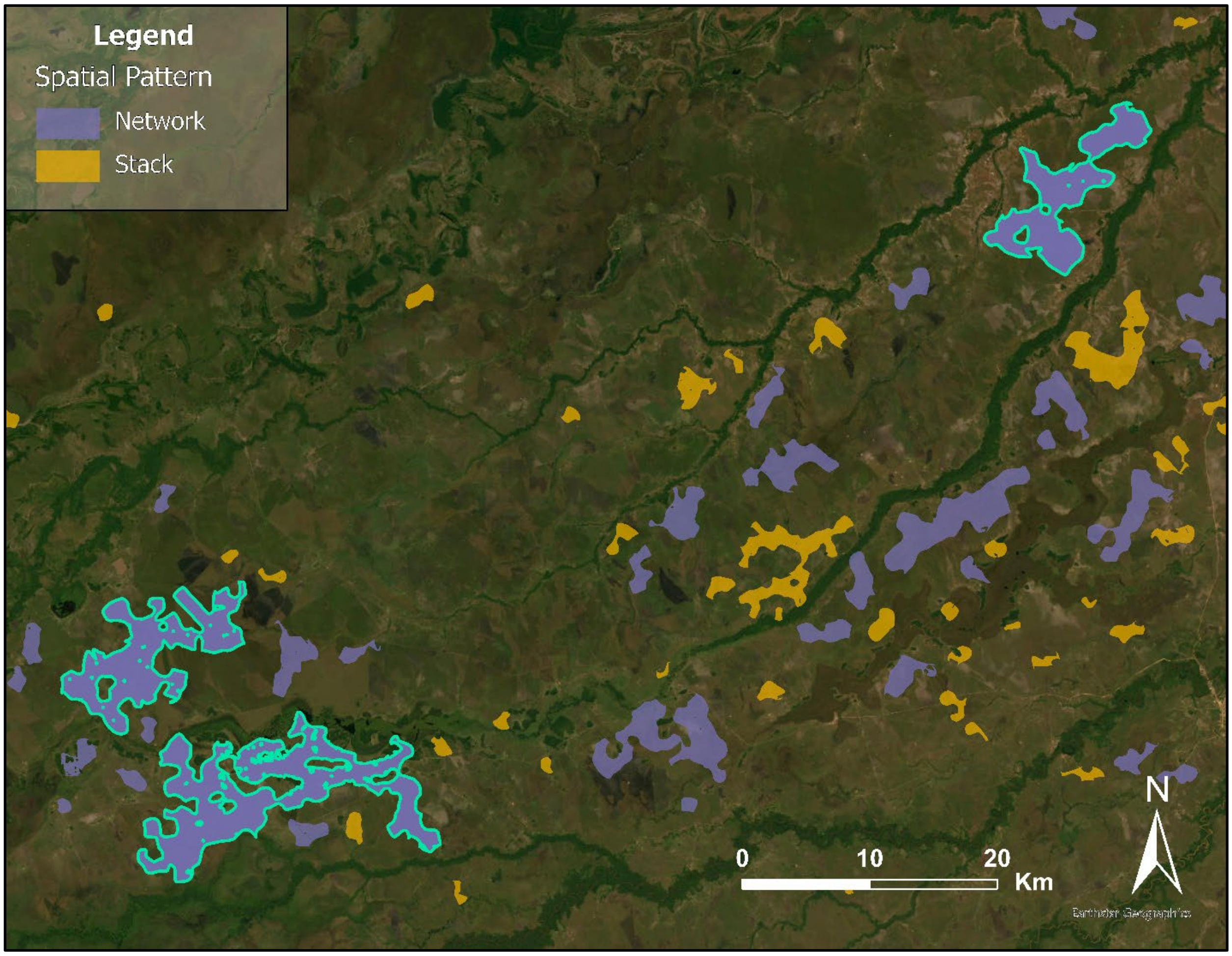


Figure 22. The three extreme outliers (highlighted in blue) in the dataset of potential wetlands, distinguished by their size, number of fish weirs, and total length of fish weirs. From left to right, O2, O1, and O3.

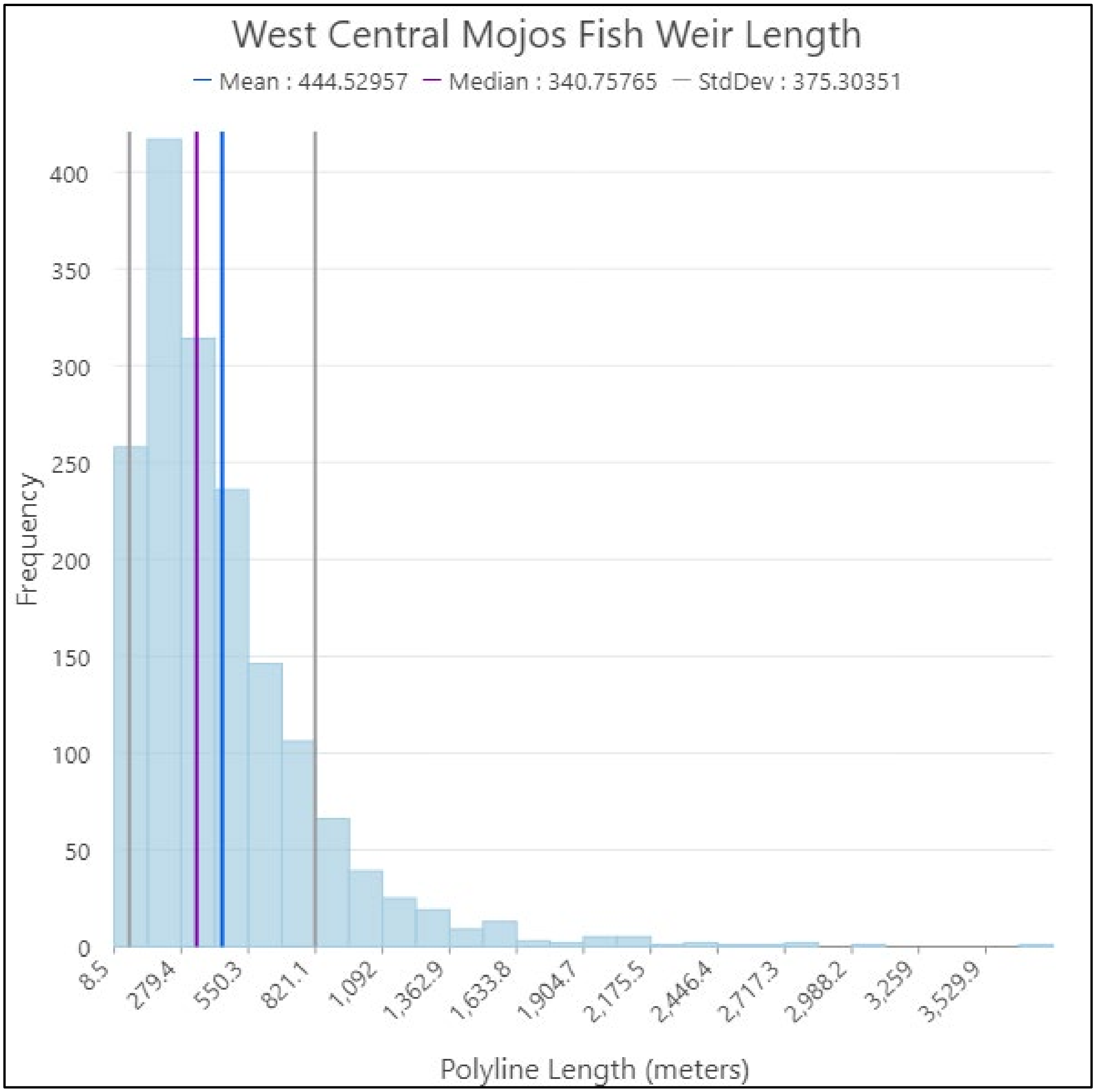


Figure 23. Histogram representing the lengths of each individually mapped polyline in the WCM dataset. A majority of the features are less than half a kilometer in length, but several reach up to 3.5 km, positively skewing the dataset.

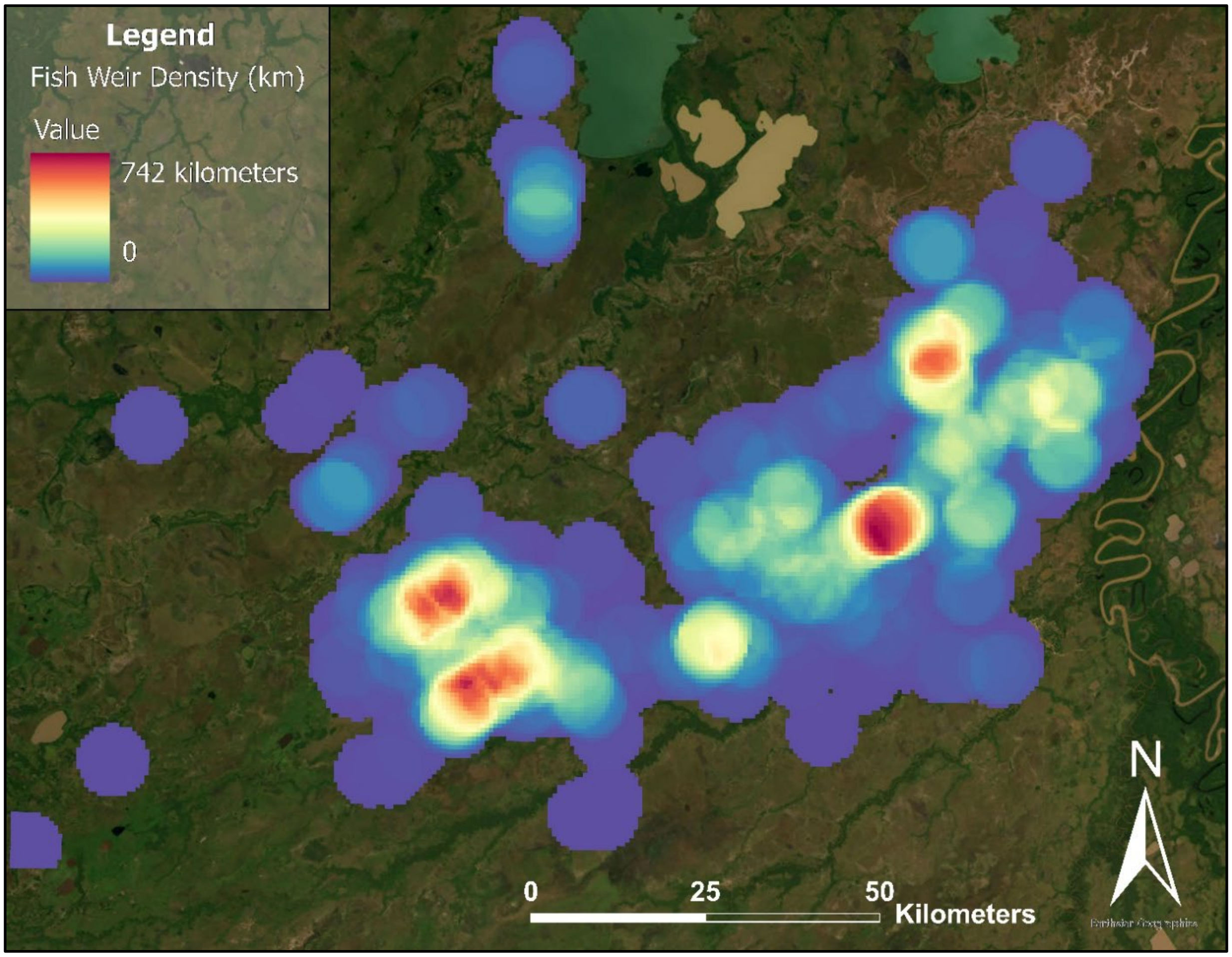


Figure 24. A line density map, showing the total kilometers of fish weirs per square kilometer of land.

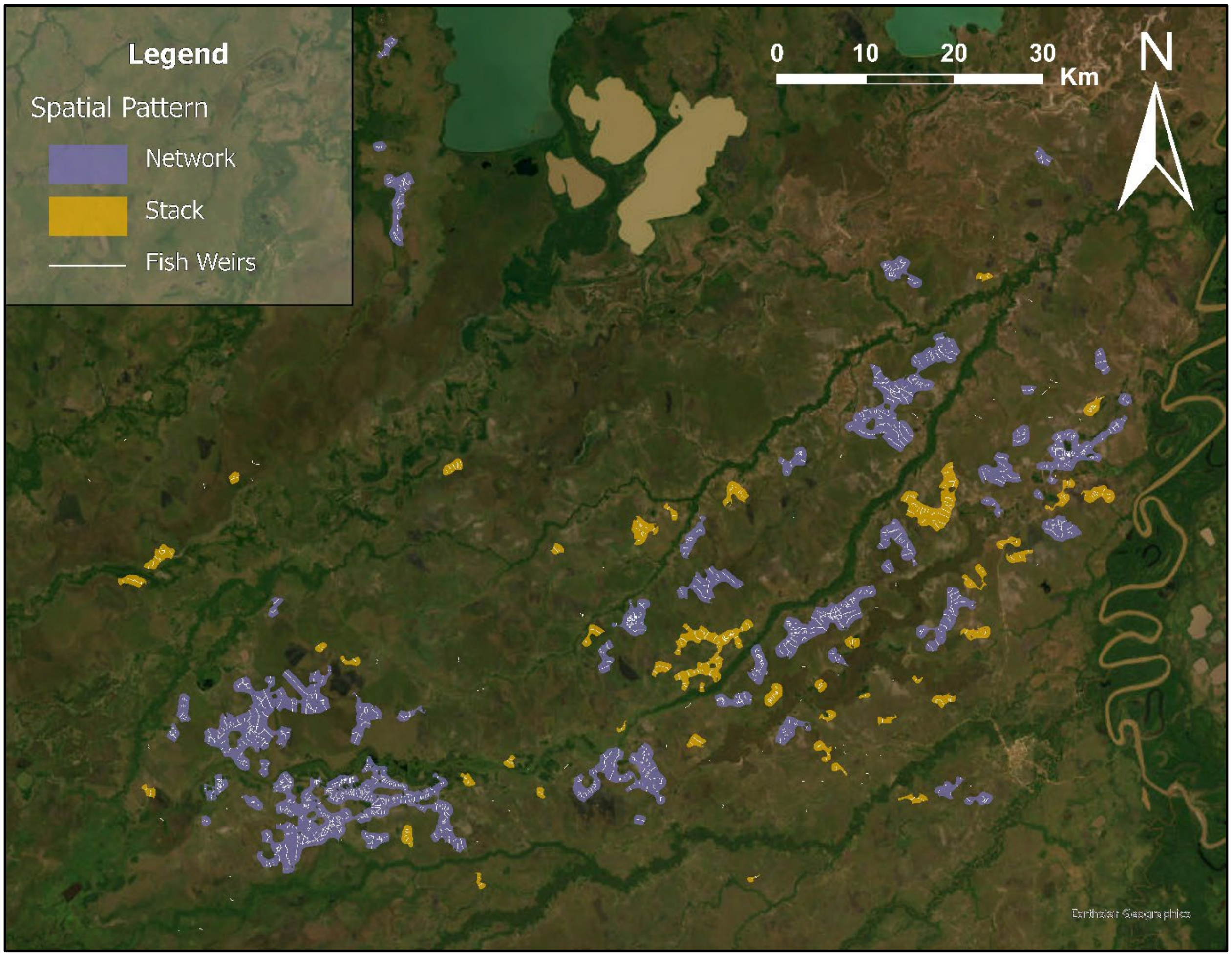


Figure 25. The schema used to define potential wetlands produced 149 polygons around distinct clusters of fish weirs differentiated by their spatial patterning.

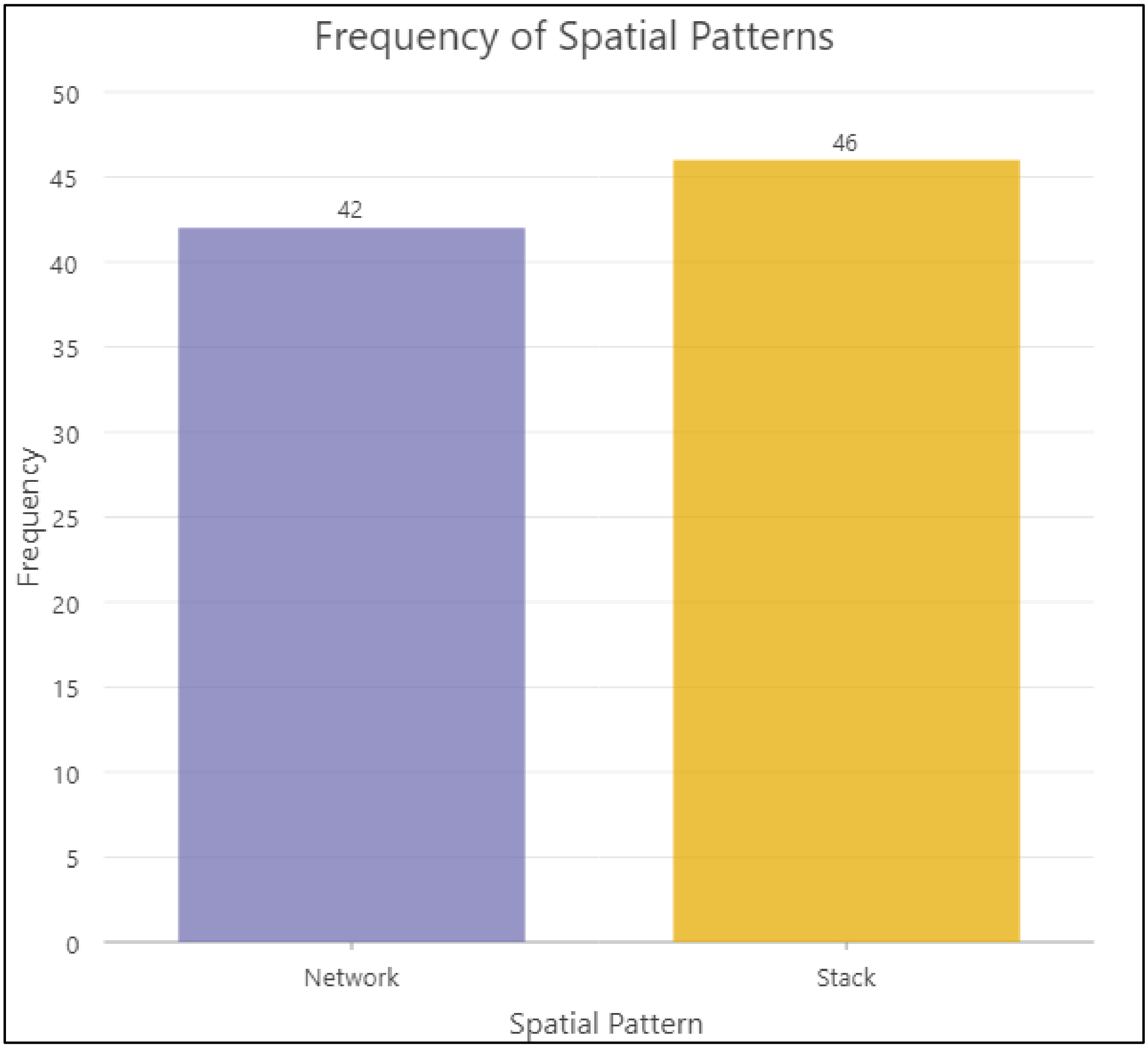


Figure 26. Grouped barplot representing the frequency with which potential wetlands represented each spatial pattern, networks or stacks.

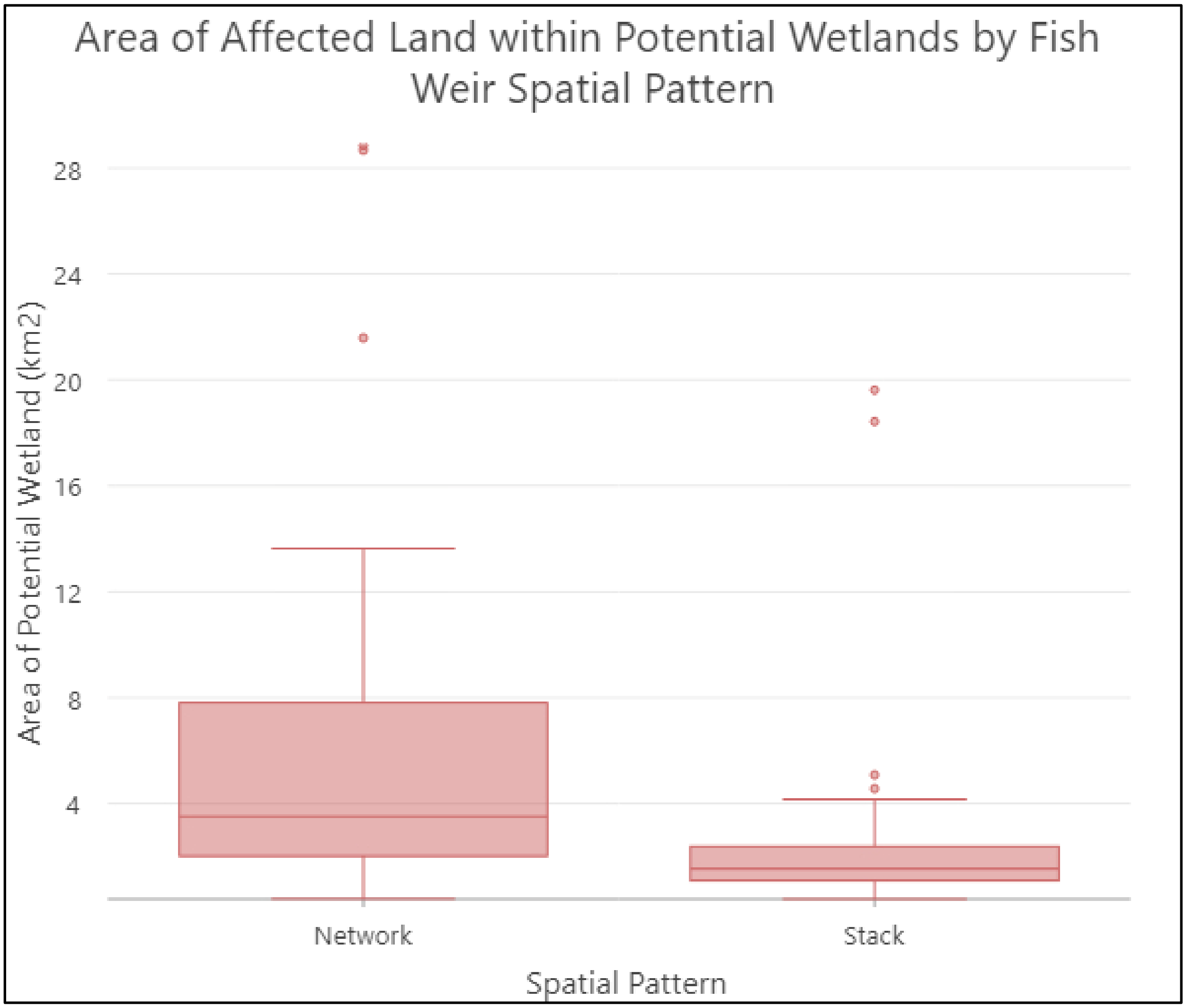


Figure 27. Boxplots representing the size in km^2 of potential wetlands representing networks or stacks of fish weirs.

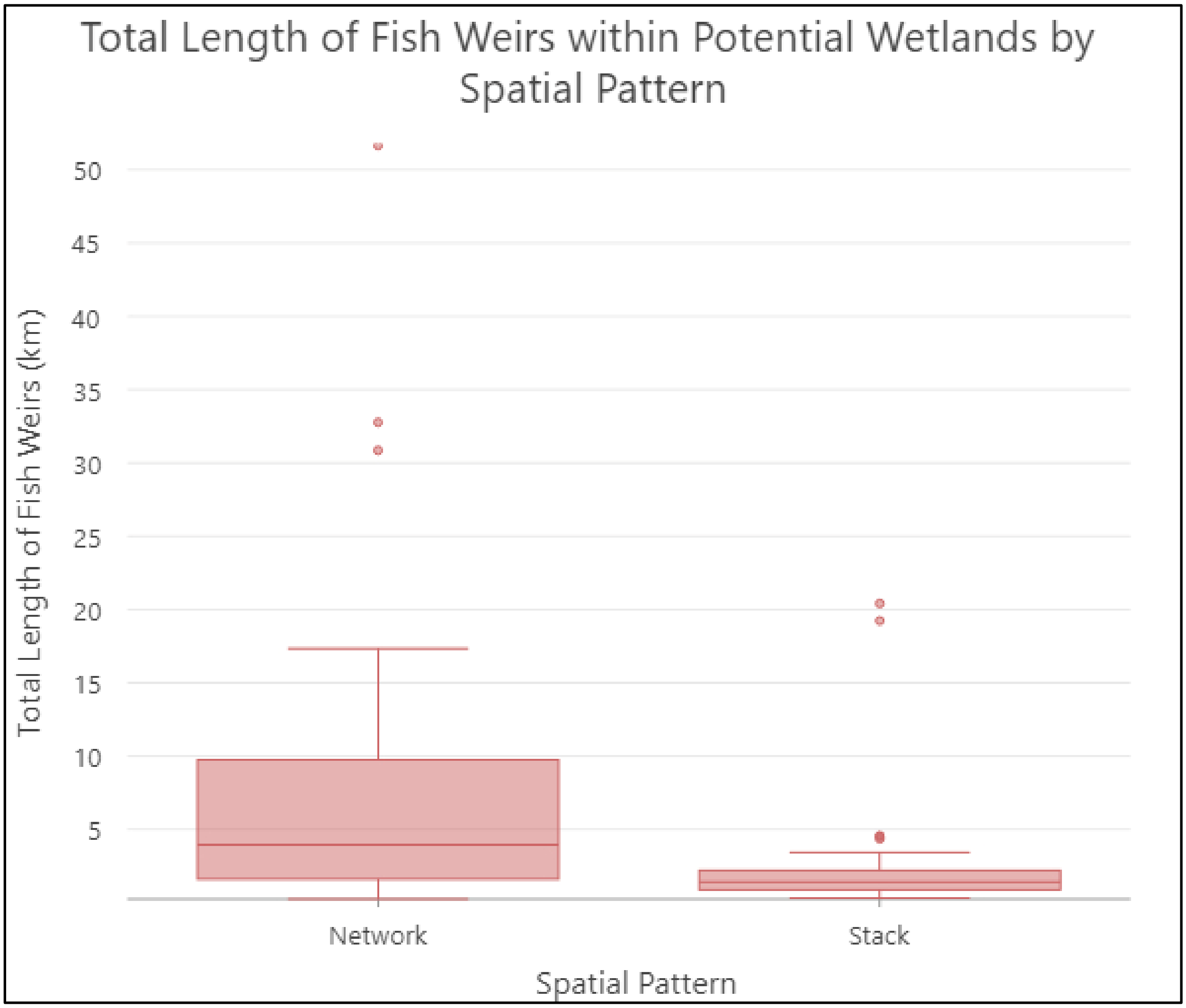


Figure 28. Boxplots representing the total length of fish weirs (km) contained within each potential wetland by spatial pattern.

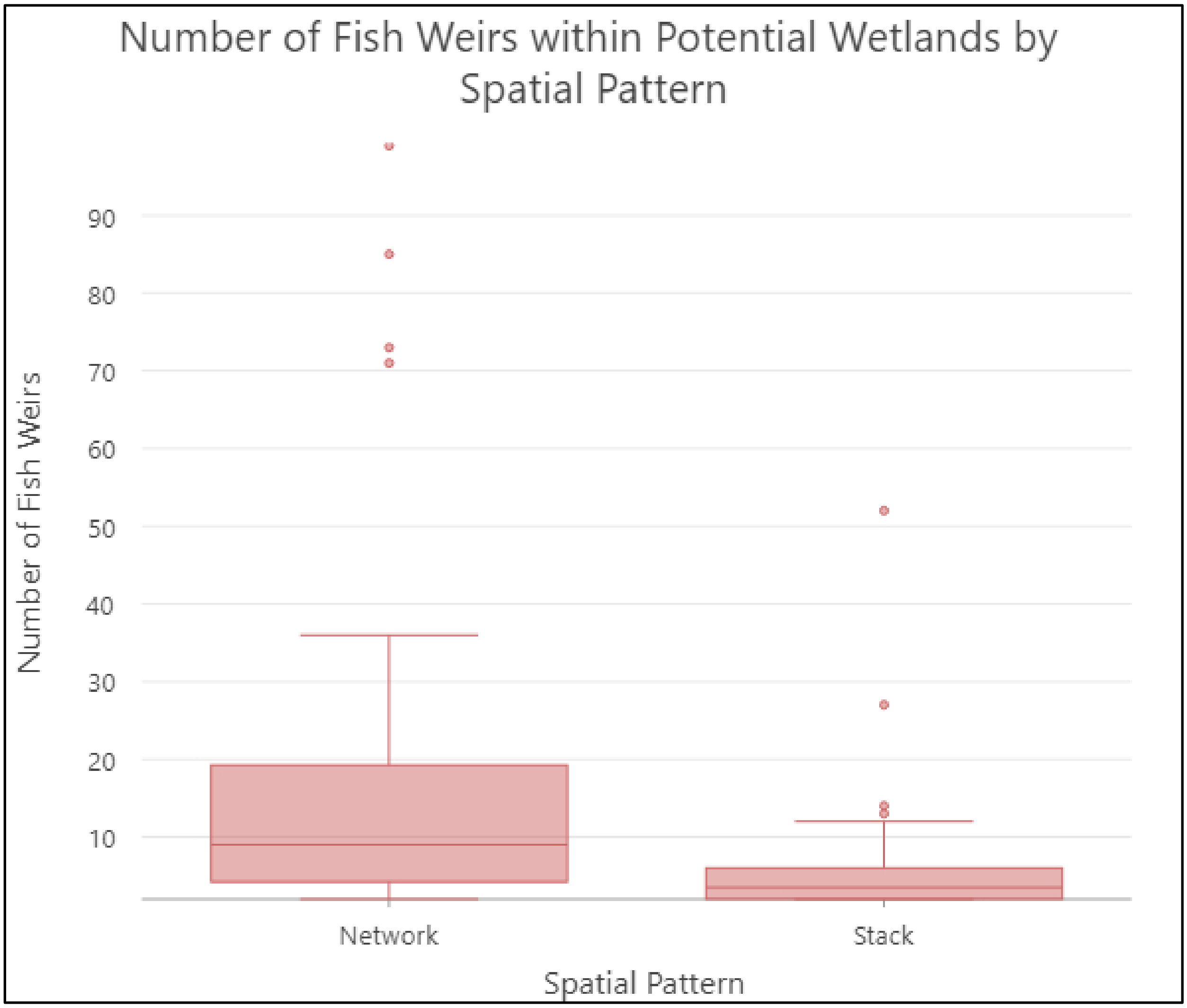


Figure 29. Boxplots representing the number of fish weirs within each potential wetland categorized as either a network or stack.

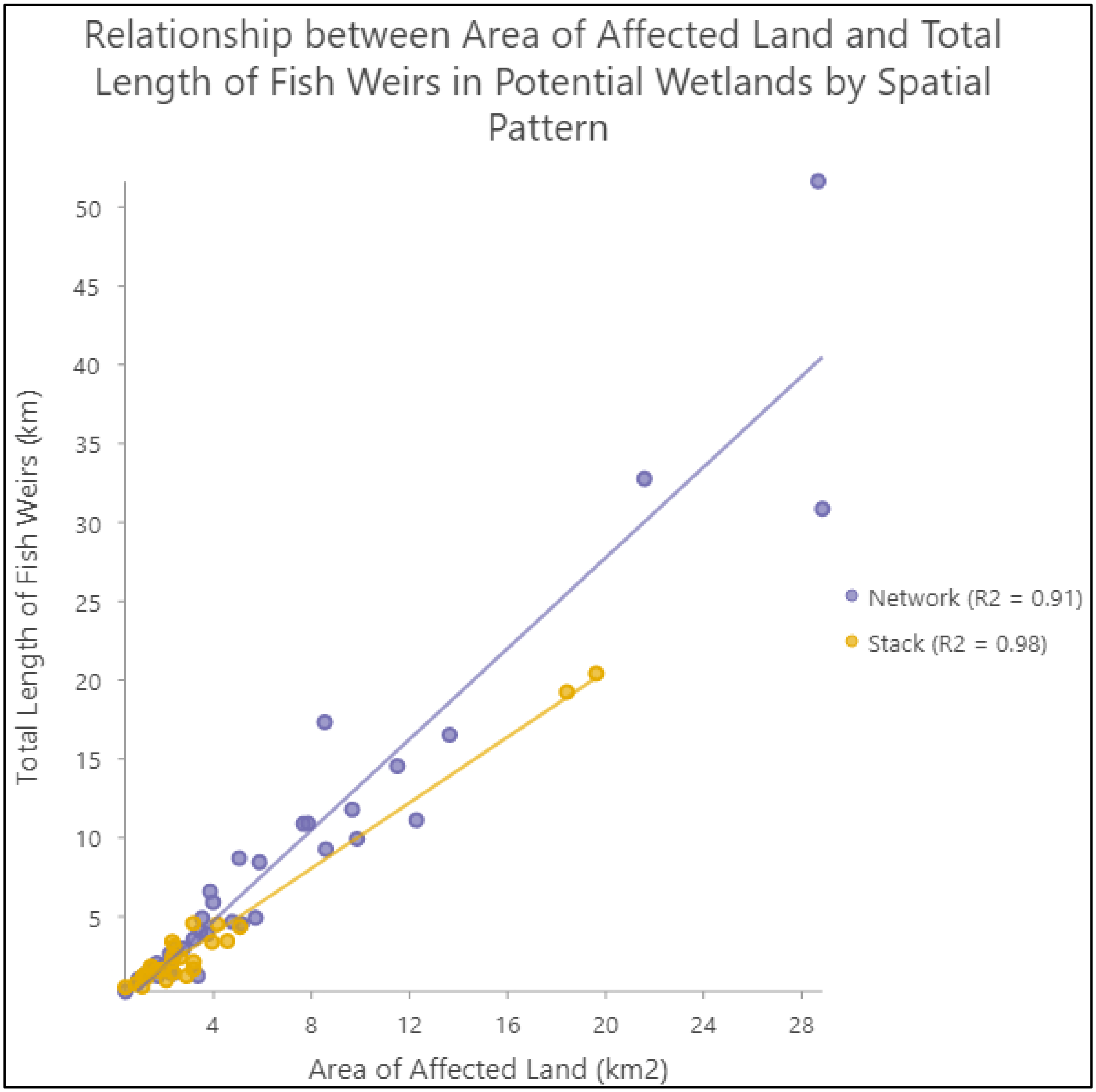


Figure 30. Scatterplot visualizing the relationship between the area of affected land and total length of fish weirs in potential wetlands by spatial pattern.

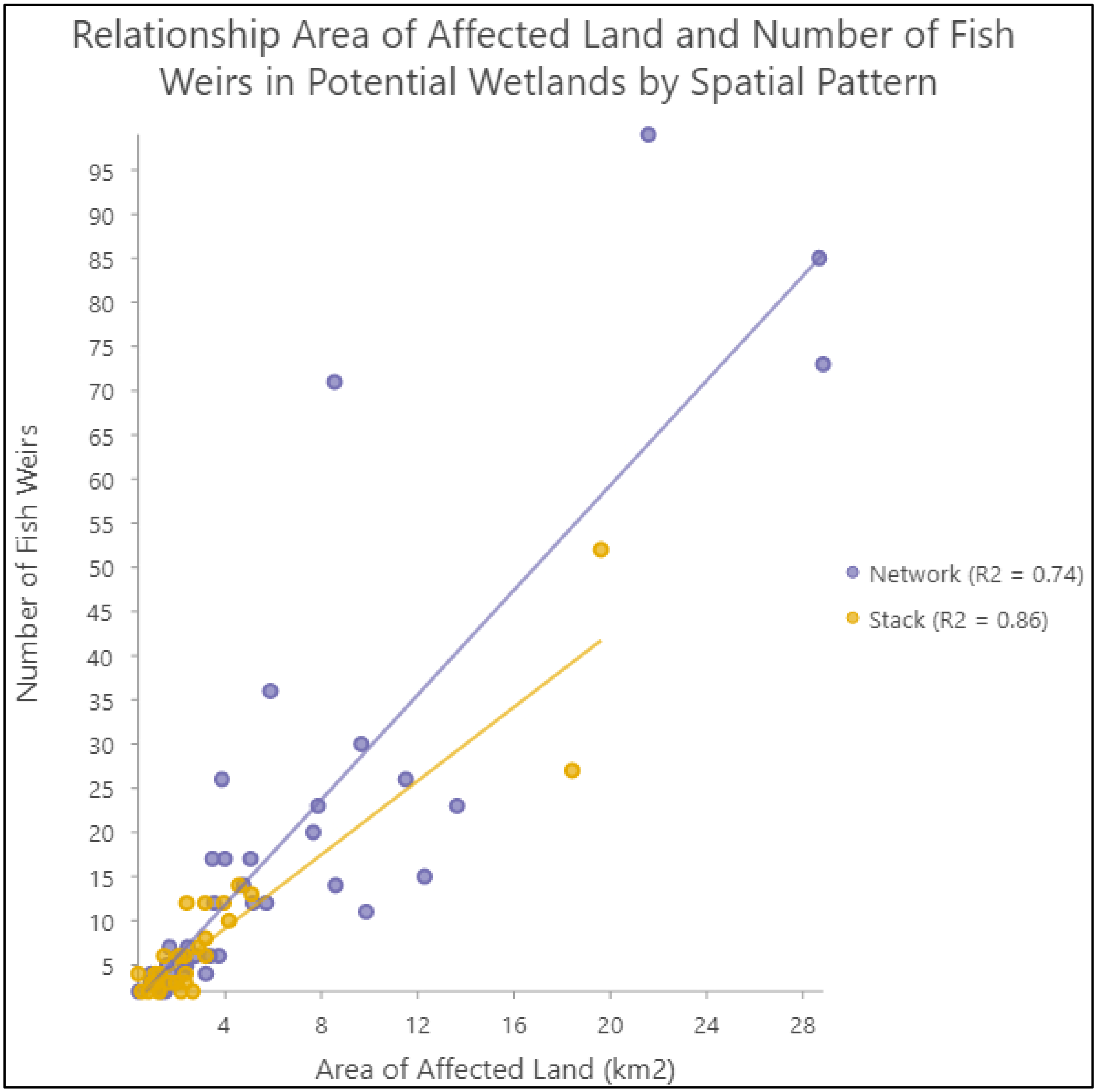


Figure 31. Scatterplot visualizing the relationship between the area of affected land and the number of fish weirs in potential wetlands by spatial pattern.

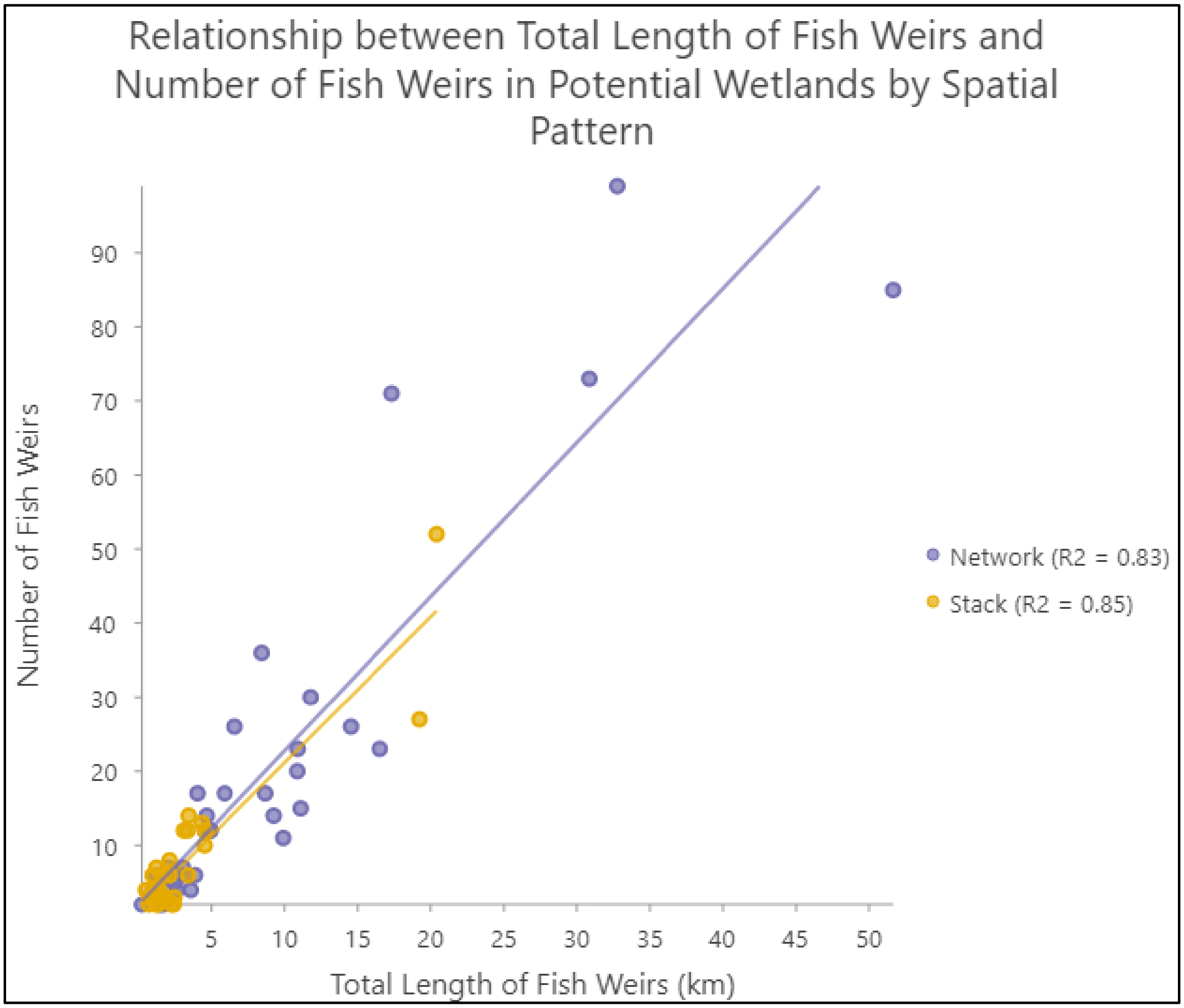


Figure 32. Scatterplot visualizing the relationship between the total length of fish weirs (km) and the number of fish weirs in potential wetlands by spatial pattern.

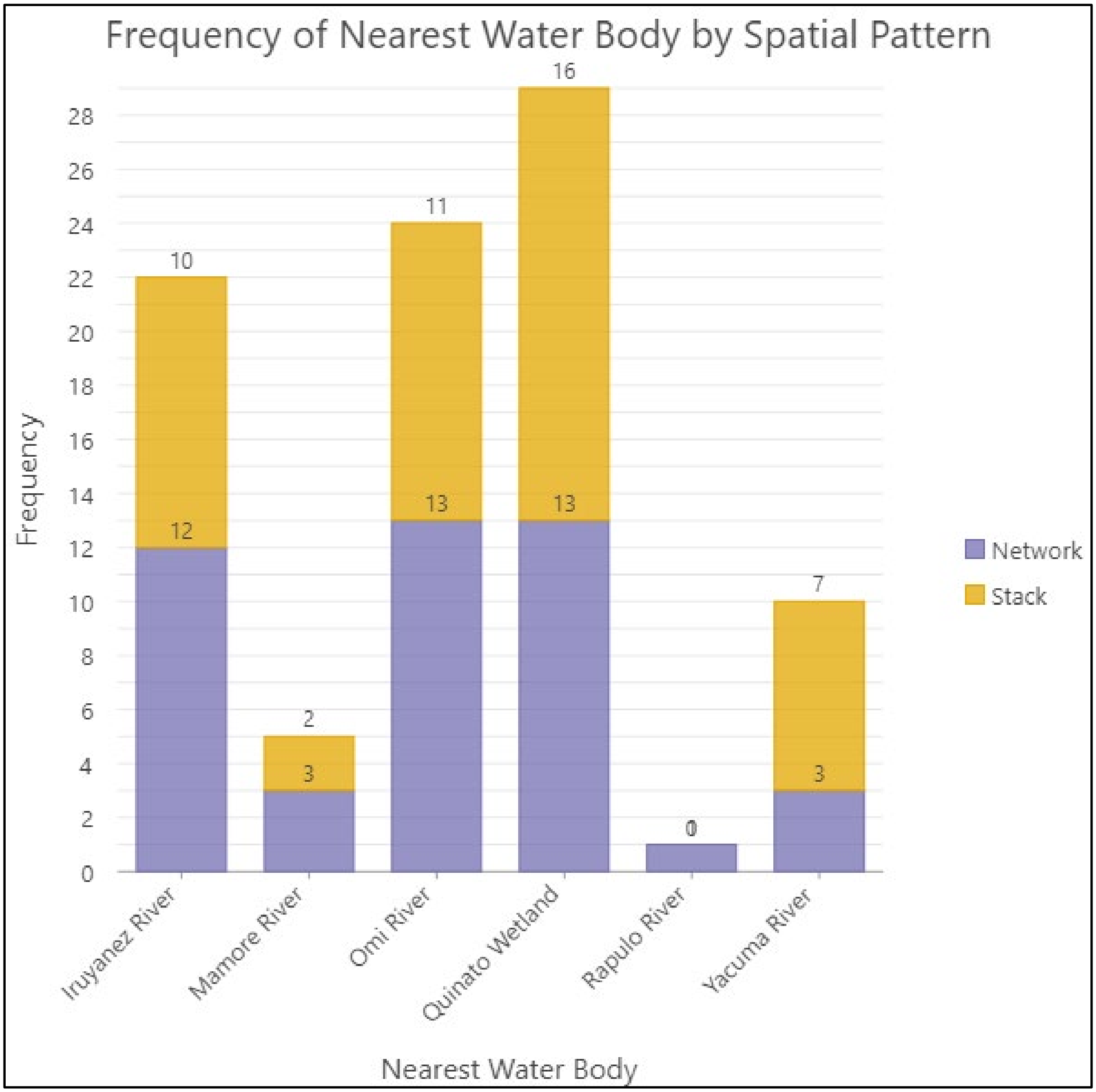


Figure 33. Grouped barplot illustrating the frequency with which potential wetlands of different spatial patterns were found closest to each large body of water in the WCM study area. The Apere River is not shown because it was the closest large body of water to zero potential wetlands.

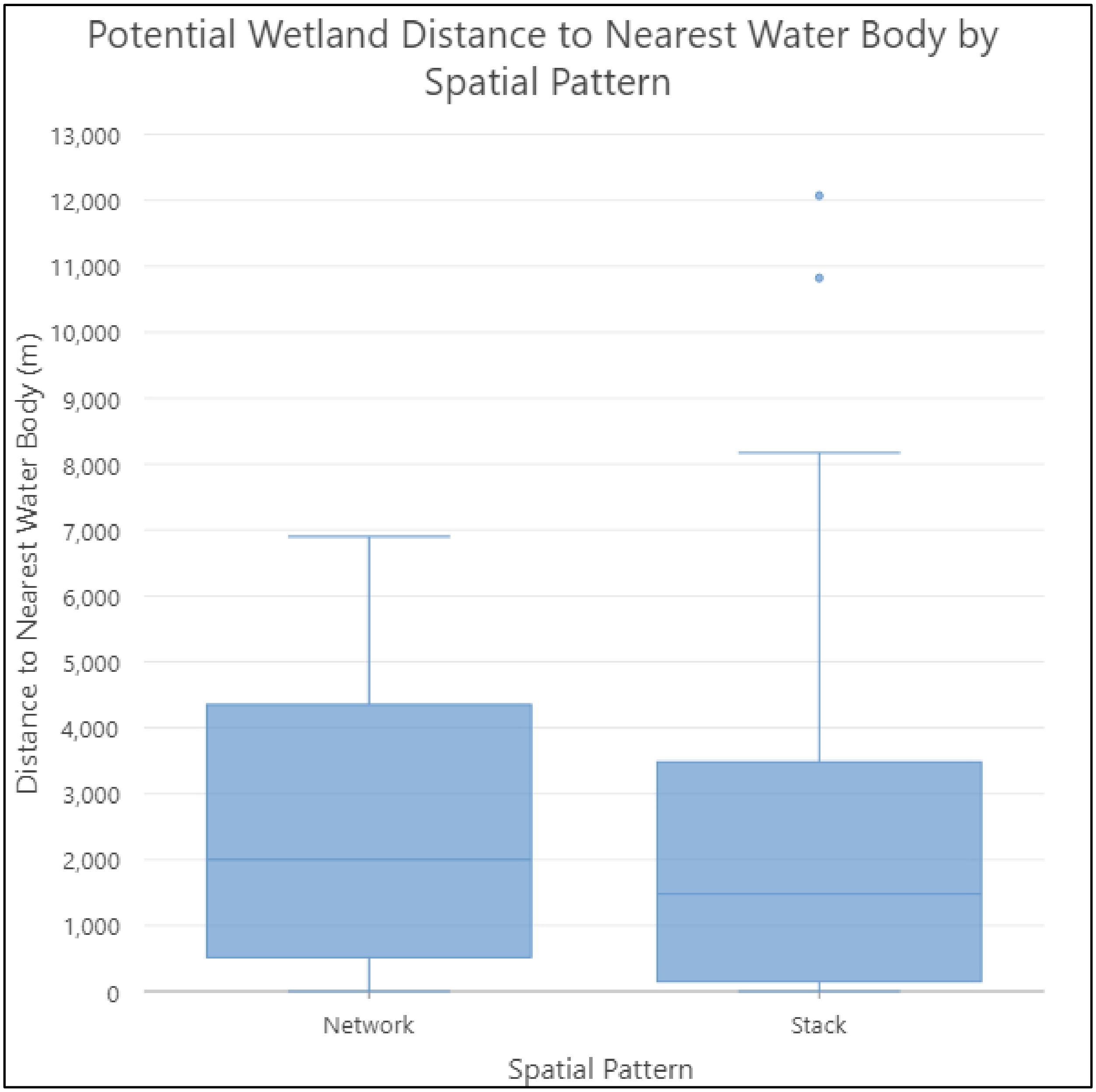


Figure 34. Boxplot representing the distance of each potential wetland to its nearest body of water by spatial pattern.

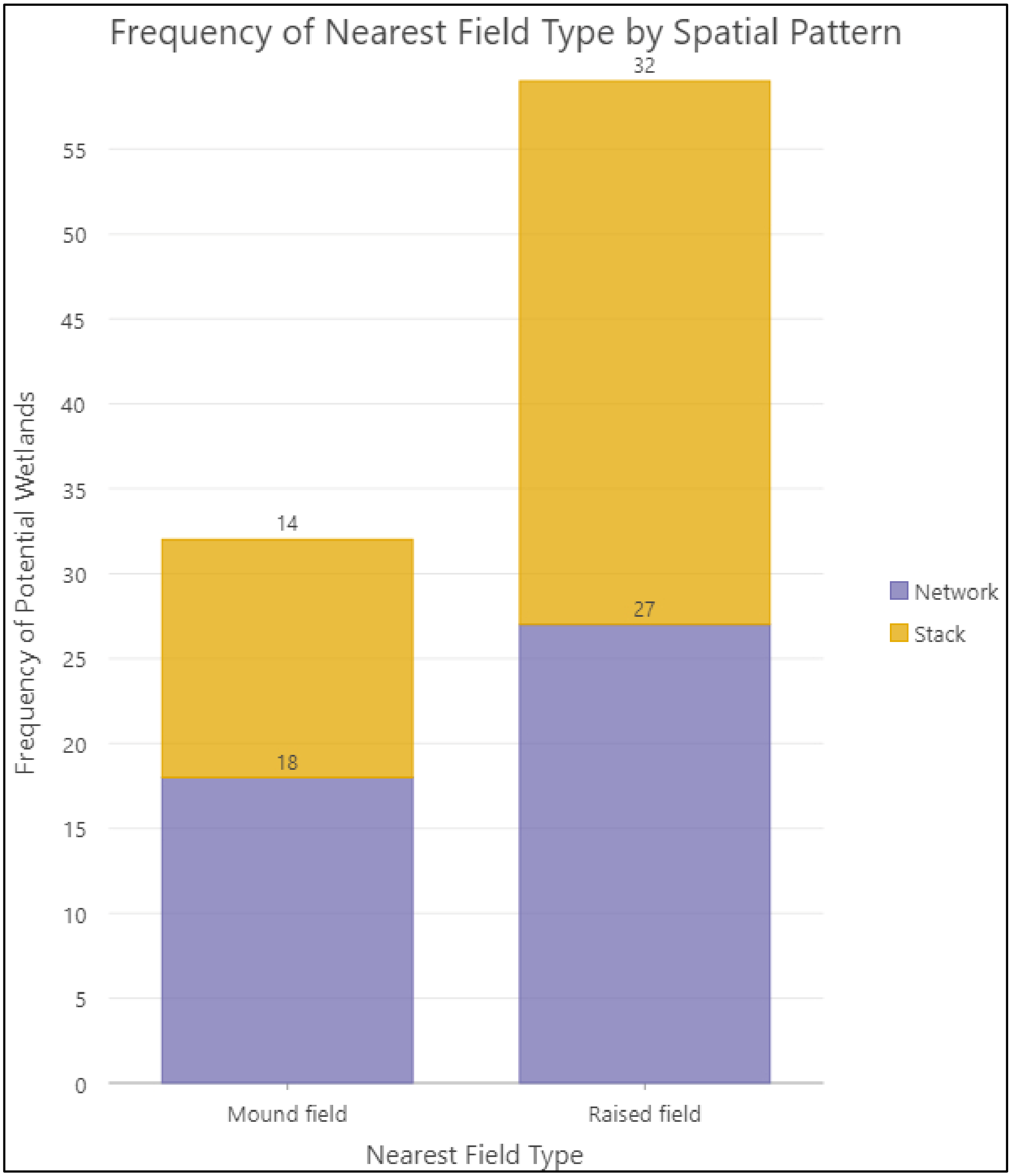


Figure 35. Barplot representing the frequency with which potential wetlands of different types are found nearest to mounded and raised field types.

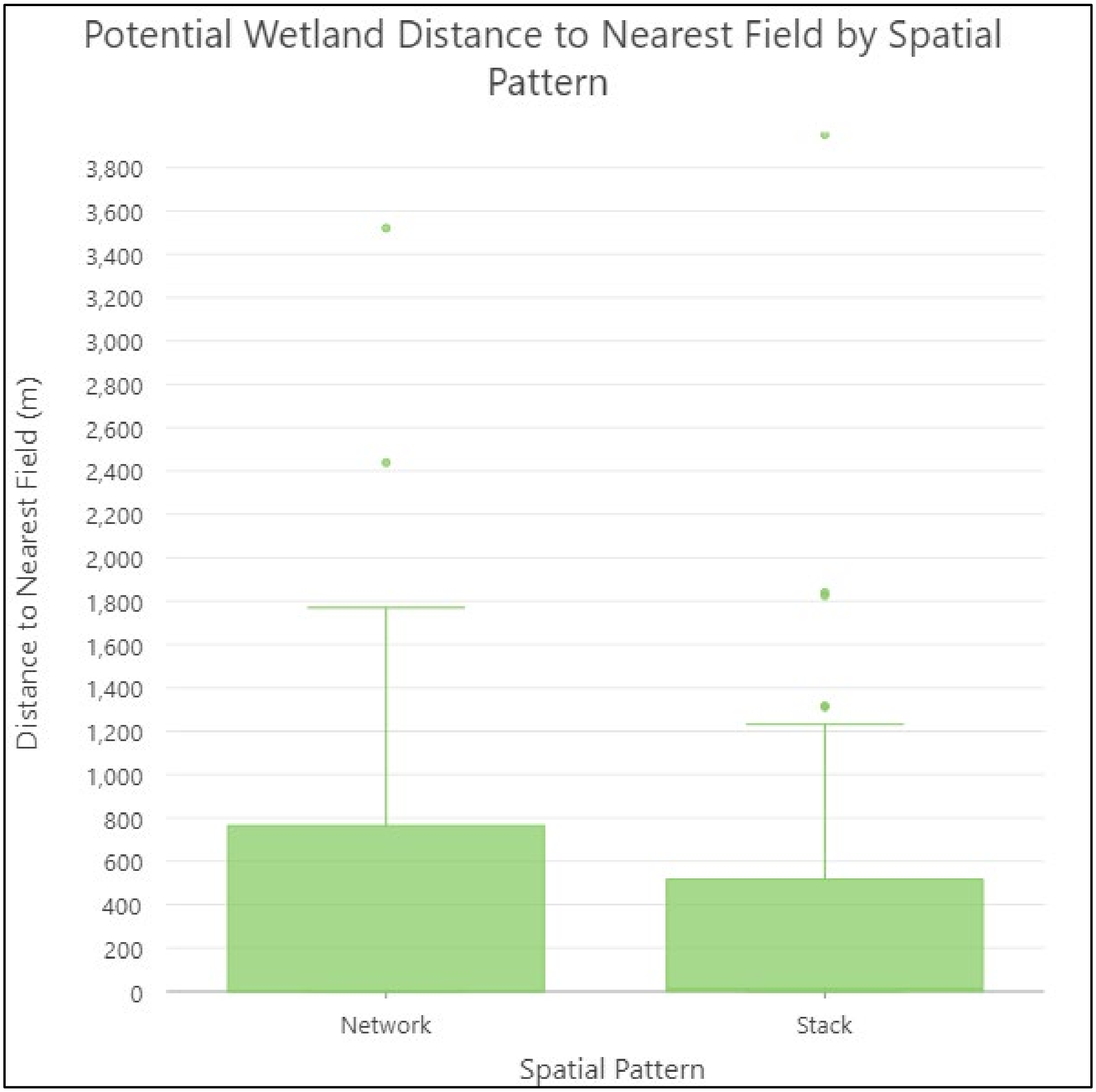


Figure 36. Boxplots representing the distance to the nearest field by spatial pattern.

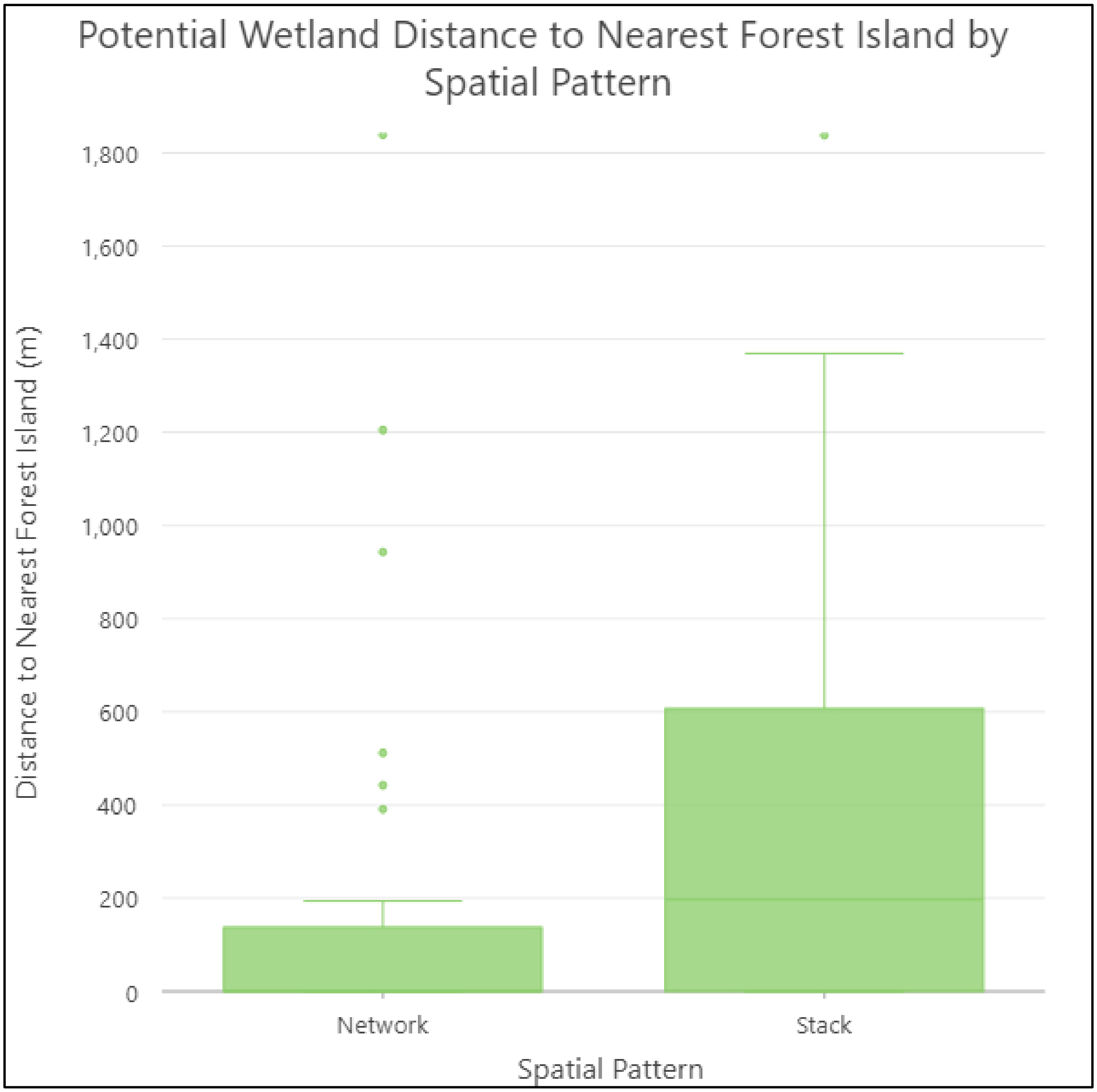


Figure 37. Boxplots representing the distance to the nearest forest island by spatial pattern.

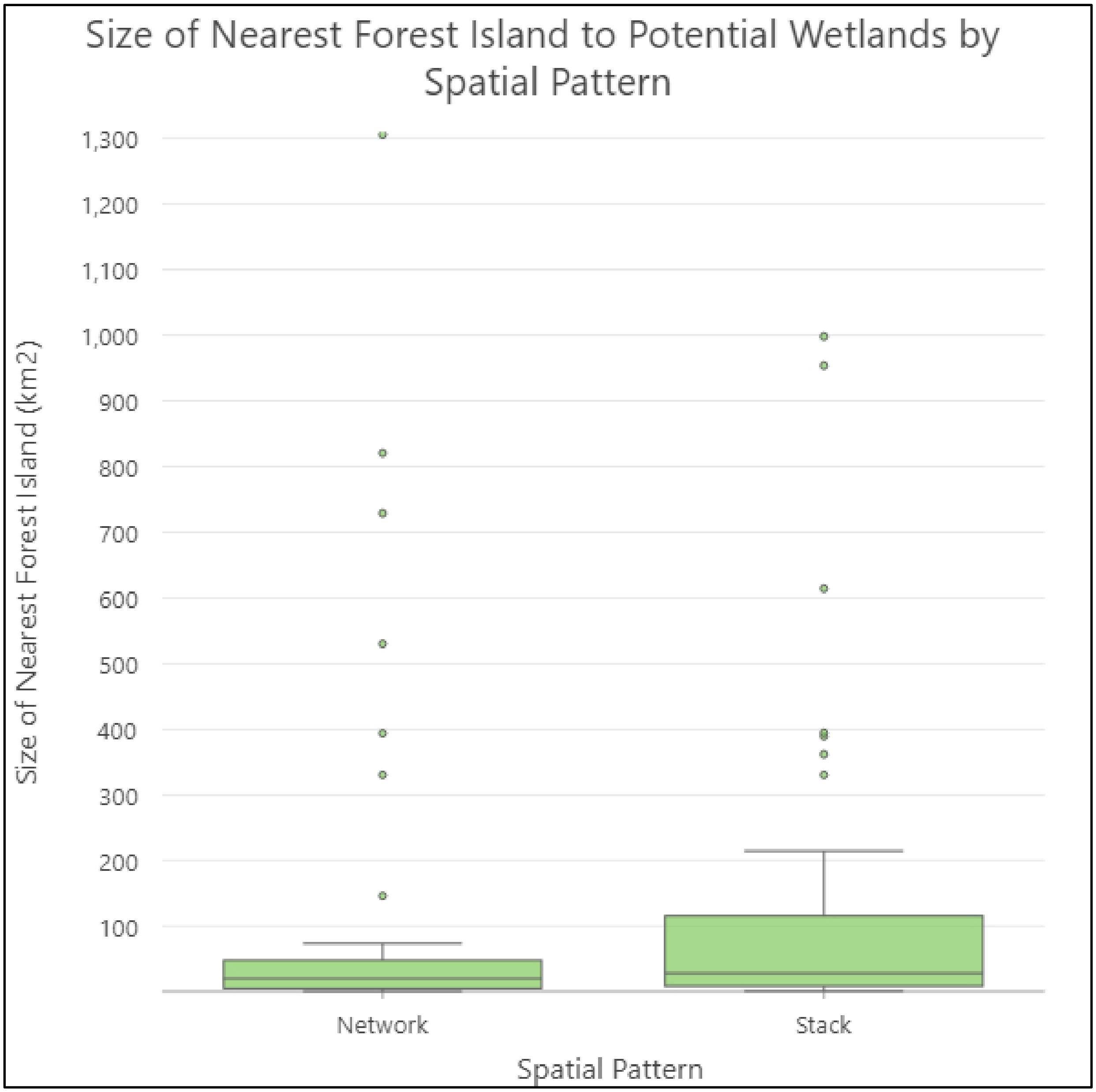


Figure 38. Boxplots representing the size of the nearest forest island to each potential wetland by spatial pattern.

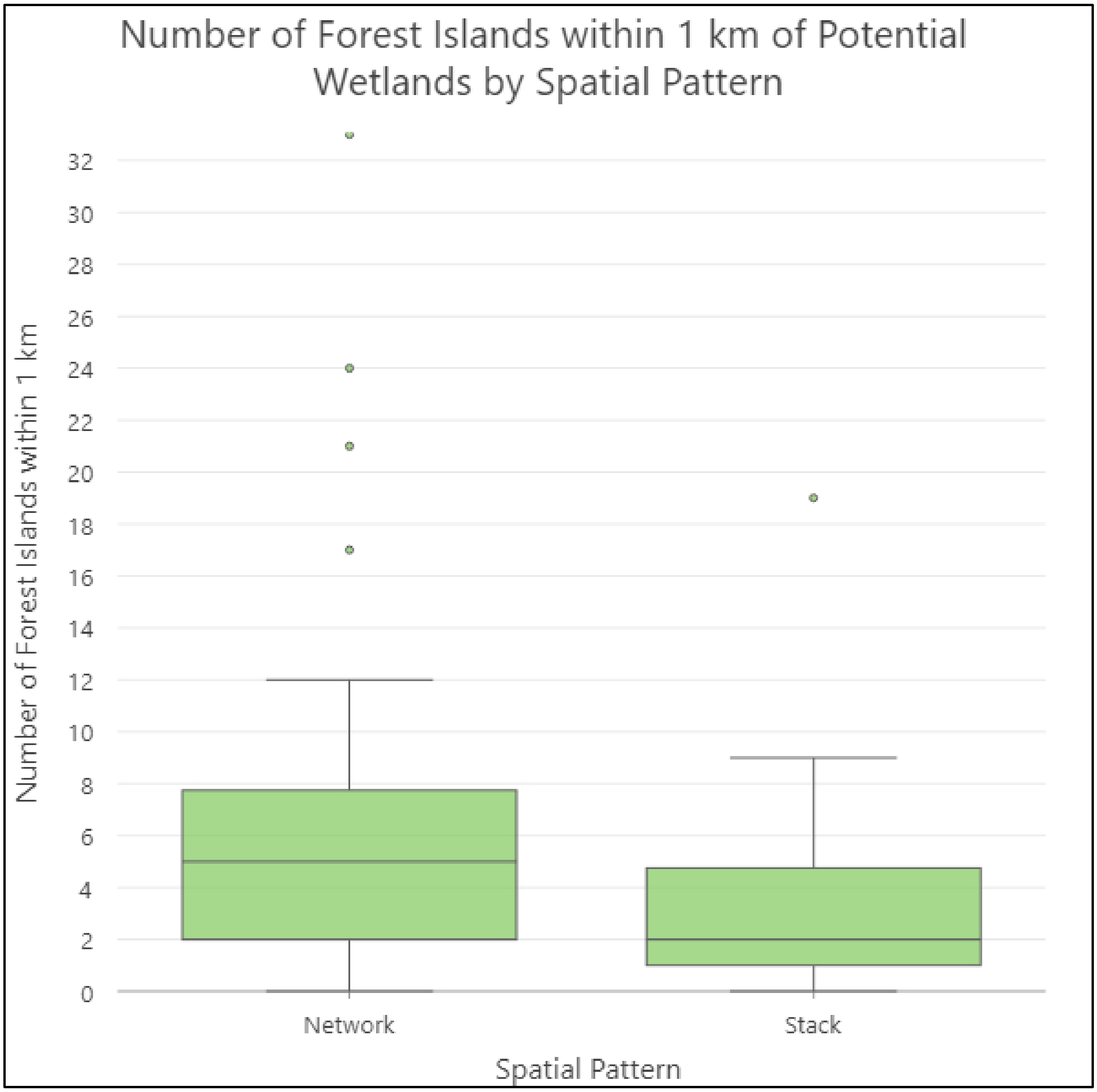


Figure 39. Boxplots representing the number of forest islands within 1 km of each potential wetland by spatial pattern.

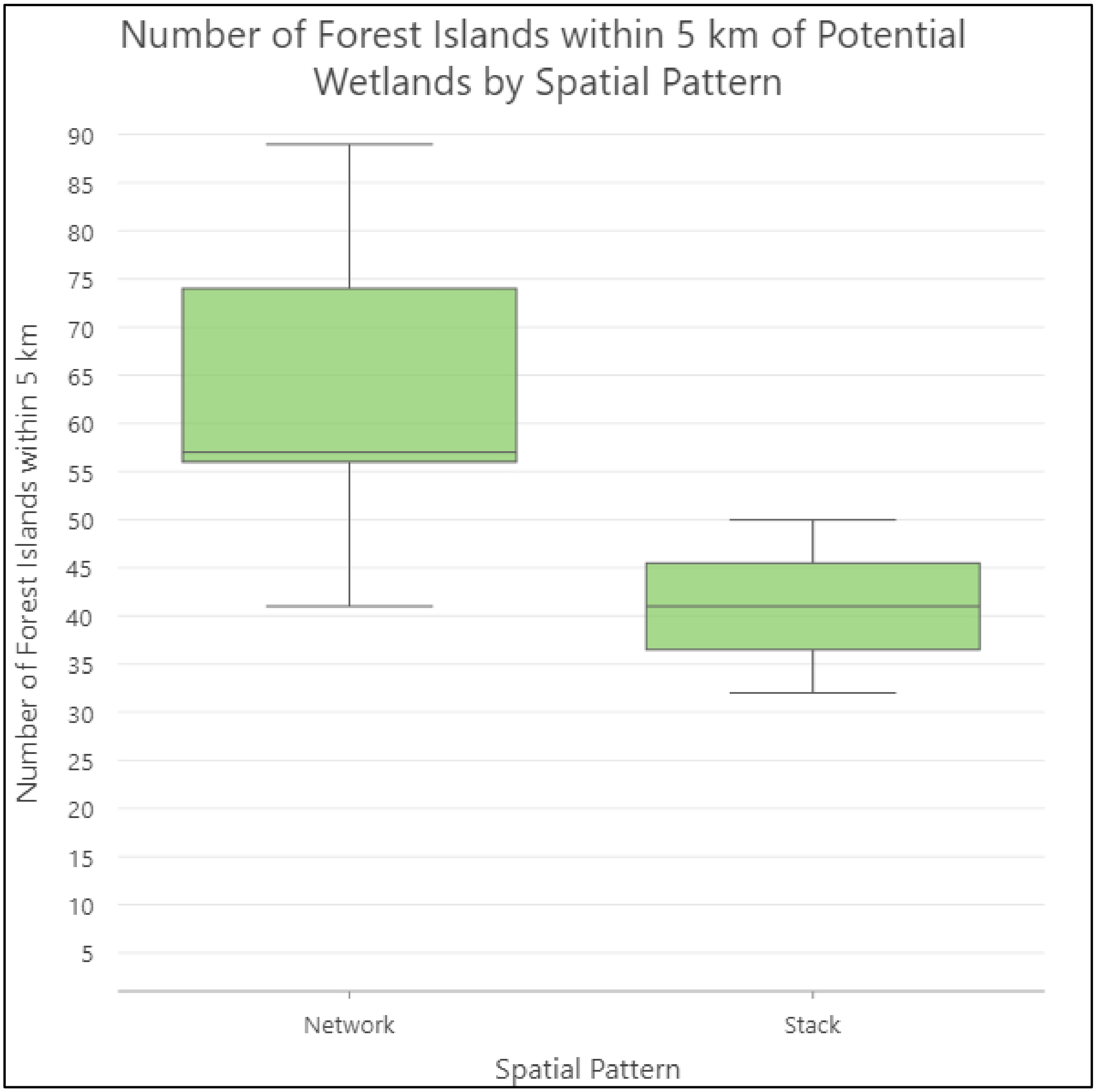


Figure 40. Boxplots representing the number of forest islands within 5 km of each potential wetland by spatial pattern.

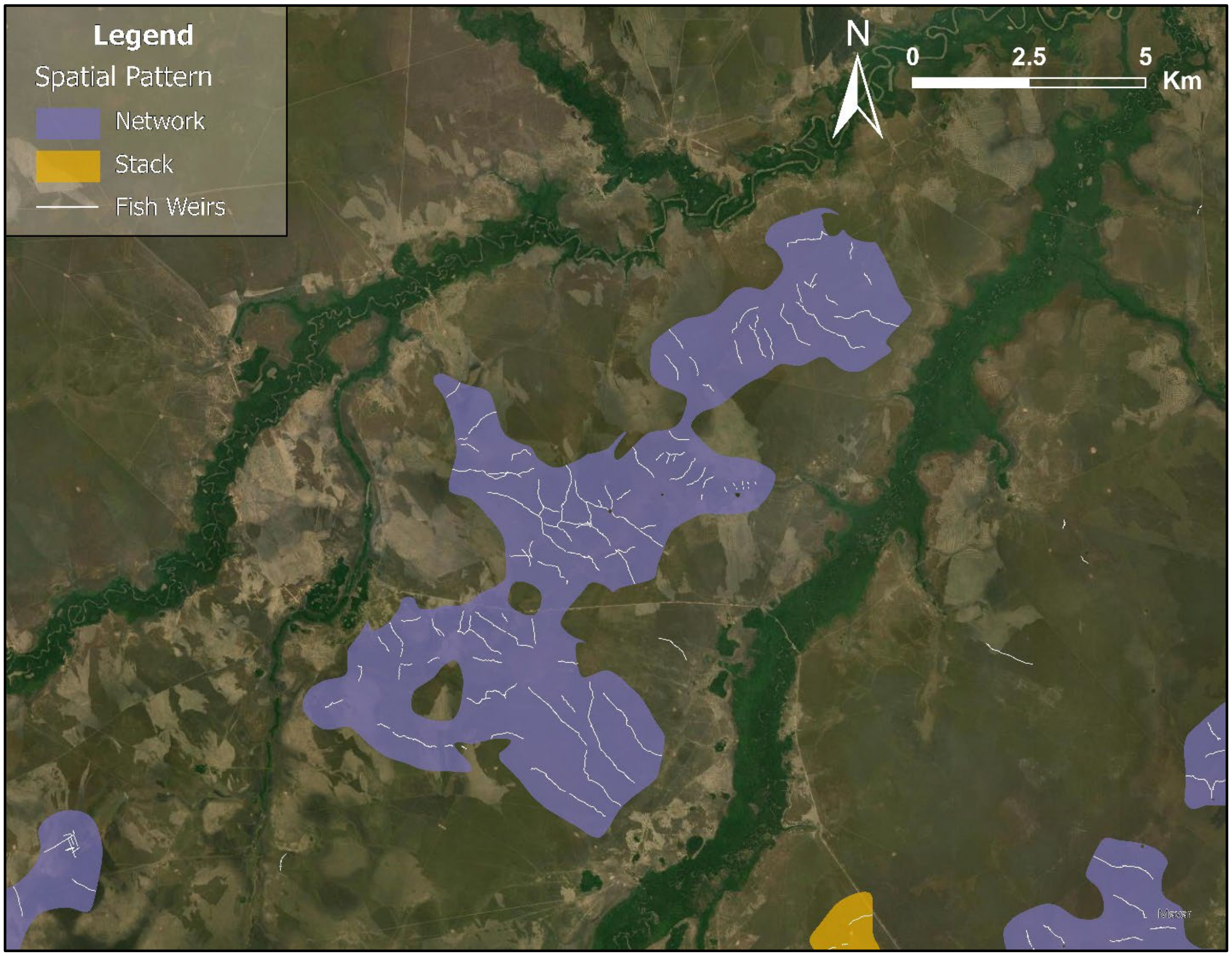


Figure 41. Extreme outlier O3, located between the Iruyañez and Omi Rivers. This is the third largest potential wetland created by the 500 m buffer methodology.

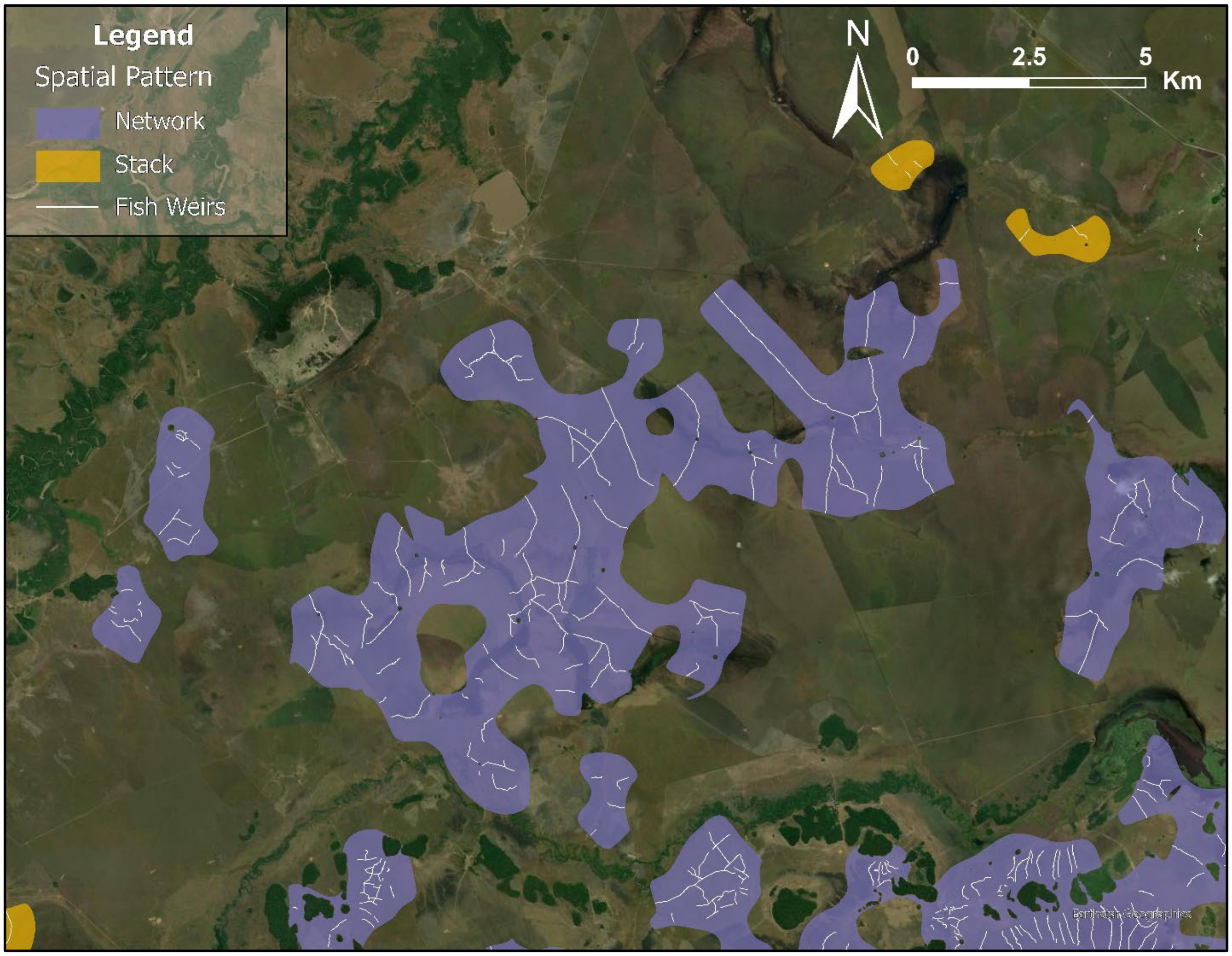


Figure 42. Extreme outlier O2, located north of the terminus of the Omi River and north of O1. This is the second largest potential wetland created by the 500 m buffer methodology.

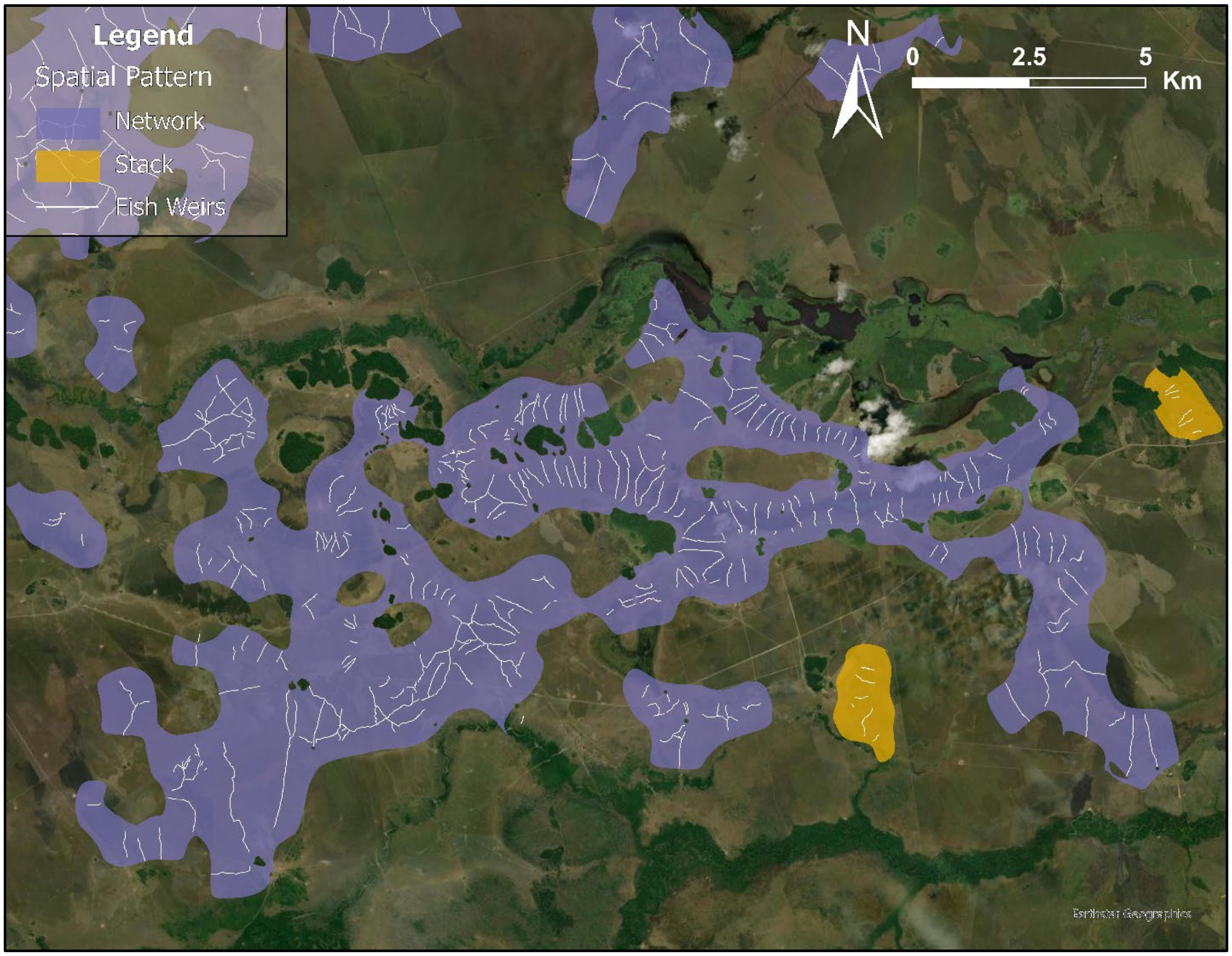
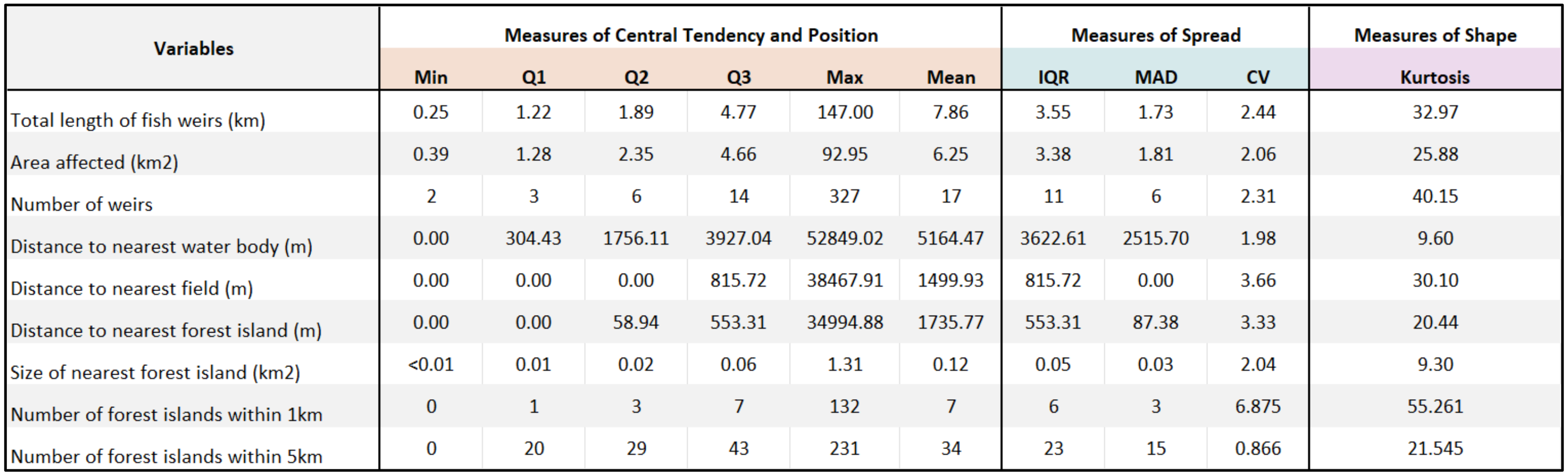


Figure 43. Extreme outlier O2, located south of the terminus of the Omi River and south of O2. This is the largest potential wetland created by the 500 m buffer methodology.

APPENDIX B: TABLES

Table 1. Pooled Descriptive Statistics: Measures of central tendency and position (minimum, quartiles, maximum, and mean), spread (interquartile range, median absolute deviance, and coefficient of variation), and shape (kurtosis) for each continuous and discrete variable in pooled dataset. Given the effect of outliers in skewing the data, median and median absolute difference are more representative statistics than mean and standard deviation (not calculated).



Variables	Measures of Central Tendency and Position						Measures of Spread			Measures of Shape
	Min	**Q1**	**Q2**	**Q3**	**Max**	**Mean**	**IQR**	**MAD**	**CV**	**Kurtosis**
Total length of fish weirs (km)	0.25	1.22	1.89	4.77	147.00	7.86	3.55	1.73	2.44	32.97
Area affected (km2)	0.39	1.28	2.35	4.66	92.95	6.25	3.38	1.81	2.06	25.88
Number of weirs	2	3	6	14	327	17	11	6	2.31	40.15
Distance to nearest water body (m)	0.00	304.43	1756.11	3927.04	52849.02	5164.47	3622.61	2515.70	1.98	9.60
Distance to nearest field (m)	0.00	0.00	0.00	815.72	38467.91	1499.93	815.72	0.00	3.66	30.10
Distance to nearest forest island (m)	0.00	0.00	58.94	553.31	34994.88	1735.77	553.31	87.38	3.33	20.44
Size of nearest forest island (km2)	<0.01	0.01	0.02	0.06	1.31	0.12	0.05	0.03	2.04	9.30
Number of forest islands within 1km	0	1	3	7	132	7	6	3	6.875	55.261
Number of forest islands within 5km	0	20	29	43	231	34	23	15	0.866	21.545

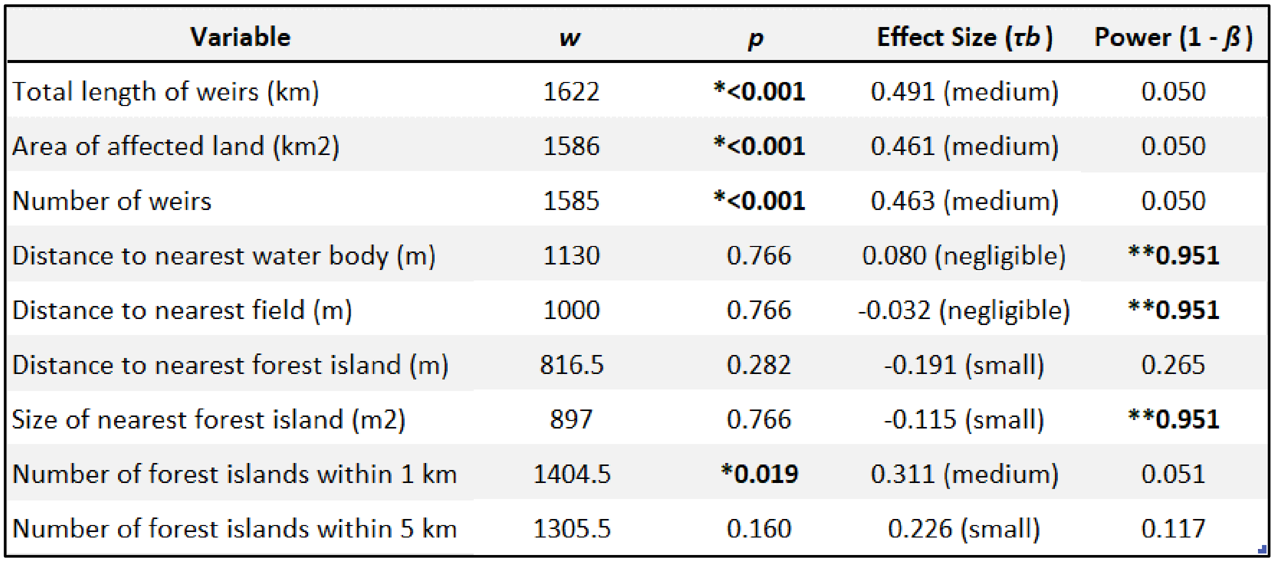
Table 2. Grouped Descriptive Statistics for Stacks: Measures of central tendency and position (minimum, quartiles, maximum, and mean), spread (interquartile range, median absolute deviance, and coefficient of variation), and shape (kurtosis) for each continuous and discrete variable in the grouped dataset belonging to potential wetlands with stacks. Given the effect of outliers in skewing the data, median and median absolute difference are more representative statistics than mean and standard deviation (not calculated).

Variables	Measures of Central Tendency and Position						Measures of Spread			Measures of Shape
	Min	Q1	Q2	Q3	Max	Mean	IQR	MAD	CV	Kurtosis
Total length of fish weirs (km)	0.31	0.87	1.42	2.22	20.41	2.43	1.35	1.04	1.61	16.81
Area affected (km2)	0.39	1.10	1.53	2.39	19.62	2.59	1.29	1.12	1.43	16.37
Number of weirs	2	2	4	6	52	6	4	2	1.35	20.84
Distance to nearest water body (m)	0.00	144.53	1475.30	3480.21	44636.61	4482.94	3335.68	2187.28	1.93	11.09
Distance to nearest field (m)	0.00	0.00	11.91	551.86	14192.90	701.30	551.86	17.66	3.08	35.44
Distance to nearest forest island (m)	0.00	0.00	256.73	858.37	34994.88	1476.83	858.37	380.63	3.57	38.47
Size of nearest forest island (km2)	<0.01	0.01	0.03	0.12	1.00	0.12	0.11	0.04	1.82	7.59
Number of forest islands within 1km	0	1	2	5	19	3	4	3	1.09	7.94
Number of forest islands within 5km	0	19	26	36	53	27	17	13	0.50	-0.34

Table 3. Grouped Descriptive Statistics for Networks: Measures of central tendency and position (minimum, quartiles, maximum, and mean), spread (interquartile range, median absolute deviance, and coefficient of variation), and shape (kurtosis) for each continuous and discrete variable in the grouped dataset belonging to potential wetlands with networks. Given the effect of outliers in skewing the data, median and median absolute difference are more representative statistics than mean and standard deviation (not calculated).

Variables	Measures of Central Tendency and Position						Measures of Spread			Measures of Shape
	Min	Q1	Q2	Q3	Max	Mean	IQR	MAD	CV	Kurtosis
Total length of fish weirs (km)	0.25	1.70	4.54	10.91	147.00	13.40	9.21	4.89	1.93	16.48
Area affected (km2)	0.40	2.16	3.73	8.59	92.95	9.99	6.43	3.19	1.72	13.04
Number of weirs	2	5	12	23	327	29	18	12	1.88	20.77
Distance to nearest water body (m)	0.00	514.94	2000.84	4350.65	52849.02	5861.14	3835.71	2832.99	1.99	8.31
Distance to nearest field (m)	0.00	0.00	0.00	1151.45	38467.91	2316.30	1151.45	0.00	3.21	16.02
Distance to nearest forest island (m)	0.00	0.00	0.00	188.71	30632.79	2000.46	188.71	0.00	3.16	12.36
Size of nearest forest island (km2)	<0.01	0.01	0.02	0.05	1.31	0.11	0.04	0.02	2.31	11.18
Number of forest islands within 1km	0	2	5	10	132	10	8	4	2.027	29.055
Number of forest islands within 5km	0	23	33	53	231	42	30	21	0.920	12.495

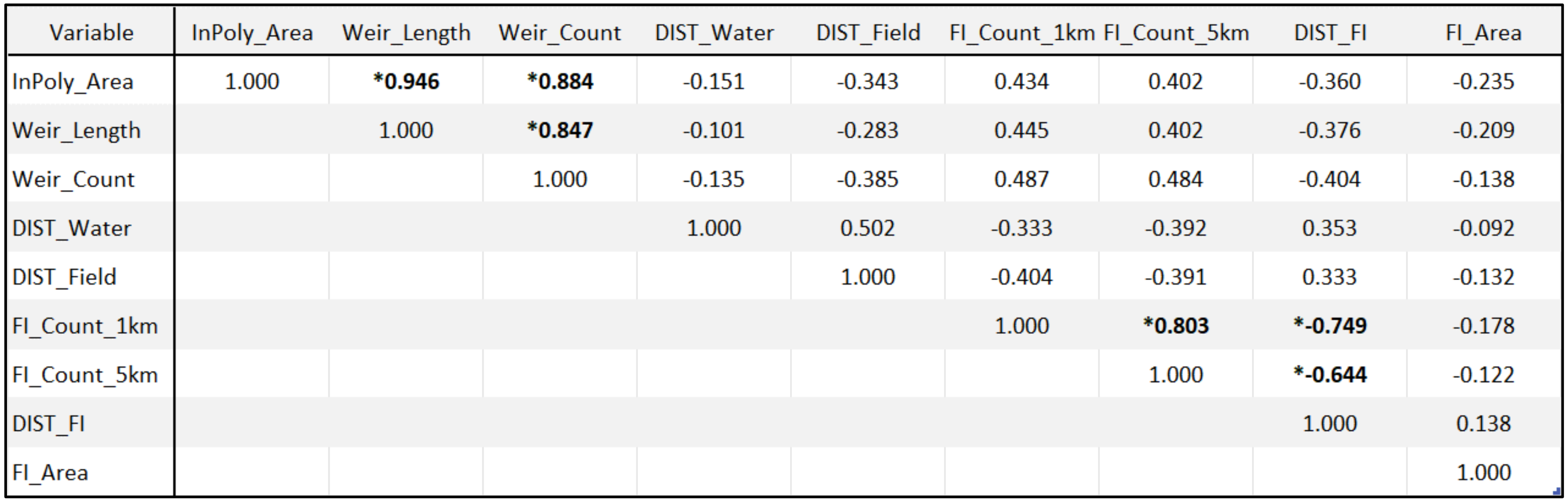
Table 4. Mann-Whitney U Two-Tailed Hypothesis Test Results: For each continuous and discrete variable listed, the Mann-Whitney test statistic (w) is listed along with the Hochberg's adjusted p-value (p), Kendall's Tau-b effect size (τ_b), and test power ($1 - \beta$).



Variable	w	p	Effect Size (τb)	Power ($1 - \beta$)
Total length of weirs (km)	1622	***<0.001**	0.491 (medium)	0.050
Area of affected land (km2)	1586	***<0.001**	0.461 (medium)	0.050
Number of weirs	1585	***<0.001**	0.463 (medium)	0.050
Distance to nearest water body (m)	1130	0.766	0.080 (negligible)	****0.951**
Distance to nearest field (m)	1000	0.766	-0.032 (negligible)	****0.951**
Distance to nearest forest island (m)	816.5	0.282	-0.191 (small)	0.265
Size of nearest forest island (m2)	897	0.766	-0.115 (small)	****0.951**
Number of forest islands within 1 km	1404.5	***0.019**	0.311 (medium)	0.051
Number of forest islands within 5 km	1305.5	0.160	0.226 (small)	0.117

* $p = 0.05$, after Hochberg's alpha correction
** $1 - \beta = 0.8$

Table 5. Pooled Spearman's Rho Correlation Coefficients: For each continuous and discrete variable, Spearman's rho (ρ) correlation coefficients for the pooled dataset.

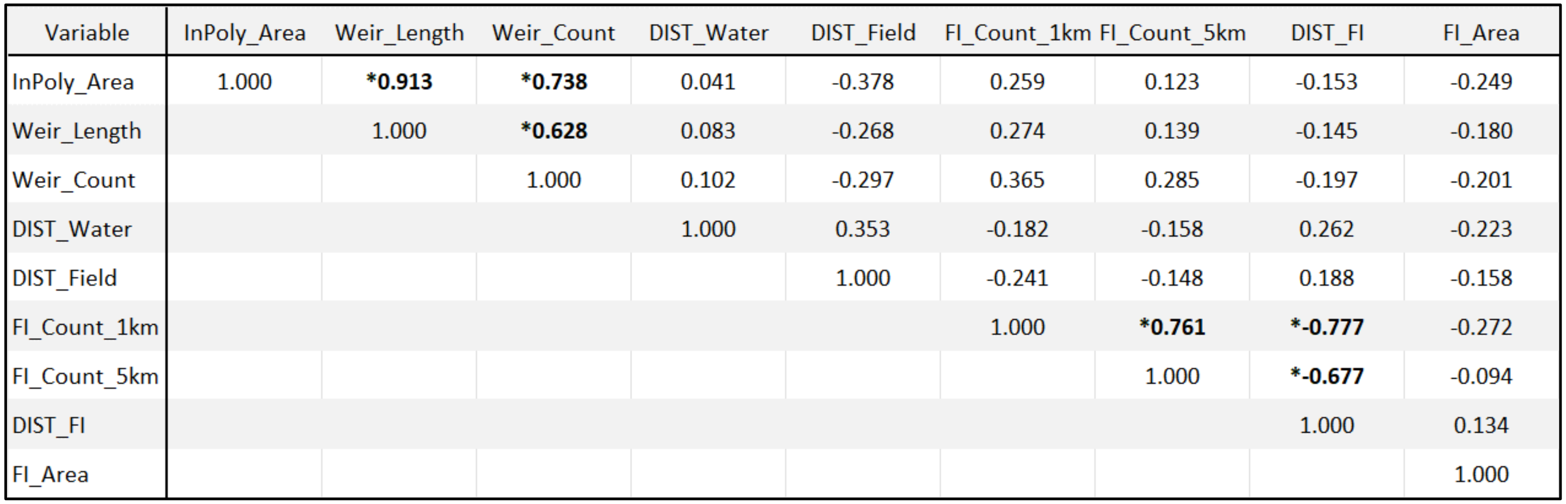


Variable	InPoly_Area	Weir_Length	Weir_Count	DIST_Water	DIST_Field	FI_Count_1km	FI_Count_5km	DIST_FI	FI_Area
InPoly_Area	1.000	***0.946**	***0.884**	-0.151	-0.343	0.434	0.402	-0.360	-0.235
Weir_Length		1.000	***0.847**	-0.101	-0.283	0.445	0.402	-0.376	-0.209
Weir_Count			1.000	-0.135	-0.385	0.487	0.484	-0.404	-0.138
DIST_Water				1.000	0.502	-0.333	-0.392	0.353	-0.092
DIST_Field					1.000	-0.404	-0.391	0.333	-0.132
FI_Count_1km						1.000	***0.803**	***-0.749**	-0.178
FI_Count_5km							1.000	***-0.644**	-0.122
DIST_FI								1.000	0.138
FI_Area									1.000

Note. InPoly_Area = Area of affected land; Weir_Length = Total length of weirs; Weir_Count = Number of weirs; DIST_Water = Distance to nearest water body; DIST_Field = Distance to nearest field; FI_Count_1km = Number of forest islands within 1 km; FI_Count_5km = Number of forest islands within 5 km; DIST_FI = Distance to nearest forest islands; FI_Area = Size of nearest forest island.

* $\rho = 0.60$

Table 6. Grouped Spearman's Rho Correlation Coefficients for Stacks: For potential wetlands with stacks, Spearman's rho (ρ) correlation coefficients for each pair of continuous and discrete variables in the grouped dataset.



Variable	InPoly_Area	Weir_Length	Weir_Count	DIST_Water	DIST_Field	FI_Count_1km	FI_Count_5km	DIST_FI	FI_Area
InPoly_Area	1.000	***0.913**	***0.738**	0.041	-0.378	0.259	0.123	-0.153	-0.249
Weir_Length		1.000	***0.628**	0.083	-0.268	0.274	0.139	-0.145	-0.180
Weir_Count			1.000	0.102	-0.297	0.365	0.285	-0.197	-0.201
DIST_Water				1.000	0.353	-0.182	-0.158	0.262	-0.223
DIST_Field					1.000	-0.241	-0.148	0.188	-0.158
FI_Count_1km						1.000	***0.761**	***-0.777**	-0.272
FI_Count_5km							1.000	***-0.677**	-0.094
DIST_FI								1.000	0.134
FI_Area									1.000

Note. InPoly_Area = Area of affected land; Weir_Length = Total length of weirs; Weir_Count = Number of weirs; DIST_Water = Distance to nearest water body; DIST_Field = Distance to nearest field; FI_Count_1km = Number of forest islands within 1 km; FI_Count_5km = Number of forest islands within 5 km; DIST_FI = Distance to nearest forest islands; FI_Area = Size of nearest forest island.

* $\rho = 0.60$

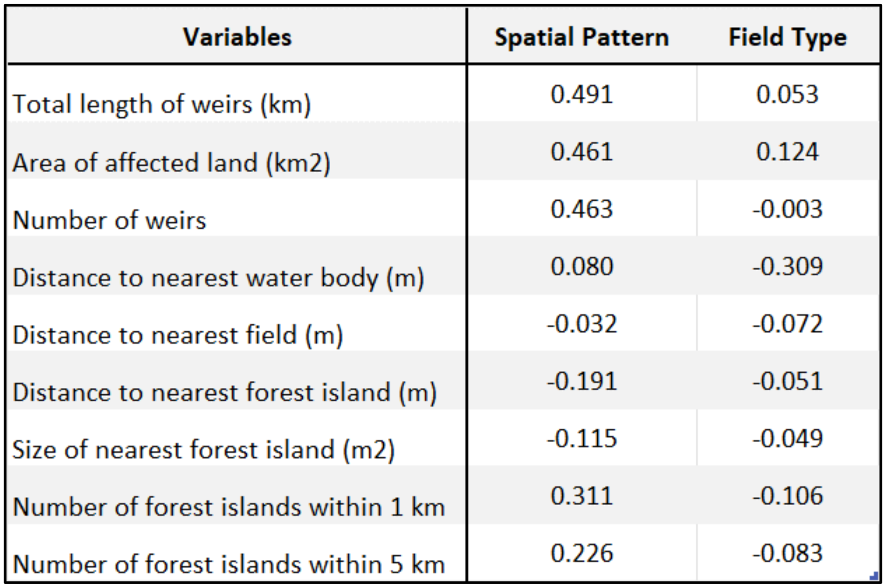
Table 7. Grouped Spearman's Rho Correlation Coefficients for Networks: For potential wetlands with stacks, Spearman's rho (ρ) correlation coefficients for each pair of continuous and discrete variables in the grouped dataset.

Variable	InPoly_Area	Weir_Length	Weir_Count	DIST_Water	DIST_Field	FI_Count_1km	FI_Count_5km	DIST_FI	FI_Area
InPoly_Area	1.000	***0.913**	***0.738**	0.041	-0.378	0.259	0.123	-0.153	-0.249
Weir_Length		1.000	***0.628**	0.083	-0.268	0.274	0.139	-0.145	-0.180
Weir_Count			1.000	0.102	-0.297	0.365	0.285	-0.197	-0.201
DIST_Water				1.000	0.353	-0.182	-0.158	0.262	-0.223
DIST_Field					1.000	-0.241	-0.148	0.188	-0.158
FI_Count_1km						1.000	***0.761**	***-0.777**	-0.272
FI_Count_5km							1.000	***-0.677**	-0.094
DIST_FI								1.000	0.134
FI_Area									1.000

Note. InPoly_Area = Area of affected land; Weir_Length = Total length of weirs; Weir_Count = Number of weirs; DIST_Water = Distance to nearest water body; DIST_Field = Distance to nearest field; FI_Count_1km = Number of forest islands within 1 km; FI_Count_5km = Number of forest islands within 5 km; DIST_FI = Distance to nearest forest islands; FI_Area = Size of nearest forest island.

* $\rho = 0.60$

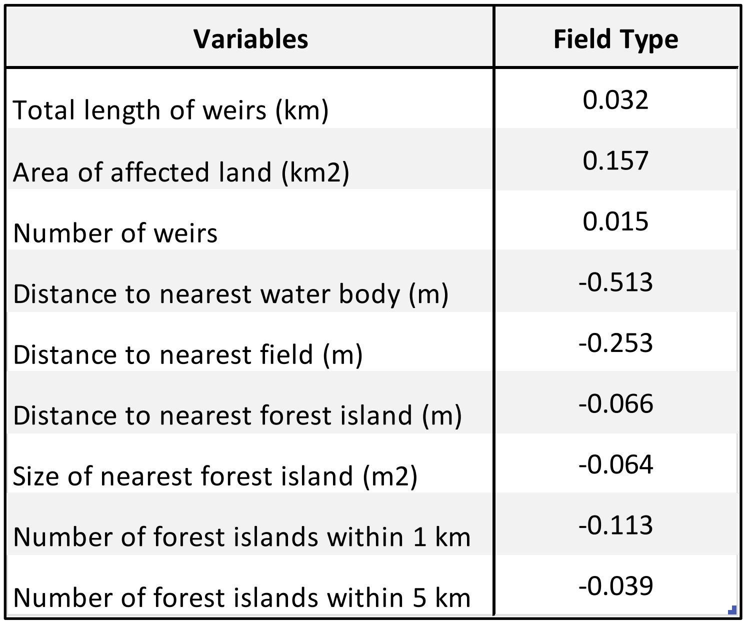
Table 8. Pooled Pointbiserial Correlation Coefficients: Pointbiserial correlation coefficients (*r*) for the two binary categorical variables at the level of the pooled dataset, fish weir spatial patterns and type of nearest field. This identifies any relationships present with continuous and discrete variables. Note that the coefficients for spatial pattern are also the effect sizes for the two-tailed hypothesis tests.



Variables	Spatial Pattern	Field Type
Total length of weirs (km)	0.491	0.053
Area of affected land (km2)	0.461	0.124
Number of weirs	0.463	-0.003
Distance to nearest water body (m)	0.080	-0.309
Distance to nearest field (m)	-0.032	-0.072
Distance to nearest forest island (m)	-0.191	-0.051
Size of nearest forest island (m2)	-0.115	-0.049
Number of forest islands within 1 km	0.311	-0.106
Number of forest islands within 5 km	0.226	-0.083

* r = 0.6

Table 9. Grouped Pointbiserial Correlation Coefficients for Stacks: Pointbiserial correlation coefficients (*r*) for the remaining binary categorical variable within the stacks group of potential wetlands.



Variables	Field Type
Total length of weirs (km)	0.032
Area of affected land (km2)	0.157
Number of weirs	0.015
Distance to nearest water body (m)	-0.513
Distance to nearest field (m)	-0.253
Distance to nearest forest island (m)	-0.066
Size of nearest forest island (m2)	-0.064
Number of forest islands within 1 km	-0.113
Number of forest islands within 5 km	-0.039

* r = 0.6

Table 10. Grouped Pointbiserial Correlation Coefficients for Networks: Pointbiserial correlation coefficients (*r*) for the remaining binary categorical variable within the networks group of potential wetlands.

Variables	Field Type
Total length of weirs (km)	0.136
Area of affected land (km2)	0.161
Number of weirs	0.049
Distance to nearest water body (m)	-0.087
Distance to nearest field (m)	0.047
Distance to nearest forest island (m)	-0.064
Size of nearest forest island (m2)	-0.063
Number of forest islands within 1 km	-0.089
Number of forest islands within 5 km	-0.121

* r = 0.6

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