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Second cycle degree (MSc) in Sustainable Agriculture

Saltwater intrusion in the Po River Delta: Farmers’ perspectives and hotspot mapping using remote sensing

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Abstract

Saltwater intrusion poses a significant threat to coastal agriculture. Plant and soil health are both impacted by the presence of saline water and the damage varies from yield losses to desertification. Sea-level rise and more frequent and severe droughts associated with climate change are only exacerbating the problem. The Po River Delta is an important agricultural territory in the northeastern region of Italy. Water availability and quality are very important for the agricultural sector given that 70% of the territory's agricultural lands are irrigated. Therefore, when irrigation canals are contaminated with saltwater, the consequences can be very drastic. While this problem is well-noted and widely felt by the farmers of the region, quantitative means of measuring and predicting this phenomenon remain limited, preventing timely decisions regarding planting, irrigation, and harvesting. This thesis aims to contribute to the body of knowledge on the threat of saltwater intrusion to agriculture in the Po River Delta via a transdisciplinary approach. Personal accounts of farmers (and stakeholders) in the Po River Delta and a temporal and spatial analysis based on remote sensing data (satellite imagery from Landsat 5 and 8; and Sentinel-2) and two spectral indices (the Normalized Difference Vegetation Index (NDVI) and Salinity Index (SI4)) were considered together in this approach. The analysis examines data from 2000 to 2024. Two techniques were employed to carry out this analysis exclusively on active cropland. The first was to train a script in the cloud-based geospatial analysis platform, Google Earth Engine, with a classification function. The second was to use a novel, high resolution, near-real time land use/land cover dataset. In doing so, the dynamic nature of salinity processes, heterogeneity in landscapes, and how plant phenology influences salinity indices and is itself influenced by salinization, were taken into account. The results are hotspot maps that indicate where saltwater intrusion is consistently a severe problem and which best reflect the dynamic relationship between saltwater intrusion and active crop growth. These maps can help water authorities and farmers mitigate the phenomenon through structural and non-structural solutions and assist policymakers in developing sustainable and effective guidelines to protect coastal agriculture.

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1. Introduction

1.1. Coastal agriculture

Coastal agriculture is a unique and important category of agriculture which up until recently has largely not been the target of specific studies (Viaud et al., 2023). No universally accepted definition exists for coastal agriculture, but the term generally refers to agricultural activities carried out within coastal areas or whose proximity to coastal ecosystems has a notable influence on these activities. The United Nations (UN) in their Millennium Ecosystem Assessment used both a distance and elevation threshold to determine "coastal areas": 100 km from the coast and 50 m in elevation. The distance threshold is important for denoting an area susceptible to coastal pressures, whereas the elevation threshold is important for identifying hazard vulnerability (ESA, 2007). Eurostat defines coastal areas to be land area units (LAUs) "that border the coastline or LAUs that have at least 50 % of their surface area within a distance of 10 km from the coastline" while coastal regions are identified by "having a border with a coastline, having more than half their population within 50 km of the coastline, or having a strong maritime influence" (Eurostat, 2018). Many authors have used 10 m as the elevation threshold for their works (Merkens et al., 2016; Martinez et al., 2007; Gopalakrishnan et al., 2019). Regardless of the variation in these definitions, they are all derived from an understanding that distance to the coastline, elevation, and the presence of unique landforms such as river deltas are all factors which can have a strong impact (in both negative and positive terms) on the communities, natural habitats and economies in these areas. Agriculture is influenced by the coastal area's impacts on the climate, land, water resources, and socioeconomics. Coastal climates are often favourable for agriculture, being milder and more humid, and alluvial accumulation plains along coasts offer advantageous growing conditions (FAO, 1998). But the proximity to the sea can also present unique challenges such as flooding, soil salinization, storms, and rising sea levels (FAO, 1998). Located near dense urban areas and with easy access to ports, they have a strategic position for both domestic and international markets. A 2016 study estimated that in 2010 2.7 billion people, 38% of the world's population, were living in coastal areas, defined as being 100 km from the coast with an elevation up to 100 m (Kummu et al., 2016). In this delineated coastal area, 13% of global agriculture can be found and 5% of global pasture (Kummu et al., 2016).

The maintenance and protection of these areas is important for the numerous ecosystem services that they provide. Ecosystem services are the direct and indirect benefits to humans from an ecosystem. These can be classified into four categories: provisioning services, regulating services, cultural services, and supporting services (MEA, 2005). Provisioning services are the material, energy, and nutrient outputs from an ecosystem such as water and agricultural products. In coastal areas examples include outputs from the primary sector such as fish and crops, timber from coastal forests, and pharmaceutical compounds derived from vegetation and marine life. Regulating services moderate natural phenomena and include pest control, carbon storage, and flood control. In coastal areas mangroves and deltas are both good examples of natural features which provide several regulating services. Cultural services include providing spaces for spiritual connection and recreational activities. Coastal areas often have a unique cultural heritage which is reflected in traditions, ceremonies, and lifestyles, and which reaches wider populations via art and tourism. There are a number of coastal areas which have been recognized for their cultural services. Everglades National Park in the United States, adjacent to which is the Everglades Agricultural Area, is an important habitat for a number of species and is home to the largest mangrove ecosystem in the Western Hemisphere (UNESCO, n.d.). The Po River Delta, an important region in Italy for both agriculture and its wetland habitats, is recognized as a Biosphere Reserve, by the intergovernmental MAB Programme of UNESCO meaning that it is an important ecosystem for conservation and sustainable development (Parco Delta del Po; n.d.). The cocoa agroforestry system of the African island nation Sao Tome and Principe, is recognized by FAO as a Globally Important Agricultural Heritage System (GIAHS) for its sustainable production methods and cultivation of the prized Amelonado Seleção de São Tomé (SST) cocoa (FAO, n.d.).

Supporting services are the fundamental, natural processes which support ecosystems and therefore also humans. These include nutrient cycling, photosynthesis, and the water cycle (NWF, n.d.). Various environments found in coastal ecosystems such as deltas, lagoons, and saltmarshes provide numerous supporting ecosystem services like sediment supply, nutrient cycling, soil fertility, and habitat provision.

Coastal ecosystems in particular provide a high level of ecosystem services for their size. In fact, when compared to other systems which cover larger areas, coastal ecosystems frequently provide a greater amount of ecosystem services (MEA, 2005). But it is important to note that agricultural activities often have diametric effects on ecosystems and their services. Traditional practices both make use of and maintain cultural ecosystem services. Agricultural activities can support regulating and supporting ecosystem services but can also threaten ecosystem services via soil degradation and habitat destruction. An example of the latter occurs in coastal areas when mangroves are cleared for agriculture (MEA, 2005). It is important to recognize the various threats facing coastal agriculture and the ecosystems in which they are embedded. One of these major threats is saltwater intrusion. This is seen in the loss of livelihoods, decreased water quality and availability, and land use change (Islam et al., 2023). River deltas are a key interface between land and oceans (ESA, 2007) and in 2020 there were 600 million people living or working in deltas (Hutton et al., 2020). Figure 1 shows a global map of deltas put forth by Dunn et al. (2017).

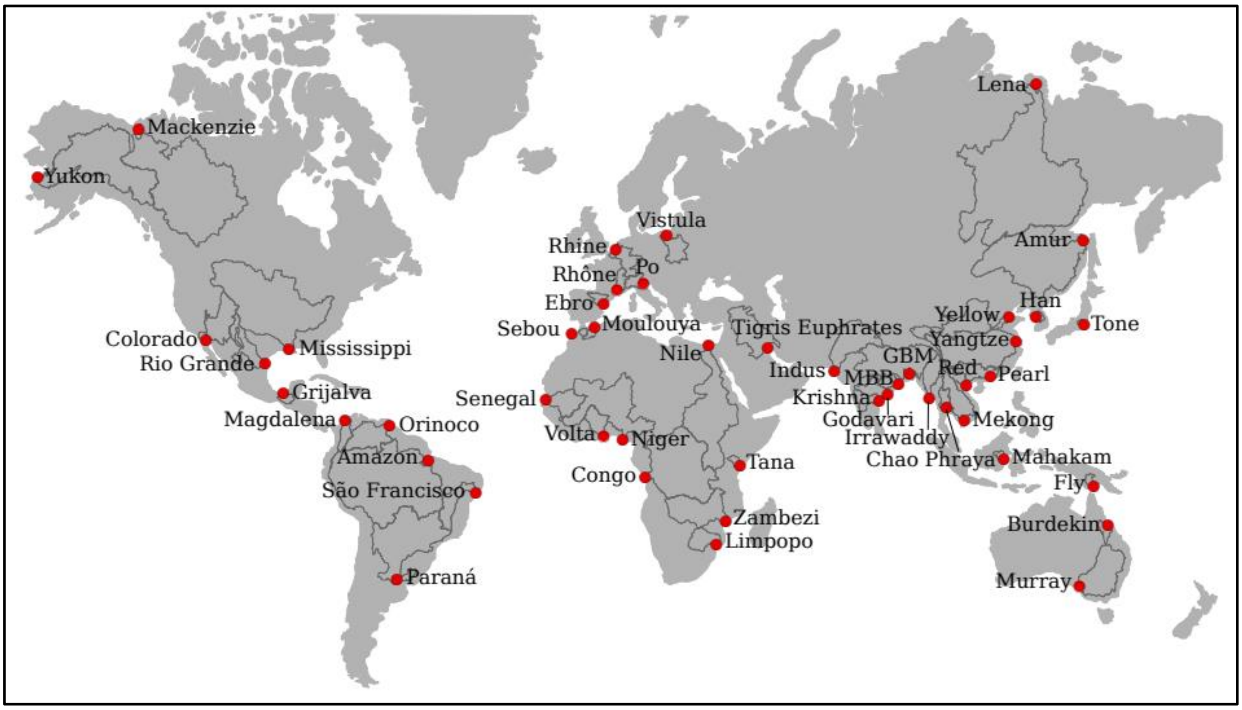


Figure 1 - Global map of deltas (Dunn et al., 2017)

Deltas typically host a high level of biodiversity, and as discussed above, provide important ecosystem services. Deltas, like most coastal ecosystems, are unique for their higher-than-average productivity of these services. Using just 0.5% of global land, deltas contribute 4% to the world's food production (Mekonnen et al., 2011). The Po River Delta in Italy is part of the Po Valley which is often referred to as Italy's breadbasket and is responsible for more than 30% of the country's agricultural production (Angelini et al., 2009). Not only is the level of production relevant, but also the type of crops cultivated in these areas. River deltas in Asia provide most of the world's rice, a staple in the diets of half the world population and are therefore very important for global food security (Schneider & Asch, 2020). But these valuable lands are under threat due to anthropogenic activities. These include, but are not limited to, climate change, sand mining, logging, and reservoir and dam construction (Opperman et al., 2018; He et al., 2019).

The intersection of coastal agriculture, saltwater intrusion, and delta ecosystems presents a complex set of problems that require thoughtful solutions which take into consideration a vast network of stakeholders. These much-needed solutions align with several of the UN's Sustainable Development Goals: No poverty, Zero hunger, Clean water and sanitation, Responsible consumption and production, Climate action, Life below water, and Life on land (United Nations, 2023).

1.2. Saltwater intrusion and agriculture

Saltwater intrusion is defined by the World Meteorological Organization (WMO) as the "process by which saltwater invades freshwater in surface water or groundwater bodies" (2013). This can be the result of both natural processes and anthropogenic activities. Natural processes occurring over long timescales which can trigger saltwater intrusion include sea level rise, geologic uplift, and subsidence; while in shorter timescales extreme events such as tsunamis, hurricanes, droughts, and climate oscillations act as the primary causative agents (White et al., 2017). The contamination of freshwater resources by saline water can have devastating consequences for communities and agriculture when drinking water supplies and irrigation waters are impacted. High levels of salinity negatively impact crop yields, soil structure, and can decimate the microbial community in soils resulting in a phenomenon known as micro-desertification.

Figure 2 - Micro-desertification in a field in the Po River Delta (Author: Aurora Ghirardelli)

Saltwater intrusion threatens important deltas worldwide, such as the Mekong Delta in Vietnam (Eslami et al., 2021), the Pearl River Delta in China (Zhang et al., 2013), the Ganges-Brahmaputra - Meghna Delta in India and Bangladesh (Bricheno et al., 2021), and the Yangtze River Delta in China (Xu et al., 2018). Götte et al. provide an estimate of saltwater intrusion on a global scale (Figure 3) using the predictive model put forth by Savenije (1993) (2020).

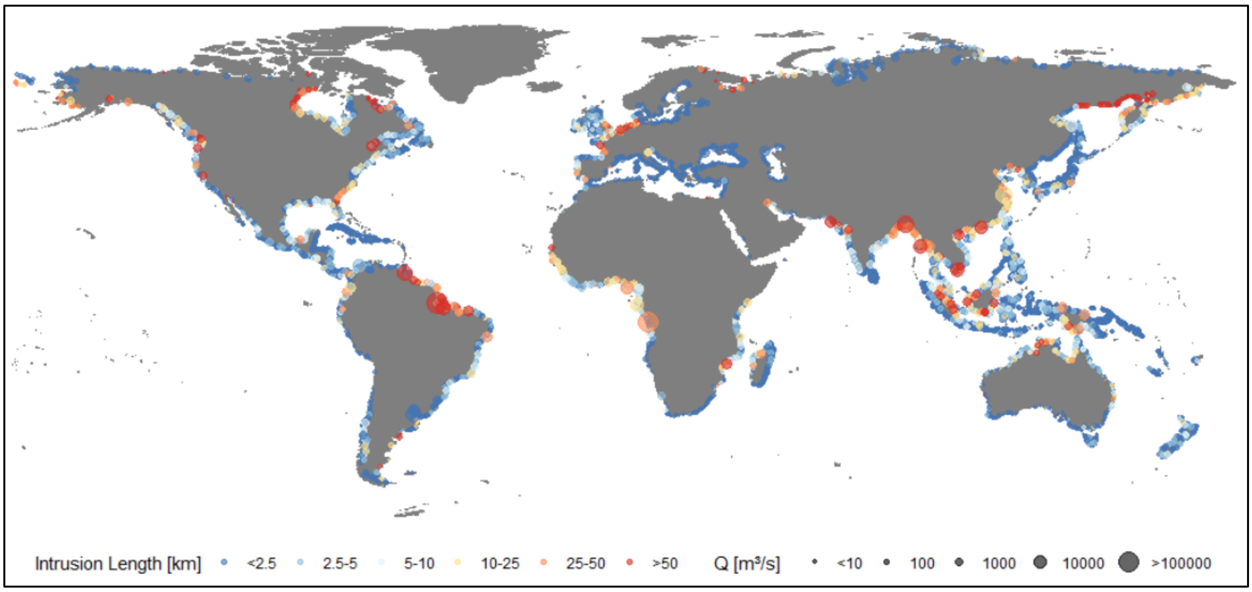


Figure 3 - Modelled saltwater intrusion length around the globe (Götte, 2020)

As can be seen, while the degree to which saltwater intrusion is occurring in different deltas varies greatly, it is undoubtedly a global problem, impacting deltas on every continent. In the Italian context, the Po River Delta is the most prominent example of coastal area affected by saltwater intrusion. The main causes are reduced river discharge, extended periods of low or no precipitation, and high evapotranspiration rates in the summer. The average discharge of the river is around 1500 m^3/s, but a reduction in this discharge—a problem which is particularly prominent during periods of drought—alters the reach of the mixing zone between freshwater and saltwater. The land reclamation authority for the territory, Consorzio di Bonifica Delta del Po, has determined 450 m^3/s as a critical threshold under which the ecological functioning of the river is threatened. When the discharge of the river is significantly reduced seawater from the Adriatic flows into the river and arrives inland. The result is essentially a shifting coastline as saltwater penetrates the river branches. The extent of this phenomenon has been recorded to reach as far as 40 km inland (Tarolli et al., 2023).

In recent years various authors have conducted studies to describe saltwater intrusion in the Po River Delta—Bellafiore et al (2021), Luo et al (2024), Matsoukis et al (2022), and Tarolli et al (2023)—but the dynamic and highly variable nature of the process makes it difficult to translate these findings into actionable solutions for stakeholders. This paper aims to contribute to the growing body of knowledge on the subject with the generation of saltwater intrusion hotspot maps based on active cropland data together with personal accounts from farmers (and other stakeholders) in the territory.

The relevance of saltwater intrusion for the agricultural sector is soil salinization and reduced water quality and availability. Salt affected soils can be defined as those with one of the following criteria met: electrical conductivity (Ece) greater than 2 dS/m, exchangeable sodium percentage (ESP) greater than 15%, or pH greater than 8.2 (FAO, 2021). According to FAO's 2021 Global map of salt-affected soils, 424 million hectares of topsoil (0-30 cm) and 833 million hectares of subsoil (30-100 cm) worldwide are salt-affected. According to a 1995 estimate, 20% of irrigated arable lands were impacted by soil salinization (Ghassemi et al., 1995). Given that this is a growing threat, the percentage today could very well be much larger. A more recent evaluation of the economic losses on irrigated, salt-impacted lands estimates an annual, global loss of approximately US$ 27.3 billion due to the impact on crop yields (Qadir et al., 2014). Soil in the Po River Delta is typically classified as slightly saline, with electrical conductivity values between 0.4 and 1 ms/cm in the first 50 cm of the soil profile and 1-2 mS/cm at 50-100 cm depths (ARPAV, 2020; Lazzaretto, 2023). But localized areas can become saline following the seasonal patterns of salinization and in particular in times of drought. This was observed by Oğuzhan (2024) who measured EC values of 8.77 dS/m and 9.98 dS/m at depths of 95 cm and 85 cm, respectively, in the municipality Porto Tolle in 2024. But in the context of climate change, the seasonal patterns of salinization are likely to shift and further intensify the impacts on agriculture.

1.3. Saltwater intrusion and climate change

The challenges resulting from the overlapping threats of saltwater intrusion and climate change mark the meeting point of anthropogenic forces and natural processes. Human activities and manipulation of the environment have resulted in an increased threat from both saltwater intrusion and climate change. In the IPCC's Sixth Assessment report, it is projected with high confidence that variability and extremes in the hydrological cycle will increase and that this will put an increasing proportion of the global population at risk (Caretta et al., 2022). River deltas face a series of risks associated with climate change such as more frequent and severe storm surges, sea level rise, and increasing frequency and intensity of droughts (Rahman et al., 2019). River discharge, sea level, tides, and wind all govern the processes behind saltwater intrusion and once saline waters reach agricultural fields a dynamic set of interactions occurs within the soil and crops. This is what makes it so challenging to accurately describe saltwater intrusion and its impact on agriculture and to determine the most effective solutions. Additionally, just as climate change is impacting the hydrological aspects of saltwater intrusion, it also impacts vegetation growth and microbial activity in the soil. The intersection of these two problems related to the shift in climate in the Po River Delta will be discussed in greater detail in the Study Area chapter of this paper.

1.4. Two approaches to describe the problem: personal accounts and hotspot mapping

This paper takes a dual approach to describing the threat of saltwater intrusion in the Po River Delta. Farmer and stakeholder personal accounts were collected for the European Horizon project PHITO: *Platform for Helping small and medium farmers to Incorporate digital Technology for equal Opportunity*. The project takes a transdisciplinary research approach and its inclusion in this paper helps to align the overall analysis to the core fundamentals of transdisciplinary research. The fundamentals are as follows, research that: 1) focuses on a societally relevant problem(s); 2) enables mutual learning processes among researchers from different disciplines, as well as actors from outside academia; and 3) aims at creating knowledge that is solution-oriented, socially robust, and transferable to both the scientific and social practice (Lang et al., 2012). These concepts originate in the field of sustainability science which aims to better connect problems and solutions and is one of the main scopes of this paper. The findings from the PHITO project are paired with a temporal and spatial analysis based on multi-temporal satellite data. Spectral indices were calculated and used to generate hotspot maps to illustrate how saltwater intrusion may impact the growth of vegetation and salinization processes in the upper part of the soil during the primary growing season.
This paper focuses on saltwater intrusion in the Po River Delta located in Northern Italy in the coastal region of the Adriatic Sea. Not only are agricultural lands under threat in this region, but also the health of the delta—a very valuable ecosystem.

1.5. Objectives of the thesis

This paper aims to contribute to the information and tools available to address the threat of saltwater intrusion to agriculture in the Po River Delta. Using remote sensing data from Landsat 5, Landsat 8, and Sentinel-2 satellite missions, both a longitudinal and high resolution, near real-time analysis were carried out to identify patterns of temporal and spatial distribution of impacts of saltwater intrusion on agricultural lands under cultivation. These patterns were translated into hotspots which can be used to prioritize responses to the threat of saltwater intrusion. Farmer and stakeholder personal accounts were collected and analysed in order to contextualize these findings and provide a model approach for how these kinds of quantitative and qualitative data can be used together to implement effective, localized solutions. A methodological tool, with the structure of a decision support system, was proposed as a process that can support water authorities and policymakers and encourage collaborative decision making with farmers and other stakeholders in the primary sector.

2. Study area

The Po River Delta is located in the northeast region of Italy and covers approximately 400 square km. The Po River, responsible for this delta, is the longest river in Italy with a length of 652 km starting in the Western alps along the French-Italian border and ending at the Adriatic Sea. For the purposes of this paper the boundaries used to represent the delta (Figure 4) will be those of the land reclamation authority that operates the irrigation canals of the area. Given that this paper focuses on agriculture in the Po River Delta and 70% of agricultural lands in the area are irrigated, this area provides a good sampling of important and representative agricultural lands. The area of the Po River Delta under the land reclamation authority of the Consorzio di Bonifica Delta del Po is 66,297 hectares.

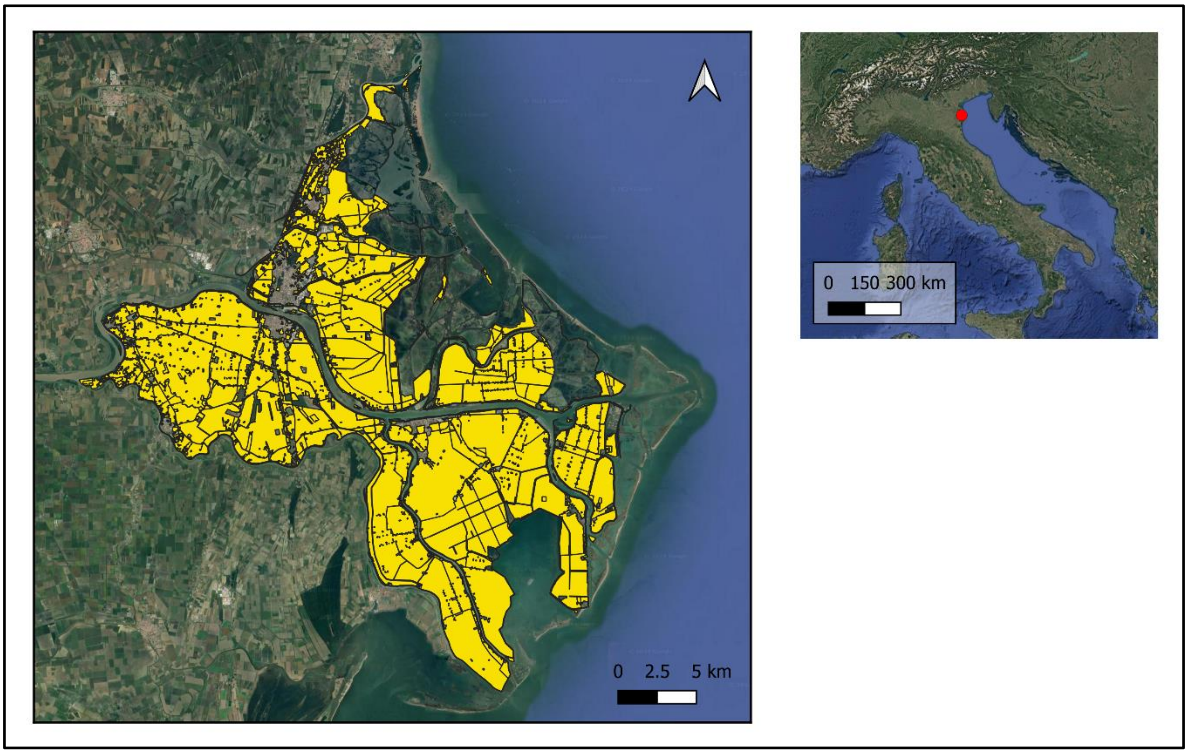


Figure 4 - Cropland region of the Po River Delta

2.1. Geographical history of the land

The geomorphology of the Po River Delta today is quite different from that of its formation in approximately 30,000 BC when its progradation into the Adriatic Sea began. Today, there are seven primary branches of the Po River: Po di Pila, Po di Maistra, Po di Tolle, Po di Gnocca, Po di Goro, Po di Volano and Po di Levante, but at that time there were two main branches that fed into the Adriatic: Po di Adria and Po di Spina. In the centuries that followed natural processes including divisions of major branches, deposition, and flooding significantly changed the fluvial geomorphology (Consorzio di Bonifica Delta del Po.a., n.d.). But in 1600 the first of many human interventions to control the flow of the river and its branches was initiated by the Doge Marino Grimani of the Republic of the Serenissima to construct the "Taglio di Porto Viro"–a diversion of the river, sending waters east as opposed to northeast. Political motives as well as a recognition of the threats of the dynamic delta to the current landscape, specifically the Venetian lagoon and its ports, prompted the decision to carry out these works. The works lasted 4 years and the result was a diversion which protected the city of Venice and the Venetian lagoon from the river's flow and deposits coming from the Central and Western Po valley. These works were fundamental in shaping the coastal area today that runs from Venice to Ferrara (Zaniboni, n.d.). The construction of the Taglio di Porto Viro was just the beginning in a long series of hydraulic interventions in the delta that continues today. In fact, today the land could not exist as it is without these interventions. In the second half of the nineteenth century steam-powered drainage pumps allowed for extensive reclamation of the land. This was superseded by and intensified with the development of drainage pumps powered by diesel and electricity and by the 1940s the vast majority of the delta's wetlands had been drained (Parrinello et al., 2021). Anthropogenic forces have determined the course of these lands for the past four centuries and halting these systems would mean relinquishing these lands. Today, some areas in the territory are as much as 3.50m below sea level and without the management of the land reclamation authority these lands could not be used and inhabited as they are today (Consorzio di Bonifica Delta del Po.b., n.d.). The work of the land reclamation authority is fundamental not only for ensuring adequate drainage of the area—so that these cities and lands remain habitable—but also for the irrigation of the agricultural lands in the territory.

It should also be noted that hydrological interventions have not been the only significant influence on the geomorphology of the territory. While in the early modern period the coastline extended into the Adriatic Sea, human exploitation of these lands led to subsidence and a halting of progradation. Construction of hydroelectric reservoirs, sand and gravel mining, and methane extraction had significant impacts on the delta. Methane extraction exacerbated natural processes of subsidence and contaminated and threatened irrigation waters. Between 1956 and 1961 the rate of subsidence was around 15cm/yr, as compared to 1.5cm/yr in the first half of the century before the period of methane extractions (Parrinello et al., 2021). The result was a series of floods which brought attention to the issue and in 1963 a permanent extraction ban was put into place for the entirety of the Po River Delta (Parrinello et al., 2021).

The irrigation network of the land reclamation authority, Consorzio di Bonifica Delta del Po, consists of both intensive and extensive irrigation infrastructure. In total, the authority administers water across 239.87 km of irrigation canals within 29 irrigation systems in 5 territorial units (Table 1 and Figure 5): Sant'Anna, Rosolina, Porto Viro, Ariano Island, and Porto Tolle (Consorzio di Bonifica Delta del Po.c., n.d.).

Table 1 – Extent of irrigation canal network (km) by territorial unit of the Consorzio di Bonifica Delta del Po

Territorial Unit	Extent of irrigation canals (km)
S. Anna	25.90
Rosolina	18.03
Porto Viro	20.53
Ariano Island	96.21
Porto Tolle	79.20

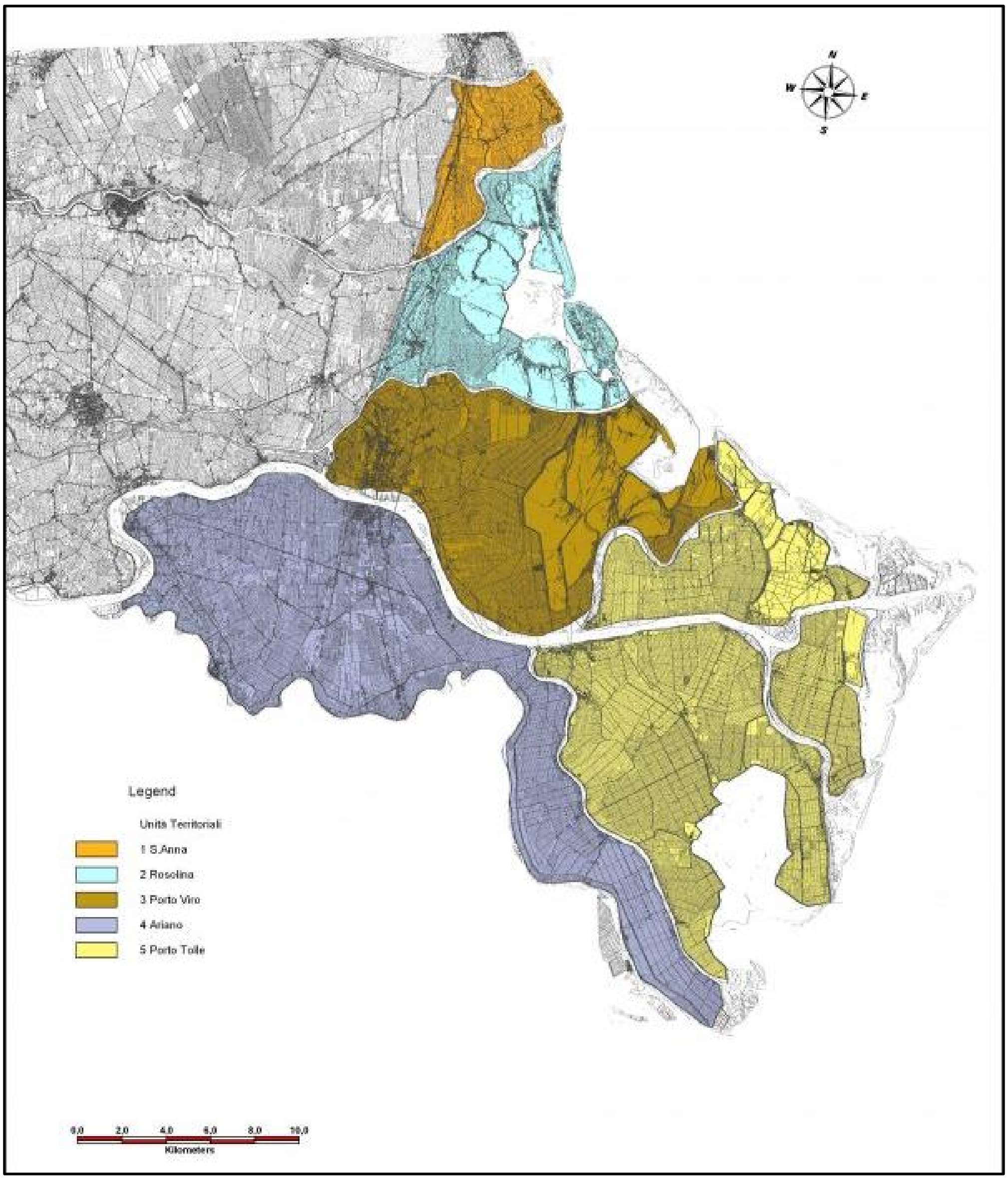


Figure 5 - Map of the territorial units of the land reclamation authority

The soils in the territorial units of Sant'Anna, Rosolina, and Ariano Island are predominantly sandy and therefore intensive irrigation is practiced in these areas via a pressurized pipe network. In the territorial units of Porto Viro and Porto Tolle the soils are medium-textured or clayey and therefore extensive irrigation is practiced in these areas via concrete and earthen channels (Consorzio di Bonifica Delta del Po.c., n.d.). To support management decisions the land reclamation authority sets a flow rate threshold for the Po River. When the flow rate falls below this threshold, it signals a critical situation—the ecological functioning of the river is at risk and the threat of saltwater intrusion is elevated. Prior to 2010 this value was set at 330 m3/s (Consorzio di Bonifica Delta del Po, 2021), but this did not adequately take into consideration the ecological health of the river. Instead, it was based on irrigation demands and the risk of salt-wedge intrusion. Therefore, to better safeguard this resource, the value was modified to 450 m3/s (Consorzio di Bonfica Delta del Po, 2021). The monitoring of the territory's water resources and maintenance of critical infrastructure by the land reclamation authority is fundamental to the local communities, but without question, of particular importance for the agricultural sector.

2.2. Importance of agriculture to the territory

The Po River Delta represents an important section of the larger Po Valley (the Pianura Padana), one of the most important agricultural regions in Italy with 41% of the land used for agriculture (JRC, n.d.). The main crops grown in the Po River Delta are wheat, rice, soybean, maize and sugar beet. There are also a number of agricultural products from the territory recognized by the EU's Protected Geographical Indication (PGI) certification system. These include green asparagus of Altedo, peaches and nectarines from Romagna, pears from Emilia Romagna, and Po Delta rice (Gal Delta duemila, n.d.). Additionally, the Long Radicchio from Treviso and Red Radicchio from Chioggia, "Violina" pumpkin, melon from Emilia Romagna, watermelon from Ferrara, carrots from the Ferrara delta, and the Bianchetto and Marzuolo truffles are noteworthy agricultural products of the region and surrounding areas (Gal Delta duemila, n.d.).

The province of Rovigo, which runs along the Po River, includes almost the entirety of the area under the land reclamation's authority. For this reason, its statistics, while encompassing an area not synonymous with the study area and of larger size, are nonetheless telling of the agricultural sector within the larger territory of the Po Valley. In 2018, there were 5,020 agricultural and forestry businesses in the province of Rovigo which employed 5,514 people, excluding seasonal workers (Veneto Agricoltura, 2020). 121,437 ha of land is cultivated in the province representing 15.6% of all agricultural lands in the Veneto region (Veneto Agricoltura, 2020). The primary sector predominates both the landscape and the economy in the territory and therefore support for agriculture is important from an environmental and socioeconomic point of view. Threats such as saltwater intrusion put entire communities at risk and therefore merit attention and resources.

2.3 Climate change, saltwater intrusion, and agriculture in the Po River Delta

Using the Köppen climate classification system, the current climate of the Po River Delta is humid, subtropical with no dry season and hot summers (Cfa), but under the RCP scenario 8.5, it is predicted to shift to a climate which is both warmer and drier: hot semi-arid (BSh) (Beck et al., 2023; OSU, n.d.). This shift to a climate characterized by a low level of precipitation will simultaneously increase the probability of reduced river discharge and increase the demand for irrigation of crops. Climate shifts in the Italian Alps will also contribute to this problem as decreased snowfall results in decreased snowmelt and again reduced river discharge, especially when water withdrawals are high (Figure 6). Shifting snow regimes and increased evaporation rates that come with this climate shift also impact snowmelt in the Alps and ultimately river flow rates (Montanari et al., 2023).

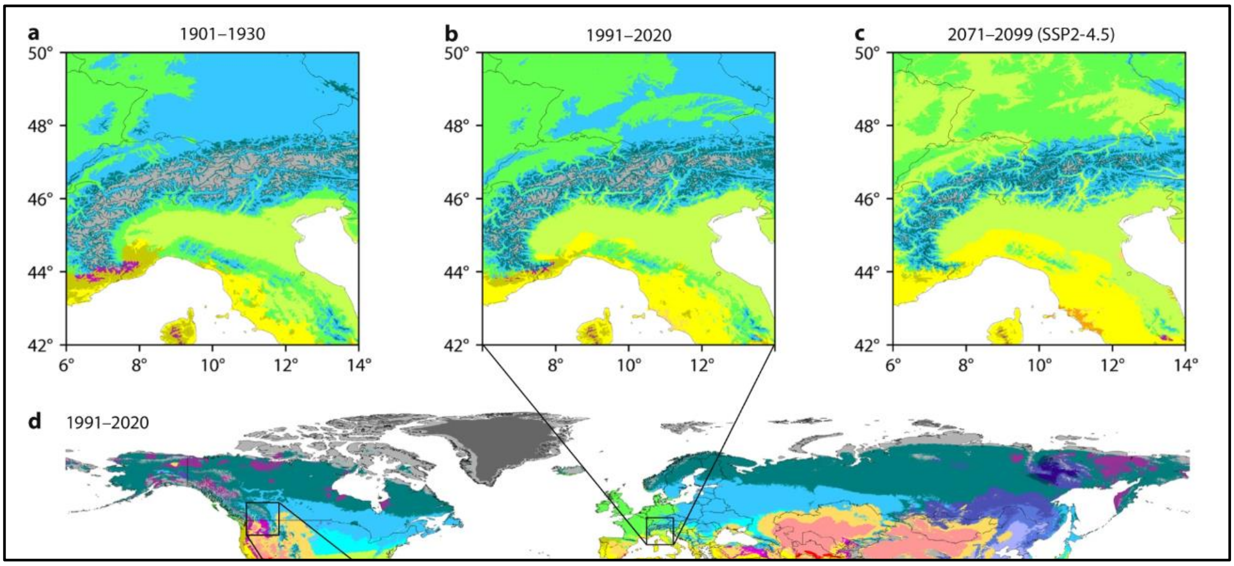


Figure 6 - Climate shifts in Northern Italy (Beck et al., 2023)

A study by Bellafiore et al. in 2021 predicts that due to climate change, using the RCP8.5 climate scenario as reference, saltwater intrusion will increase its reach in the main branch of the Po River from 13.8 to 24.8 km. Additionally, they predict that the persistence of this phenomenon will increase by 100% (Bellafiore et al., 2021). Colombani et al. investigated the impact of relative sea level rise associated with climate change on the salinization of freshwater sources in the Po River Delta and found that by 2050 both the aquifer and surface waters will be increasingly susceptible to salinization (2016). They predict that there will be a 30% increase in salinization of the drainage canal system and fresh groundwater availability will decrease by 46% (Colombani et al., 2016). The relationship between the canal system, irrigation withdrawals, and the recharge of unconfined aquifers in Ferrara, a city along the Po and almost 100km from the Adriatic Sea has also been described by Colombani et al. (n.d.). The findings demonstrate an important linkage between these processes, unsurprising given the anthropogenic shaping of these lands, and that irrigation is critical to the recharge of the unconfined aquifer of Comacchio (Colombani, n.d.). This is an important consideration for the implementation of adaptative solutions. For instance, more salt resistant varieties could permit farmers to irrigate with brackish waters and thus protect crop yields and support farmer incomes, but if the recharge to the aquifer is not with freshwater, this can create issues for the fresh groundwater supplies in the territory. Or if more drought resistant varieties are used and/or reduced irrigation is practiced, even in the case of favourable agricultural outcomes, again the unintended consequence may be that the aquifer suffers from diminished recharge. This underscores the need for an ecosystem lens when evaluating potential solutions for coastal agriculture. Grilli et al., using a long-term data series from 1971 to 2015, found that repeated periods of drought caused the annual mean flow rate of the Po River to decrease and that from 2006 to 2015 the number of days with extremely high flow rates decreased (2020).

It is important to clarify however that in the Po River Delta, agricultural drought is more common than meteorological or hydrological droughts. This is due largely to water withdrawals upstream. So, while meteorological drought and the impacts of climate change are felt in the region, the position of the delta as the terminal end of the river means that it often faces an additional threat of water shortages due to competition for freshwater and its disadvantaged location along the river.

Figure 7 - Impacts of saltwater intrusion in the Po River Delta (Authors: Aurora Ghirardelli & Vincenzo Baldan)

Given the severity and scale of this problem, a variety of solutions have been proposed, including both nature-based and structural solutions. These will be presented in the *Discussion of results* section of this paper.

3. Materials and Methods

3.1. Farmers' perspectives

3.1.1. PHITO Project overview

PHITO: *Platform for Helping small and medium farmers to Incorporate digital Technology for equal Opportunity*, is a European Horizon-funded project which lasts 5 years and has a budget of 5 million euros. It began in 2023 and will conclude in 2028. It aims to bridge the digital divide between large farms and small and medium farms (SMFs). It involves 18 partners representing 10 different countries: the Netherlands, Italy, Romania, Albania, Portugal, Aruba, Bonaire, Spain, Austria, and

Hungary. These partners were selected for their collective experience in innovation, digital technologies, agricultural research, and communication.

Recognizing that small and medium farmers consistently have lower rates of adoption of digital technologies (Cimino et al., 2024), the objective of the project is to develop a digital platform which is low-barrier and co-created with this subset of farmers to best meet their unique needs. It has been well documented that SMFs face a multitude of barriers to adopting digital technologies such as undeveloped markets, lack of access to capital, and limited knowledge or education (FAO & IPA, 2023). While there are many digital platforms to support farmers already in existence, the price and design often make these platforms unsuitable for SMFs. For this reason, PHITO is based on two key pillars: stakeholder involvement in the development of the platform and utilization of open source global geodata to provide high quality, data-driven advice at low to no cost to users.

Therefore, the main outputs from the project should be an app with a user-friendly interface, a means of connecting SMFs to promote local Agriculture Knowledge Innovation Systems (AKIS), and that provides advice (derived from open source geodata,) to support agricultural planning and decision making. The entire process and development of the platform takes into consideration the unique challenges and needs of SMFs. This co-creation occurs with 8 food system partners (Table 2) which represent a diverse range of farming systems and needs of SMFs (small in economic terms).

Table 2 – European Horizon project PHITO (Platform for Helping small and medium farmers to Incorporate digital Technology for equal Opportunity) Food System partners

Albania – Albanian Greenhouse System
Aruba & Bonaire
Hungary – Great Hungarian Plain
Italy – Alpine Foothills
Italy – Po River Delta
Portugal – Tras-os-Montes e Alto Douro
Romania – Moldavian Plateau
Spain – Comunitat Valenciana

In the five-year duration of the project, the development and creation of the platform occurs in three phases: the Roots, the Branches, and the Leaves. The first phase, Roots, lasts 18 months with the purpose of conducting a standardized needs-assessment in all 8 food systems to gain a foundational understanding of the needs of SMFs and to rollout beta testing in these food systems to get immediate and direct feedback from potential users. In the Branches phase, utilizing the feedback obtained in the first phase, the first beta version of the app will be updated and modified resulting in the release of a second beta version. Additionally, in this phase the long-term business model of the digital platform will be elaborated and tested in the second beta release. In the final phase, the Leaves, there will be a third beta release, built upon the feedback and testing of the two previous phases. There will be particular attention given to an aspect of the platform known formally as “Transition Pathways” which supports farmers in transitioning their farm systems towards greater sustainability. The phase will conclude with an alpha (live) release of the app to the general public. Dissemination and exploitation of the projects’ networks will be an important task in this phase. The estimated number of active users at the end of this phase is 10,000.

The first round of user needs assessment was carried out in 2024 as part of the Roots phase of the project. This paper will consider the assessment of the Po River Delta food system. There were two main objectives related to the Work Package 2: User needs & impact assessment. The first (WPO2.1), is entitled “Inventorying the needs and capacities of SMFs to inform the design of the PHITO app” and consisted of Tasks 2.1-2.3. The second objective (WPO2.2), entitled “Measuring the impact of PHITO in improving economic and environmental performance of SMFs, including the impact for marginalised stakeholder groups” consisted of Task 2.4. There were 4 tasks in total for this Work Package (Table 3).

Table 3 – WP3 tasks of European Horizon project PHITO (Platform for Helping small and medium farmers to Incorporate digital Technology for equal Opportunity)

Task 2.1. Developing a user centred design approach
Task 2.2. Inventory of food system specific information needs
Task 2.3. From food system needs to user needs
Task 2.4. Developing and tracking food system specific economic and environmental performance indicators to measure the impact of PHITO for SMFs

A stratified sampling method was used within food systems to survey small and medium-sized farms (in economic terms) and other relevant stakeholders such as service providers, cooperatives, and local water authorities. This approach relied upon the local expertise of the partners in each food system to determine the most appropriate individuals for the surveying. In doing so the main actors were identified for each food system representing the potential end-users of the app in the area.

Two methods were used to collect potential user information: a standardized, anonymous questionnaire and in-person focus groups conducted by project members. A Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis provided the framework for the focus group discussions. The questionnaire was available in seven languages (English, Hungarian, Spanish, Italian, Albanian, Portuguese, and Romanian) and consisted of 156 questions (Annex 1).

3.1.2. User needs assessment

Understanding the unique characteristics of a food system is necessary to fully understand the challenges that it faces. Droughts are a threat worldwide but understanding the specific consequences of this climatic threat in a specific area require that it is contextualized. Information such as which crops are grown, demographics, farming systems, agricultural practices, use of technologies and services, and local perspectives provide a more systemic understanding of the issue and support sustainable solutions. In the field of sustainability science, the value of participatory approaches has been widely discussed and demonstrated. The inclusion of stakeholders' perspectives in this paper aims to make use of transdisciplinarity per the definition of Lang et al.: "a reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge" (2012). Lang et al. proposes three phases for a transdisciplinary research process. The first being Phase A: Collaborative problem framing and building a collaborative research team, then Phase B: Co-creation of solution-oriented and transferable knowledge through collaborative research, and lastly Phase C: (Re-)integrating and applying the co-created knowledge (Figure 8). It should be noted that this is intended to be a reflective and cyclical process in which there can be overlapping phases. The PHITO project design and methodology follows this approach.

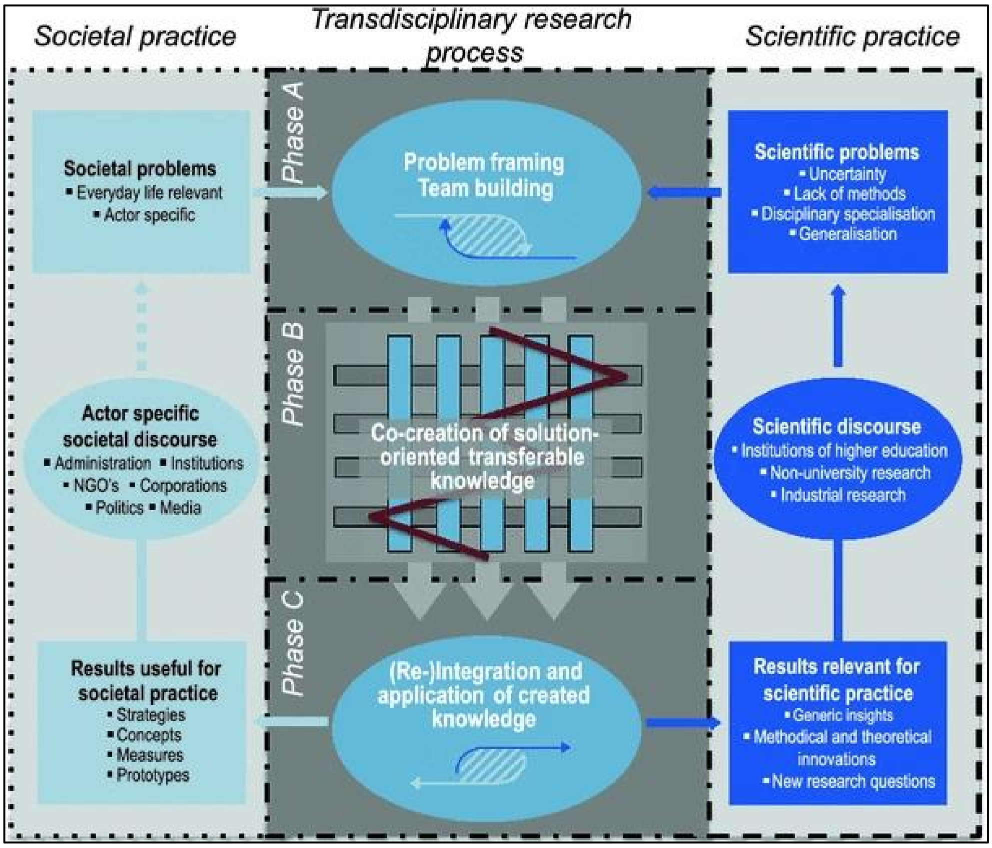


Figure 8 - Transdisciplinary research process (Lang et al., 2012)

Lang et al. identifies a series of tasks for Phase A: 1) identify and describe a real-world issue; 2) set an agreed upon research object; 3) design a conceptual and methodological framework for knowledge integration; and 4) build a collaborative research team (2012). The digital divide between small and medium farms (SMFs) and large farms is the real-world problem of interest to PHITO. The food system partners, research partners, and innovation partners agreed upon this problem and that the primary aim of the project would be to better understand how overcoming this divide could support SMFs in facing agricultural challenges and increase their resiliency to climate change. The user needs assessment is the conceptual and methodological framework which supports knowledge integration as it is an iterative process. With each round, the body of knowledge surrounding the problem and potential solutions builds. There is a continuous exchange of feedback between all project partners and repeated engagement with food system stakeholders. This is reflective of the collaborative team behind PHITO. Project partners bring expertise in agricultural and environmental sciences, agri-business, project coordination, social sciences, communications, inclusivity, and digital solutions (Figure 9). The food system partners act as important anchors to the communities and stakeholders impacted by the research problem. They ensure that the research approach is participatory.

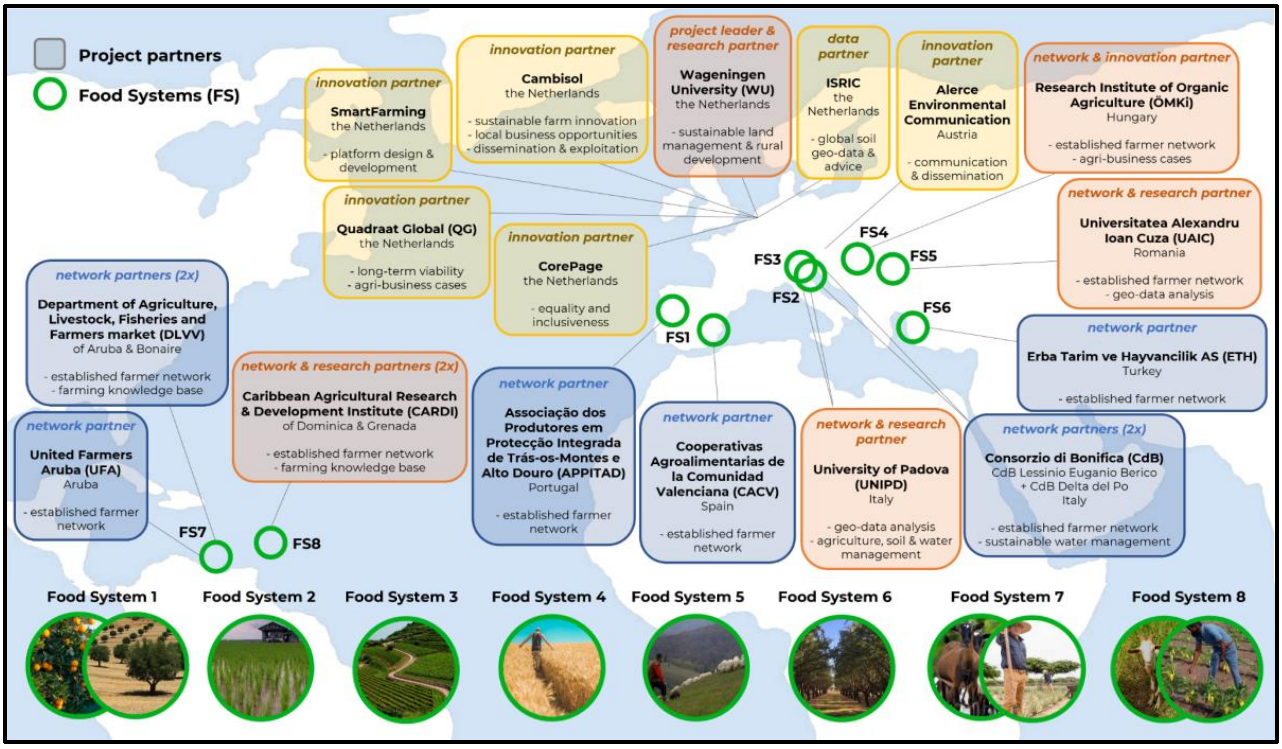


Figure 9 - Map of European Horizon project PHITO (Platform for Helping small and medium farmers to Incorporate digital Technology for equal Opportunity) partners

**Note that this map reflects the research team at the time of the proposal. CARDI and ETH are no longer partners and two Albanian food system partners have since been added.*

Phase B of Lang et al.'s transdisciplinary research process is the phase in which methodology is applied and data is collected. There are four core areas of work in which recurrent feedback is gathered and the processes are continuously refined. The user needs assessment with food system stakeholders occurs on a cyclical basis and represents one core area and methodology. Another area is the biweekly meetings held with all project partners in which there is a product demonstration. This promotes continuous collaboration and the integration of diverse feedback in every step of the app development process. A third core area is communications and dissemination. The lead partner works with all other partners to ensure that project activities, outputs, and relevant events in the food systems are communicated to a broader audience. This is done via the social media pages, the project website, and the PHITO van which serves as a mobile podcast studio and vehicle of outreach. Finally, Innovation Board Meetings are held on a monthly basis with the project leads to discuss the overall track of the project.

Phase C is the integration or reintegration of the research results into both societal practice and scientific practice. In PHITO, the beta releases of the app, followed by the alpha release, and then the commercial continuation represent the primary outputs incorporated into societal practice.

Results of the project are disseminated in the scientific space via student theses, such as this one, published papers, and conference papers.

In the Po River Delta the land reclamation authority, Consorzio di Bonifica Delta del Po, and the University of Padua are the two partners representing the food system. The first part of the user needs assessment was an in-depth meeting with the land reclamation authority to identify the key stakeholders in the territory. Four clusters were defined to represent the main actors in the agricultural sector in the Po River Delta. These are: Farmers; Government/Public Body; Administrative/Economic support; and Education, scientific, & technical support. Farms were initially broadly categorized based on soil type; in the northern part of the Po Delta farmers cultivate on sandy soils, while in the southern part they cultivate on clay soils. Where there is abundant water in the southern part of the delta, rice is cultivated. Subcontractor farmers are also noteworthy actors. The Government/Public Body cluster includes regional administration, the River Basin Authority, the municipality/mayors, and the Po Delta Land Reclamation Authority. The Administrative/economic support cluster includes agricultural consultants, agricultural cooperatives, and agricultural associations. The Education, scientific, & technical support cluster includes the Po Delta Land Reclamation Authority, the University of Padua, and the University of Venice. Then questionnaires were distributed and a focus group was organized by the land reclamation authority. 75 stakeholders completed the questionnaire and there were 27 participants at the focus group. The questions were aimed at gaining insights into the following key themes: demographics, farming system attributes, agricultural practices, labour and inputs, adoption of digital technologies, app use and preferences, perceptions about the utility of geodata and maps, and perceptions about climate change. Some of these themes are more relevant for the project's scope of building a digital platform and are not analysed or discussed in this paper. But much of the output from the questionnaire is relevant to better understanding the context in which saltwater intrusion is occurring in the Po River Delta. The questions considered by this paper are reported in Table 4.

Table 4 – Selected questions from the user needs questionnaire from the European Horizon project PHITO (Platform for Helping small and medium farmers to Incorporate digital Technology for equal Opportunity)

Farmer profile & opinions
• Please select the gender of the farmer
• Please write the year of birth
• The educational level of the farmer:

- No formal schooling
- Primary - 1-5th
- Middle school
- High school - 6th-10th
- Higher education - Above 10th class, diploma, graduated
- Other

• How satisfied are you with your farming activities overall?

Very Dissatisfied; Dissatisfied; Neutral; Satisfied; Very Satisfied

• Are you affiliated with any associations?

- Yes, at the local scale.
- Yes, at the territorial scale.
- Yes, at the regional scale.
- Yes, at the national scale.
- Yes, affiliated with associations offering incentives.
- None of the above.
- Other.

Land assets / Farm System / Crops

• What is the total land area of your farm? in hectares (ha)

• Which of the following enterprises are present in your farm? (farm system)

Arable Crops; Horticulture; Vineyards; Permanent Crops; Mixed Arable and Permanent or Horticulture; Grazing Livestock (Cattle, Sheep, Goats, Other); Monogastric (Pigs/Poultry); Mixed Livestock (Grazing); Mixed Farming (Crop-Livestock Integration); Other

• Do you cultivate any of the following crops?

Cereals; Potatoes and sugar beet; Oilseeds; Fruit; Vegetables; Grapes for wine; Olives for oil; None; Other

• Do you implement any of the following agricultural practices or principles?

Crop Rotation; Agroforestry; Intercropping; Cover Cropping; Precision Farming; Integrated Pest Management (IPM); Organic Farming; Conservation Tillage; Irrigation; Drainage & water logging management; Soil moisture conservation; Management of landscape features (e.g., hedgerows, flower strips, woodland patches)

Irrigation & Inputs

• What type of irrigation do you mainly implement in your farm?

I do not practice irrigation; Drip Irrigation; Sprinkler Irrigation; Subsurface Drip Irrigation; Furrow Irrigation; Basin Irrigation; Border irrigation; Other

• What is the main water source for irrigation?

Surface rainwater harvesting; Underground rainwater harvesting; Groundwater from farm; Groundwater outside farm; Surface water from farm; Surface water outside farm; Other

• What types of seeds do you typically purchase?

I reproduce my own seeds; Improved Varieties; Hybrid Seeds; Open-Pollinated Seeds; Organic Seeds; Conventional Seeds; Other • Do you use any of the following fertilisers? I do not use any fertiliser; Synthetic fertiliser; Compost; Manure (from farm); Manure (off farm); Biostimulants; Other
Digital Technologies & Data In your opinion, what are the most useful spatial data (maps) that an app could show to a farmer? (1 – Insignificant 2 – Not useful 3 – Useful 4 – Very useful) Natural color satellite images; Infrared satellite images; Vegetation indices derived from satellite products (e.g., green = good vegetation health; red = poor vegetation health); Soil classification data and characteristics; Precipitation meteorological data; Temperature meteorological data; Soil moisture data; Topographic data (altitude, slope, sun exposure); Hydrological data; Maps of drought stress and heatwave risk; Soil erosion risk maps; Irrigation support maps; Other (please specify) In your opinion, what is the level of adoption of new digital agricultural technologies in your region? Very low; Low; Moderate; High; Very high
Challenges & Climate change What are the consequences of climate change for your agricultural activity? 1 – Insignificant 2 – Not important 3 – Important 4 – Utmost importance Reduced yields; Difficulty in irrigation; Increased pests and diseases; Structural damage to fields; Need to change crops; Other

3.3. Hotspot mapping by remote sensing

3.3.1. Open-source geodata – satellite imagery

The objective of this paper is to contribute to the body of knowledge on the threat of saltwater intrusion in the Po River Delta via a transdisciplinary approach using farmer personal accounts (as described in the previous sections) together with an analysis of remote sensing data. The purpose of the analysis of remote sensing data is to provide temporal and spatial observations of the impact of saltwater intrusion on active cropland. Often studies utilize land cover datasets to filter satellite imagery for cropland and apply their analyses to these lands, but these classifications include fields which have been left fallow and if the dataset is static, it is unable to reflect changes in plant phenology throughout the growing season. To produce an analysis which best reflects the dynamic relationship between saltwater intrusion and active crop growth, this paper used spectral indices derived from satellite imagery which had been filtered so that only active cropland was considered. In order to provide a more comprehensive analysis, two different methods were employed, the first being favourable for identifying long term trends, and the second being favourable for observing changes throughout the growing season.

The first method used satellite imagery from the Landsat 5 and Landsat 8 missions, filtered for active cropland via a manual selection and training procedure, and a calculation of the spectral vegetation index NDVI – The Normalized Difference Vegetation Index (Rouse et al., 1974). The second method used satellite imagery from the ESA's Copernicus Sentinel-2 mission, filtered for active cropland using the Dynamic World V1 Land Use/Land Cover (LULC) dataset from Brown et al. (2022), and a calculation of NDVI and a soil salinity index: Salinity Index – 4 (SI4) (Abbas and Khan, 2001). The first method takes advantage of the long-term continuity of the Landsat missions and therefore is ideal for observing long term trends in the study area. The second method takes advantage of the high resolution and higher revisit frequency of the Sentinel-2 mission and the high resolution, near real-time data from the Dynamic World V1 Land Use/Land Cover (LULC) dataset and therefore provides a detailed spatial analysis that is highly reflective of changes in active cropland and thus reflective of the variable impacts of saltwater intrusion on crop vigour. This degree of spatial and temporal resolution is also useful given some of the characteristics of the territory. Crop rotation is a common practice (and was confirmed in the farmers' questionnaire responses) and therefore static datasets may not account for these yearly changes in land cover. Weather conditions can also vary quite a bit across the coastal area, but because there is one primary weather station, this is not always reflected in analyses or expected to be a changing variable across the area. Also, the water table is artificially controlled because the delta is a drained region, and therefore there is an added level of variability throughout the season. High resolution helps to account for both of these variations in the study area. In other words, Method 2 is a dynamic method, appropriate for studying a dynamic problem. These two methods will now be described in further detail.

In Method 1, satellite imagery from NASA/USGS' Landsat 5 and Landsat 8 missions was used. The Landsat 5 mission, developed and carried out by the United States National Aeronautics and Space Administration (NASA), launched in 1984 to provide observations of land surface conditions. It was decommissioned in 2013. The dataset covers the period of March 16th, 1984 to May 5th, 2012. Its revisit frequency was 16 days. It has the advantage of being the longest-run earth observation satellite mission, but it does not provide as high of resolution as some more recently developed products. The dataset used in this analysis was the USGS Landsat 5 Level 2, Collection 2, Tier 1 dataset which has a resolution of 30m. The Landsat 8 mission launched in February of 2013 and, crucially, provided continuity to the already 40-year long dataset provided by previous Landsat missions. It is still in commission today and has a revisit frequency of 16 days. For this analysis the USGS Landsat 8 Level 2, Collection 2, Tier 1 dataset was used. It has a resolution of 30m. The satellite images were used to calculate the spectral index NDVI – the Normalized Difference Vegetation Index (Rouse et al., 1974). In the absence of a dynamic land cover/land use dataset, like the one used in Method 2, a manually derived classification was necessary to calculate NDVI only for active cropland. This was done in Google Earth Engine (GEE) by manually identifying green vegetation, bare soil, and water from an RGB satellite image (based on median composite values for the growing season), drawing polygons for each classification, and training the script with a classification function.

A shapefile defined the boundaries of the study area and represented only agricultural lands. This was achieved by clipping the area using level I of Corine Land Cover 2018: “2. Agricultural areas” (EEA, 2020). In this way, the manually derived classifications, unique to each year of the analysis, were applied to this clipped area and therefore the identified green vegetation was only on agricultural lands and therefore a year-to-year active cropland image collection was produced. From this defined collection, the spectral index could be calculated. Given that the goal of Method 1 was to produce a time series, a median NDVI value was calculated in GEE for the growing season of each year of the analysis. The analysis was carried out from 2000 to 2024 for the months of June, July, August, and September, apart from 2012 because there was no coverage of the study area in the months of interest in that year. Although the Landsat 5 satellite was decommissioned in 2013, the dataset ends on May 5 th, 2012. These months were selected because they represent the primary growing season of the region and because it is the period in which saltwater intrusion is most critical in the study area. The output was a time series graph showing the mean NDVI value and standard deviation for each year, as well as yearly maps showing the spatial distribution of median NDVI values.

In Method 2, satellite imagery from the Copernicus Sentinel-2 mission was used together with the Dynamic World V1 Land Use/Land Cover (LULC) dataset (Brown et al., 2022). The Copernicus Sentinel-2 mission, developed and carried out by the European Space Agency (ESA), launched in 2015 and is still active today. It provides high-resolution satellite imagery (up to 10m) designed to monitor land surfaces. It has a revisit frequency of 5 days. The dataset used in this analysis was the Harmonized Sentinel-2 MSI: MultiSpectral Instrument, Level-2A dataset. The bands used from the images in this dataset have a resolution of 10m. The Dynamic World V1 Land Use/Land Cover (LULC) dataset was used in conjunction to filter for active cropland. This product is the first near real-time mapping of global land use/land cover with 10m resolution. It was developed to improve upon limitations of previous products which were static and lower resolution. Improving upon both of these points broadens the uses of such datasets. With higher resolution and dynamic data, changes in land cover/use can be detected earlier and smaller holdings or areas of interest can be spatially analysed. Additionally, this product has global coverage which is an advantage over some previously released products. These improvements were achieved thanks to important advances in machine learning and cloud storage. The training of a Fully Convolutional Neural Network (FCNN) allowed for near real-time output (model predictions) and the storage of the large quantity of data required to support this kind of a product is possible due to the use of Cloud AI Platform with GEE (Brown et al., 2022). The dataset is based on 8 land cover/land use classes: Water, Trees, Grass, Flooded Vegetation, Crops, Shrub & Scrub, Built area, Bare ground, Snow & Ice (Brown et al., 2022). Note that this dataset could not be used in Method 1 because its coverage began in June 27 th, 2015 and it was preferred to use the manual training classification method throughout the entirety of the analysis of Method 1 for consistency purposes. But its use in Method 2 is very valuable for the overall analysis of this paper because its high resolution and near real-time data provide important insights about variations occurring during the growing season which supports a better understanding of in-season dynamics between crop growth, saltwater intrusion, and soil salinization processes. The selected and filtered images were used to calculate NDVI as well as a soil salinity index (Salinity Index – 4) (Abbas and Khan, 2001). The inclusion of a soil salinity index can help to discriminate between the various factors which may cause low NDVI values. The use of these spectral indices for approximating the impact of saltwater intrusion on agricultural fields is supported by findings from other authors (Nguyen et al., 2020; Luo et al., 2024; Gad et al., 2022). Both indices will be discussed in greater detail in the following sections of this paper. The analysis was carried out from 2017 to 2024 for the months of June, July, August, and September, apart from 2015 and 2016 because while the Sentinel-2 mission launched in 2015, the datasets from the beginning of the mission do not always contain complete global coverage. This is the case for this paper’s study area and the reason why 2015 and 2016 are not included in the spatial analysis, although they were originally included in the scripts ran in GEE (which revealed the lack of coverage). As with Method 1, these months were selected because they represent the primary growing season of the region and because it is the period in which saltwater intrusion is most critical in the study area. The output was a hotspot map of critical NDVI values and a hotspot map of critical SI values, as well as yearly maps for both indices.

In order to select and filter the satellite imagery and calculate these indices, the cloud-based geospatial analysis platform Google Earth Engine was used. The following is the procedure for Method 1. For each year in the analysis (2000-2024 (except for 2012)), the median NDVI value was calculated for each pixel of the satellite imagery of the study area for the months of June, July, August, and September. In other words, using the Landsat 5 and Landsat 8 image collections, a median NDVI value, representing crop vigour, during the primary growing season was calculated for the entire surface of the study area where there was active cropland in each year of the analysis.

The output is a raster for each year of the analysis which was then visualized in QGIS to create yearly maps, showing the spatial distribution of these median values across the active cropland in the study area. In the GEE code editor, the following commands were run:

1. The date range is specified (year, months: June-September).
2. The Landsat image collection (Landsat 5 or Landsat 8) is loaded and filtered for the date range, region of interest, cloud cover (< 10%), and the required bands are selected: A) to produce the RGB image for the manual classification training (Red, Green, Blue) and B) to calculate NDVI (red, near infrared (NIR)).
3. A composite image is calculated representing RGB and NDVI values for the pixels in the filtered image collection.
4. The visualization parameters are set for the RGB image layer to be displayed in GEE.
   **This is necessary for drawing polygons for the manual classification training.*
5. A training function is written to use the data from the manually defined water, vegetation, and bare soil polygons.
6. A function is written to produce a median image based on the training data.
7. A mask is created for the vegetation class.
8. NDVI is calculated for the median image using the red and near infrared bands for Landsat (5 or 8).
9. The vegetation class mask is applied to the NDVI data layer.
   **This is necessary so that the NDVI values returned are only those for the active cropland.*
10. The output is clipped to the study area.

See Appendix 2 for the script for 2024.

In order to identify any long-term patterns in crop growth in the study area, an additional script was run in GEE to produce a time-series graph based on descriptive statistics. Each yearly raster produced from the above commands was inserted as an image collection so that from the median NDVI values in the raster, a mean and standard deviation could be calculated to represent that year. Each year's mean and standard deviation values were then plotted in a line graph using Microsoft Excel so that an analysis of the entire period, 2000-2024 (excluding 2012) could be performed.

In Method 2, utilizing a shorter time series but with a higher temporal and spatial resolution, the objective was to conduct a spatial analysis that would provide evidence of variations in crop vigour occurring throughout the growing season using two spectral indices (NDVI and SI4). For this reason, a threshold parameter was used to generate the raster data for each year of the analysis. In order to set a threshold for NDVI values that was appropriate and contextualized to the area and time period, the entire period of analysis of Method 2 (2017 to 2024), was set as a baseline period from which a value representing the 10 th percentile was calculated. Low NDVI values indicate low crop vigour and therefore any values below the 10 th percentile could be considered critical. This threshold was used for the yearly NDVI analysis; meaning that only those NDVI values calculated from the Sentinel-2 imagery in a given year which were below the threshold were reflected in the output raster. A similar approach was applied for the Salinity Index (SI) analysis, only in this case a 90th percentile value was calculated from the baseline period of 2017-2024. In this case, high salinity levels are cause for concern and therefore critical to this analysis. Thus, only SI4 values calculated from the Sentinel-2 imagery for a given year which exceeded the threshold value, were included in the output raster.

In the below commands, the baseline period refers to the years 2017 to 2024 for the months of June, July, August, and September while the target period refers to the months June, July, August, and September of one year within the baseline period. In the GEE code editor, the following commands were run for each individual year (i.e. the target period) of the analysis:

1. The baseline period (2017-2024) and target period (individual year) were set.
2. The Sentinel-2 dataset: Harmonized Sentinel-2 MSI: MultiSpectral Instrument, Level-2A, was loaded and filtered based on the baseline period and study area (boundaries of the area of jurisdiction of the land reclamation authority). Cloud coverage was filtered to retrieve images with 10% or less cloud coverage. The bands of interest for the SI4 calculation (B3, B4 and B8) were selected.

3. The Sentinel-2 dataset: Harmonized Sentinel-2 MSI: MultiSpectral Instrument, Level-2A, was loaded and filtered based on the target period and study area (boundaries of the area of jurisdiction of the land reclamation authority). Cloud coverage was filtered to retrieve images with 10% or less cloud coverage. The bands of interest for the SI4 calculation (B3, B4 and B8) were selected.
4. SI4 function (see section Salinity Index – SI4 below) was applied to the above retrieved images and a mask was applied to non-SI4 pixels.
5. A threshold of the 90^{th} percentile of the calculated SI4 values for the baseline period, 2015-2024, was computed.
6. A function was applied to select the pixels from the images retrieved for the target period (individual year) for which the SI4 value exceeded the 90^{th} percentile threshold (determined via the previous command) and to apply a mask to these pixels.
7. The sum of the above selected pixels, known as the "exceedance pixels", was used to generate a frequency distribution.
8. The results were displayed on the map in GEE.

See Appendix 3 for the GEE script used to calculate SI values for the year 2023. The same commands were run for the NDVI calculations, with two alternations to the script. Firstly, altering the calculation (command 4) and secondly, altering the threshold value for pixel selection (command 6) to 10% and then selecting and summing those pixels with values less than the 10% threshold. See Appendix 4 for an example of the script used for the year 2023.

The output rasters from both the Method 1 and Method 2 GEE codes were imported into QGIS 3.10.10 for visualization and generation of the final maps. Yearly maps were produced for both methods. For Method 2, two hotspot maps were produced to highlight areas where there were frequently critical NDVI or SI values. These were generated by summing the yearly NDVI (or SI) rasters to produce a single map representative of the active cropland for the time period 2017-2024.

3.3.2. Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a spectral vegetation index derived from remote sensing that provides an estimate of vegetation vigour. It is calculated according to the following equation and its values range from -1.0 to 1.0

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

where NIR is the near-infrared band reflectance and RED is the red band reflectance (Rouse et al., 1974). NDVI is a vegetation index with a wide range of applications, one of which being to approximate salinization. It's an effective measurement for this process because there is a significant negative correlation between salinity and NDVI values (Luo et al., 2024). Soil salinization stresses a plant and negatively impacts its vigour. This is observed in a decrease in near-infrared reflectance as well as an increase in the red reflectance which results in a lower NDVI value. This is because healthy cellular structure in plants reflects near-infrared light to a high degree. When the plant cellular structure has been compromised due to stress from disease, salinity, drought, etc. this reflectance is reduced. Additionally, chlorophyll, a plant compound fundamental for the absorption of energy from the sun, and thus plant health, is highly absorbent of red (visible) light. When there is a reduction of this compound in vegetation—a sign of stress (but also normal shifts in plant growth phases)—the reflectance of this light is increased. Golabkesh et al. evaluated six indices for the purpose of monitoring soil salinity and found that NDVI was the best index to use in the presence of vegetation cover (2021). This supports the choice to use NDVI in this study given that the objective of the analysis is to measure changes in actively growing vegetation. But because NDVI is a measure of vegetation vigour and the reasons for which vegetation may have low vigour and thus a low NDVI value are many, this paper employs the use of a soil salinity index in combination with NDVI. This method provides more robust evidence that salinization is the driving cause of any measured low NDVI values via observed patterns of corresponding high SI values.

3.3.3. Salinity Index – SI (SI4)

Given the significant threat that soil salinization poses to land productivity and crop health, specific indices have been developed with the aim of supporting the identification and monitoring of soil salinity levels and the impacts on crop growth and yield. The Salinity Index – SI4 is one such index. But "Salinity Index (SI)" actually refers to a group of indices (14 in total). They were "specifically designed to maximize the sensitivity of vegetation indices to salinity stress while minimizing the influence of other environmental factors on individual spectral bands, such as moisture" (Salem & Jia, 2024). SI is highly correlated to soil EC and therefore a useful index for monitoring soil salinity conditions in the upper layers of the soil and the impact on crop yield (Ennaji et al., 2018). SI4 is calculated according to the following equation:

$$SI4 = \frac{R\ x\ NIR}{green}$$

where NIR is the near-infrared band reflectance, R is the red band reflectance, and green the green band reflectance. Vegetation cover, however, has a strong influence on salinity indices and the stage of vegetation growth is a relevant factor which should be considered in the use of these indices. For this reason, in this analysis SI was calculated using the high resolution, near-real time land use/land cover data set. It allows for these variations in crop coverage during the growing season to be accounted for and accurately reflected in the computed SI values.

4. Analysis of results

4.1. Farmers' perspectives

The results from the PHITO user needs assessment of the Po River Delta food system should be taken as a case study. This means that while the results are valuable and can support a better understanding of the context in which exists the problem of saltwater intrusion for this community, the results should not be generalized to other food systems, nor should they even be considered statistically representative of all stakeholders of the Po River Delta food system. They do, however, align with the participatory and transdisciplinary frameworks discussed above and support good solution generation and long-term solution adherence.

The standardized, anonymous questionnaire distributed as a part of the PHITO project was completed by 75 farmers in the Po River Delta. The aim of the questionnaire was to reach a wide-reaching group of farmers in the food systems involved in the project, which had been selected for their diverse representation of agri-food systems.

The questionnaire demographics reveal a predominantly male and middle to late adulthood population, in line with demographics of many primary sectors. 16% of the respondents were female, 84% male and the average age of the respondents was 54.56. Regarding education level, 46.67% reported middle school as their highest level of education attained. 33.33% reported it being high school (6^{th}-10^{th}), 13.33% higher education (above 10^{th} grade; diploma; graduated), 4.00% reported primary (1^{st}-5^{th}), and 2.67% reported other. Collectively, the respondents cultivate 3,279 hectares of land in the Po River Delta. When asked about their level of satisfaction (dissatisfied, neutral, satisfied, very satisfied) with their farming activities, 45.95% responded "neutral", 40.54% "satisfied", 10.81% "dissatisfied", and 2.70% "very satisfied". When asked about their affiliation to associations, 55 individuals reported being affiliated to a national association, 9 to an association on a territorial scale, 4 to a local association, 3 to a regional association, and 1 who was not affiliated with any of the above categories of associations. Given the sample size relative to the overall population involved in the primary sector in the territory and the sampling procedure, these results are not appropriate for analysis or interpretation but do provide a foundational context for other findings.

The land area, in hectares, by farming systems (Figure 10) was reported as 2,255.5 ha of arable crops, 250.0 ha of mixed farming, 225.6 ha of permanent crops, 221.7 ha of mixed arable/permanent crops, 191 ha of "other", 74 ha of grazing livestock, 47.7 ha of horticulture, and 12.7 ha of vineyards. The land area by crops were reported as: 384 ha of cereals; 208.7 ha of olives (for oil), 162 ha "other"; 91.5 ha of potatoes / sugarbeet, 74 ha of oilseed; 33.5 ha of grapes (for wine); 33 ha of fruit; and 21.9 ha of vegetables.

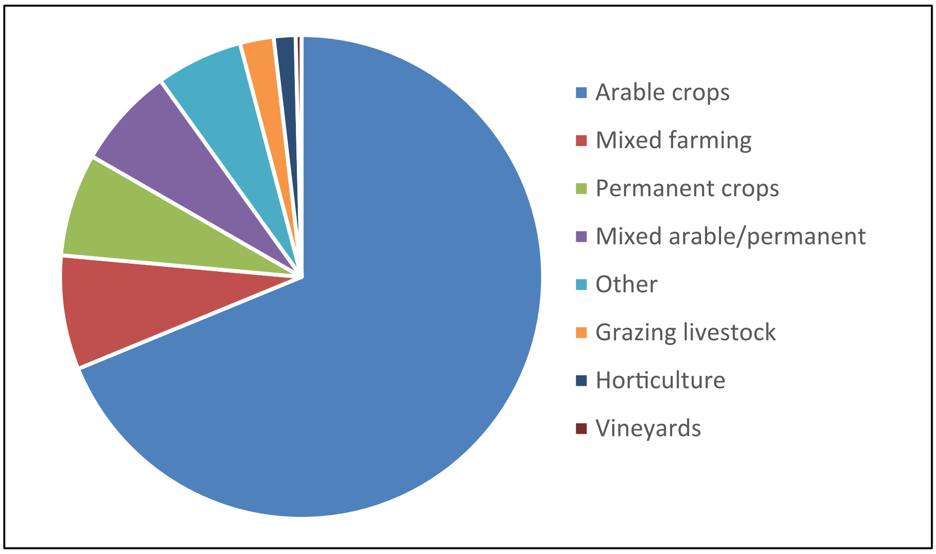


Figure 10 - Land (ha) by farming system

One of the often-proposed solutions for addressing saltwater intrusion, especially in the long term and in cases where preventative measures are too costly or seem insufficient, is a shift in cultivars. This will be further discussed in the Discussion of Results section of this paper, but it is worth noting that data on the current crop types–together with other characteristics about farms and stakeholder perspectives–is valuable data when evaluating the feasibility of a solution in terms of the willingness of individuals to adopt changes, the ease with which a new product can be introduced to a market, and the profitability of a crop type in a given region.

Stakeholders were also asked which if any of a series of practices had been implemented on the land to which their activities are connected. The practices in question were: conservation tillage, intercropping, irrigation, cover cropping, crop rotation, drainage & water logging management, integrated pest management, landscape management, organic farming, precision farming, soil moisture conservation, and agroforestry (Figure 11).

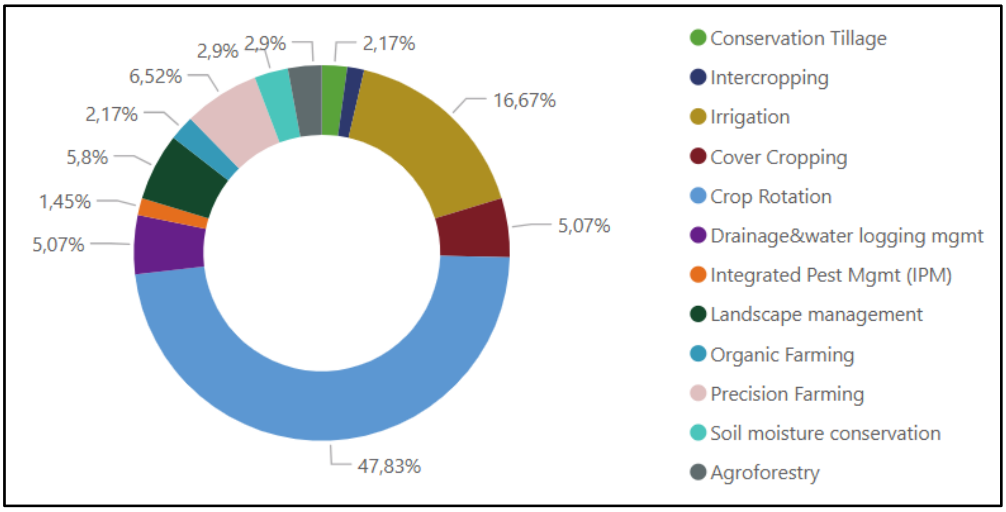


Figure 11 - Implemented practices

In terms of land management practices, crop rotation, implemented by almost half of the respondents (47.83%), is an important finding since saltwater intrusion in the Po River Delta is largely a seasonal phenomenon and represents an opportunity for a shift in cultivar within only one season while maintaining the same cultivations in the rest of the rotation. This may result in a lower perceived risk by the farmer (or involved stakeholder) if, for example, 2/3 of his/her business remains unchanged. Less than 3% (2.9%) of respondents report having implemented soil moisture conservation which can indicate a potential area of improvement for a territory in which water moratoriums are not uncommon during periods of drought and saltwater intrusion in irrigation canals. Agroforestry, also implemented by less than 3% of respondents represents an unexplored solution for these farmers. Although, mixed farming systems and mixed arable/permanent farming systems represent almost 500 ha of land of the respondents and 33 ha of fruit are cultivated by the respondents, which suggests feasibility of agroforestry systems within this land area and potentially good candidates to be "early-adopters" of this system. Organic farming, practiced by only 2.17% of respondents, is a clear area where, even if certification is not pursued, a substitution of some or all fertilizers for organic fertilizers such as manures or compost, can support soil organic carbon levels and thus soil structure and the water-holding capacity of soils—another crucial defence in the absence of irrigation water due to saltwater intrusion. Approximately 5% of respondents have implemented landscape management practices. This would be an interesting point of further discussion to identify the specific practices adopted because one strategy of landscape management

includes establishing and maintaining buffer strips along waterways. This can be a protective measure against saltwater intrusion via lateral seepage.
Cover cropping, practiced by only 5.07% of respondents, is a relatively easy solution that contributes to healthy soil structure–something that is very critical during droughts–and can be, among other things, what prevents a meteorological drought from becoming an agricultural drought. Conservation tillage, practiced by even fewer respondents (2.17%) also supports good soil structure as well as an active microbial community which both contribute to a high level of water holding capacity in soils. Irrigation was included in this question but the questionnaire contained specific questions pertaining only to irrigation and therefore will be discussed later in this section.
The majority of respondents (61.05%) use synthetic fertilizers, so as discussed above, a switch from some of these fertilizers to organic fertilizers that support soil health could be an appropriate solution for these stakeholders to adopt in order to increase resiliency to saltwater intrusion. About a quarter of respondents (26.31%) use compost or manure which represents a notable fraction and indicate the feasibility of the adoption of these practices in the region as well as established supply chains. 6.32% of respondents utilize biostimulants. This would be another point to explore further with more in-depth stakeholder interviews since there are a number of biostimulants which have been demonstrated for their efficacy against abiotic stresses such as salinity. These include chitosan and chitosan nanoparticles (du Jardin, 2015; Alenazi et al., 2024), products containing active molecules capable of inducing positive growth regulator pathways (Ertani et al., 2013), a root-promoting biostimulant (Melito et al., 2024), and microbial inoculants (Miceli et al., 2021).
Farmers were asked which types of geodata were of greatest interest to them (Figure 12). The intent of this question for the PHITO project was to better understand which features to include within the app but this information can also be useful for the scientific community, policymakers, and the "third mission" of universities both in guiding what kinds of research are undertaken and how the findings are disseminated.

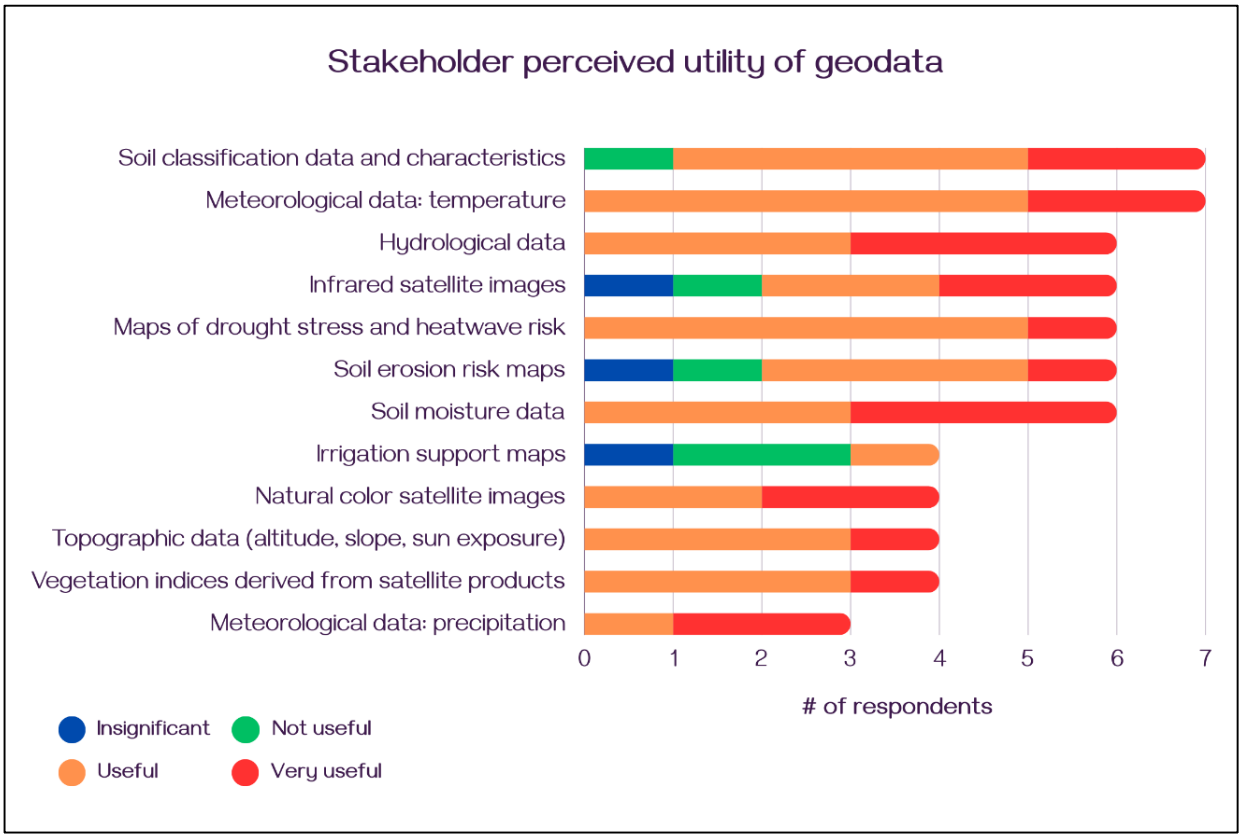


Figure 12 - Stakeholder perceived utility of geodata

To the same end, stakeholders were asked "What is the level of adoption (very low, low, moderate, or high) of new digital agricultural technologies in your region?". Most respondents said "moderate" or "low", 41 and 19 respectively, while 12 responded "very low" and only 2 responded "high". Prioritization of resources and solutions should be considered with this kind of an understanding of the interest in and willingness of stakeholders to adopt said technologies or if there are barriers present.

When asked about their perceived impact of climate change on farming operations (Insignificant, Minimal, Moderate, High, Severe), 50% of respondents reported that they perceived climate change as having a high impact on their farming operations. This represented the largest portion of respondents. 32.43% reported a perception of moderate impact, 9.46% reported severe, 6.76% reported minimal, and 1.35% reported insignificant. This demonstrates that a clear majority of these farmers are perceiving an impact on their farming operations. Farmers were further asked to rate a series of challenges related to climate change based on how significant they perceive them to be to their activities (Insignificant, Not important, Important, of the Utmost Importance). Of the five challenges asked about, reduced yields was the challenge most significant for these farmers. 71 of the 72 individuals who responded to the question rated reduced yields as of "Utmost importance" or "Important", 37 and 34 respectively. Difficulty in irrigation was also reported as being a significant challenge with 63 respondents rating it as of “Utmost importance” or “Important”. While the majority of respondents did not rate the remaining three challenges (Need to change crops; Structural damage to fields; Increased pests and diseases) as of “Utmost importance”, most did rate them as “Important” challenges. These answers reflect a high level of awareness of the challenges related to climate change, with a heightened awareness of what can be considered the “bottom-line”, the challenge with immediate and directly felt economic impacts: reduced yields.

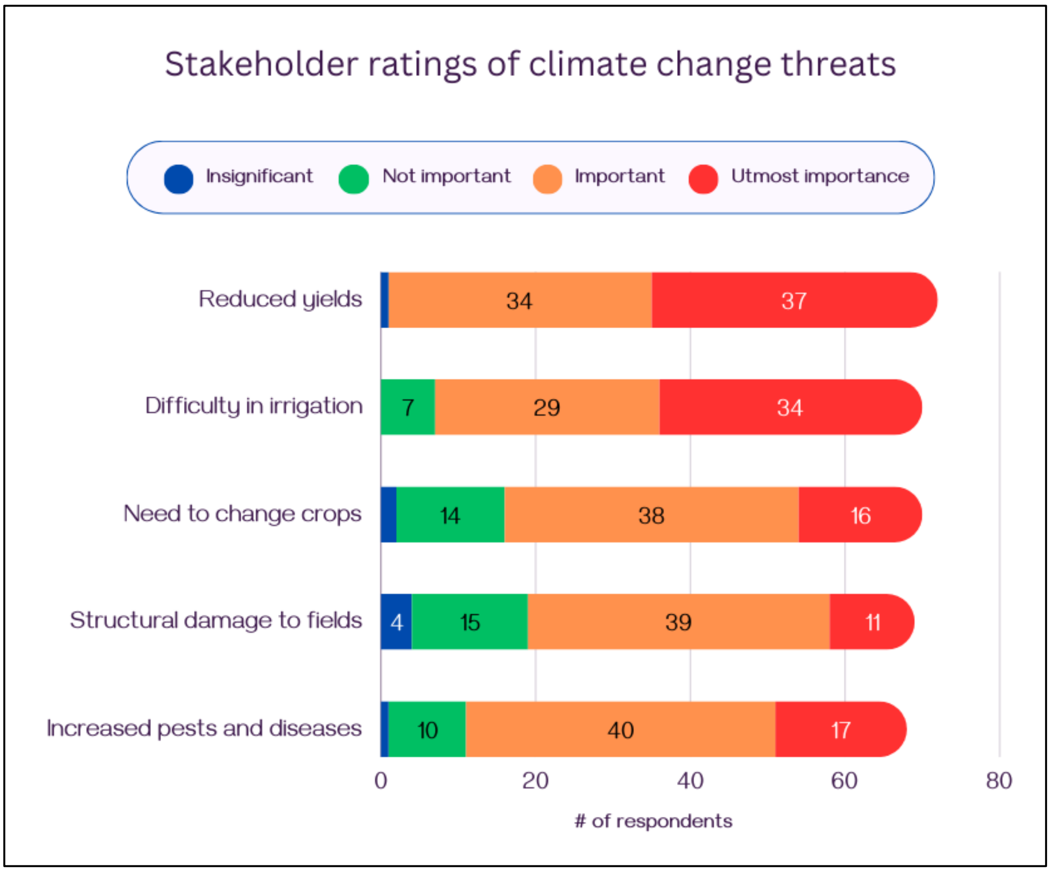


Figure 13 - Stakeholder ratings of climate change threats

Respondents were asked to specify the type of irrigation they practice: sprinkler, drip, basin, border, furrow, or if they do not practice irrigation. Almost 20% responded that they do not practice irrigation, a bit lower than the territory-wide estimate of 30% of agricultural lands not irrigated. Most stakeholders practice sprinkler irrigation (63.89%). Small portions of the respondents said that they practice drip (4.17%), basin (2.78%), border (2.78%), or furrow (1.39%) irrigation. 5.56% selected “other” as their answer. Different irrigation systems offer different benefits depending on the context, but knowing the current practices of most farmers is an important basis for the exploration of solutions such as increasing water use efficiency or remediating salt-affected soils.

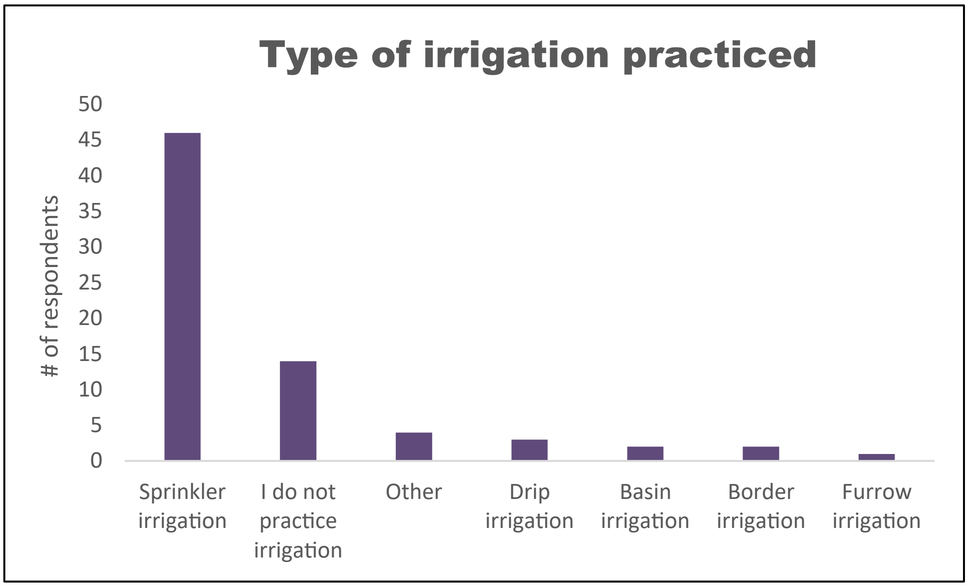


Figure 14 - Type of irrigation practiced

For those who do practice irrigation, they were additionally asked to specify the main water source for their irrigation activities. Surface water (whether from on or off the farm or from rainwater harvesting) represents the main source of irrigation water for these stakeholders. These findings align with the widely felt and highly vocalized concerns shared during the focus group about saltwater intrusion impacting irrigation schedules. Surface rainwater harvesting is practiced by a few respondents and could be an interesting practice to evaluate for a) its scalability to other farms and b) to what degree it could supplement surface waters from outside of the farm.

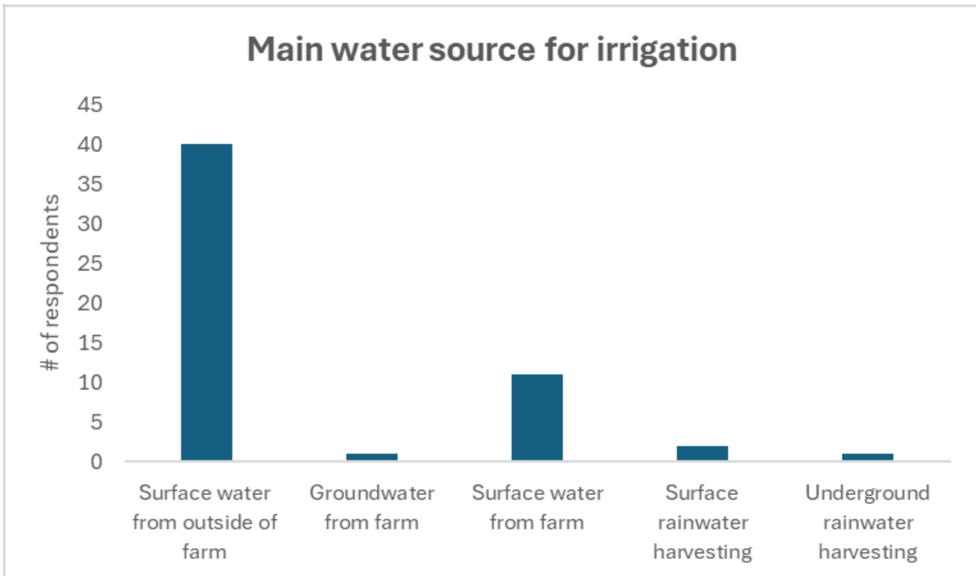


Figure 15 - Main water source for irrigation

The majority of respondents, 55.68%, purchase hybrid seeds. While 22.73% of respondents answered that they purchase conventional seeds and 12.5% responded improved varieties. Far fewer purchase organic seeds (3.41%), reproduce their own seeds (2.27%), utilize open-pollination (1.14%), or answered “other” (2.27%).

A focus group was organized and held by the land reclamation authority for the PHITO project. There were 27 participants and the focus group lasted approximately 1.5 hours. Most participants were reluctant to vocalize their opinions, but this was not unexpected given cultural norms (focus groups are not a common format for discussion in Italy). Nonetheless, those who were vocal provided valuable feedback. The main feedback from the focus group can be summarized in six points. First, participants recognized that the app could facilitate communication between farmers and public bodies (such as the Consortium). Second, participants felt that the app interface should be tailored based on the user (e.g. farmer vs. consumer). Third, it was made clear that data and alerts in real time are of particular interest to the farmers. Fourth, the marketplace feature was seen as a good opportunity to create value on a territorial scale. Fifth, data on crops suitable to a changing climate is relevant to this territory (i.e. salt tolerant crops). Lastly, a way to share experimental practices between farmers is an app feature of interest. Naturally, many of the talking points were closely tied to the PHITO app development; only the discussion points pertinent to this paper’s analysis will be further discussed.

In general, there was a strong in interest in more accessible and timelier climate, irrigation, and crop data. A key takeaway was validation of stakeholders’ perceptions of the current challenges and needs of the agricultural sector in this region. These were irrigation services, water salinization, and climate change. Irrigation is essential for cultivation in this territory and with perpetual issues of water salinization, improved monitoring and communication between farmers and the land reclamation authority was identified as a need. Long-term, a transition from a reactive system to a more proactive system emerged as something that these stakeholders are aware of and to which they are already giving consideration. Growing more salt-tolerant crops was mentioned by several members of the focus group. There was recognition of the need for this kind of a shift in production, but they requested outside expertise to support them in selecting the most appropriate crops.

At the moment there is not publicly available geodata that can provide the alert and status system for saltwater intrusion that these stakeholders are requesting. There are, however, several salinization and vegetation indices which could be useful to these farmers if the frequency and timing of the output permits timely action-taking or facilitates the identification and monitoring of trends. Data on salt tolerant crops, with consideration to the local climate and soil conditions, could be provided. Data on last month’s rainfall, winter snow deposits, flow rates of the main rivers, and volumes in the aquifers were requested in a digital platform and could be sourced from a local public body (for instance: ANBI Veneto and ARPAV). The findings of this case study, while insufficient to be statistically representative of the territory, can nonetheless serve as “points of departure”. Researchers and policymakers can use these insights to begin a process of investigation of these problems and potential solutions, which then, with adequate data, can prioritize problems and effectively allocate resources in a way that is responsive to the needs and interests of the community.

4.2. Hotspot mapping by remote sensing

4.2.1. Longitudinal analysis of median NDVI values

The results from Method 1, the longitudinal analysis from 2000 to 2024 (minus 2012) using Landsat 5 and Landsat 8 satellite imagery, were 23 year-specific maps (Appendix 5) and a timeseries line graph (Graph 1) showing mean NDVI values for each year along with standard deviation. The year-specific maps show the spatial distribution of the median NDVI values for the growing season of that year. While there are some years which stand out as having lower-on-average median values across the study area (namely 2003, 2004, 2005, 2007, 2011, and 2022), overall, there does not appear to be a significant long term upwards or downwards pattern. It is worth mentioning the years in which there was high spatial variability (indicated by standard deviation). In 7 years—2002, 2005, 2007, 2008, 2009, 2018, and 2023—the standard deviation was greater than 0.120, with 2007 being the largest with a standard deviation of 0.165. This is compared to the lowest standard deviation, .075, in 2011. The wide variation is likely the reason why there is not a clear long-term pattern.

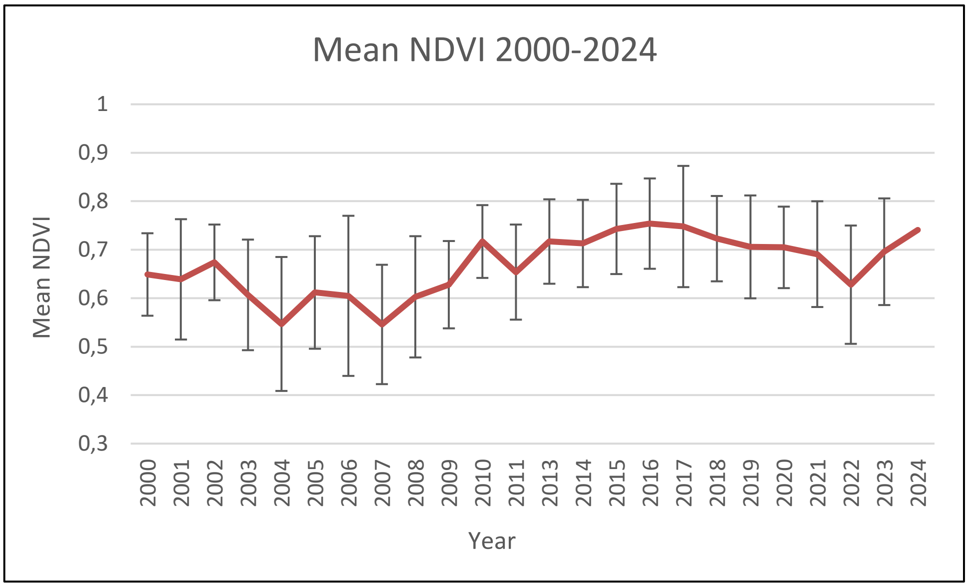


Figure 16 - Mean NDVI, 2000-2024

In years with higher spatial variability, it is easier to identify hotspots of low NDVI in the maps. In 2000, 2002, and 2005 (Figures 16, 17, 18, respectively) some hotspots of low median NDVI values are evident near the main river branch in the centre of the study area, and in the southernmost and southeastern portions of the study area.

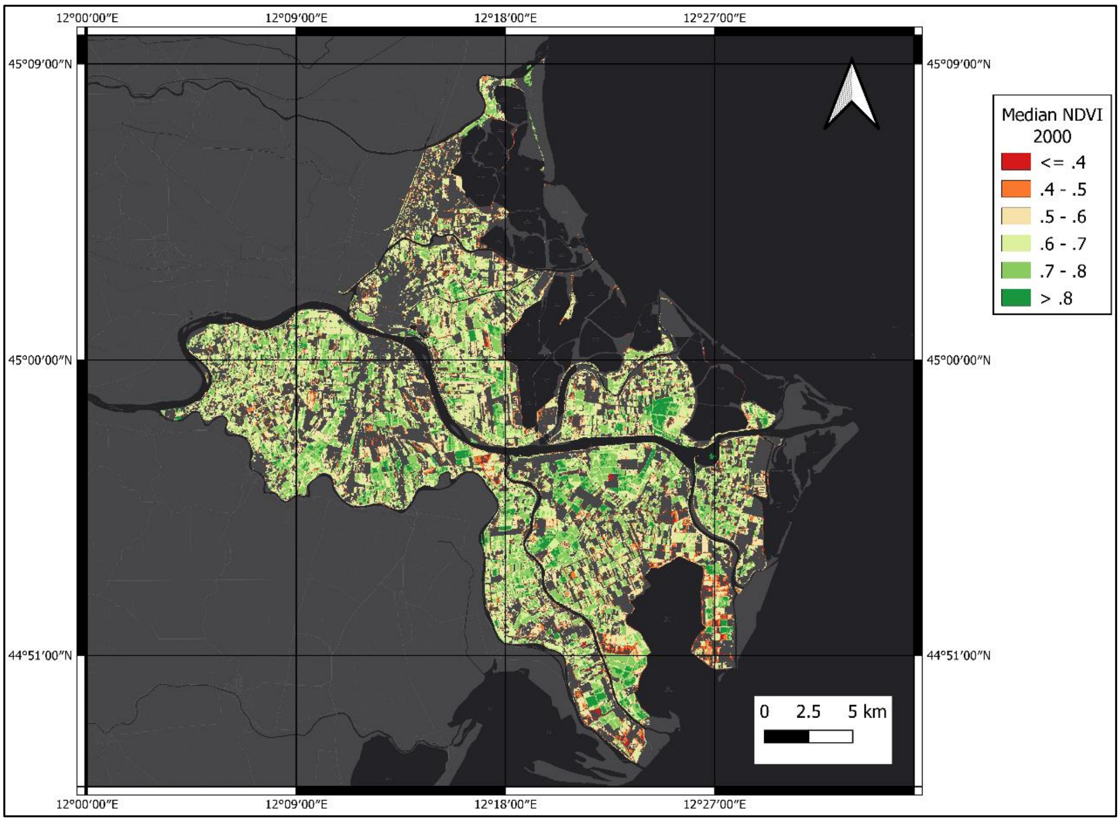


Figure 17 - Median NDVI, 2000

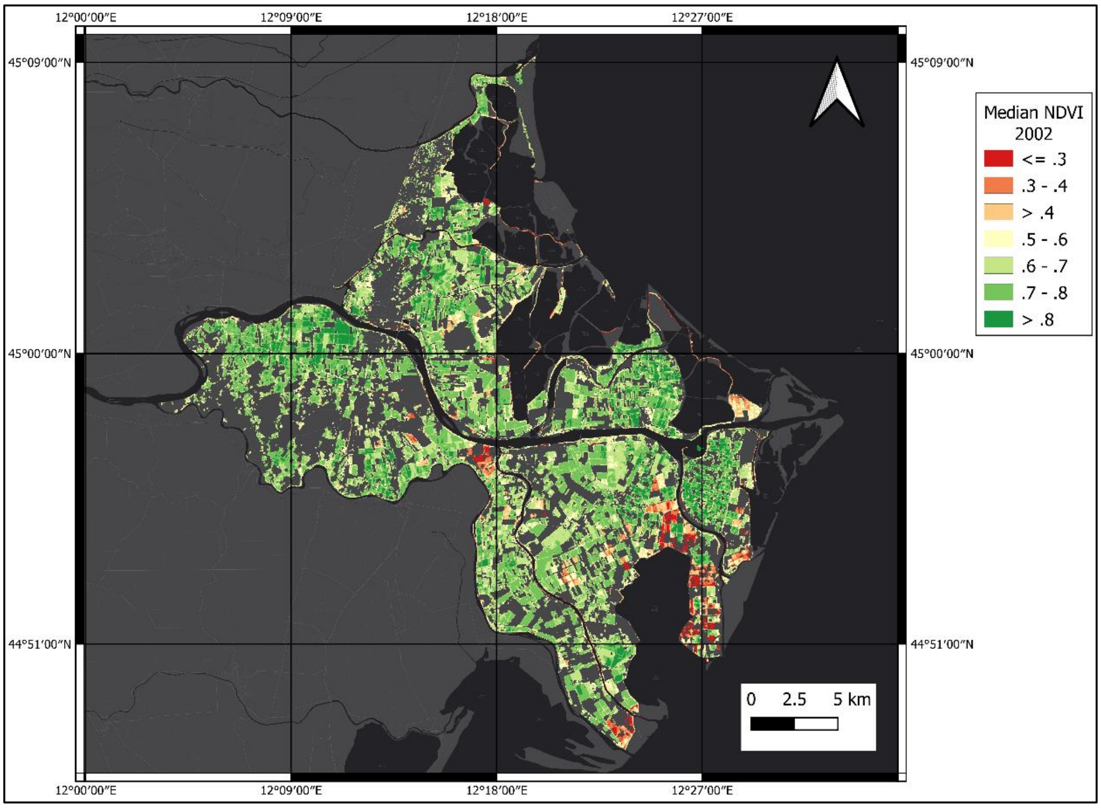


Figure 18 - Median NDVI map, 2002

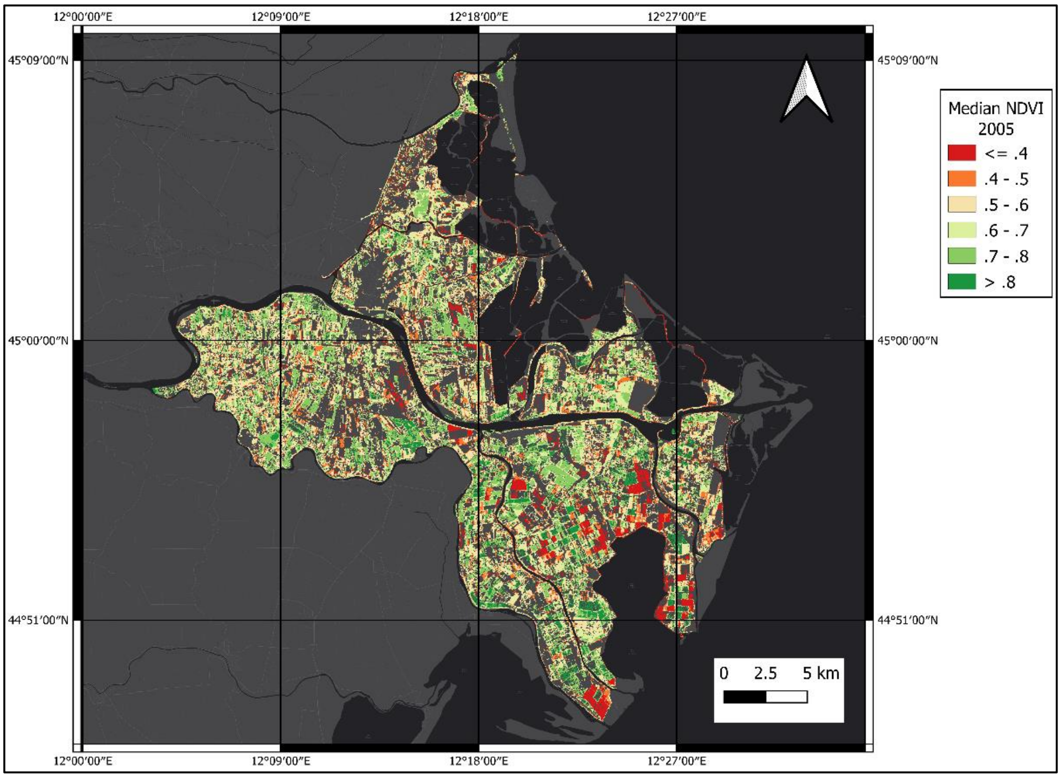


Figure 19 - Median NDVI map, 2005

In years with severe drought or water scarcity, there is often low spatial variability because there is a high level of stress across the entirety of the study area. The high level of disturbance makes it difficult to discern hotspots, as was also found other authors (Tarolli & Ghirardelli, 2023; Ghirardelli et al., 2024). This can be observed in the maps from 2003, 2011, and 2022 (Figures 16, 17, 18).

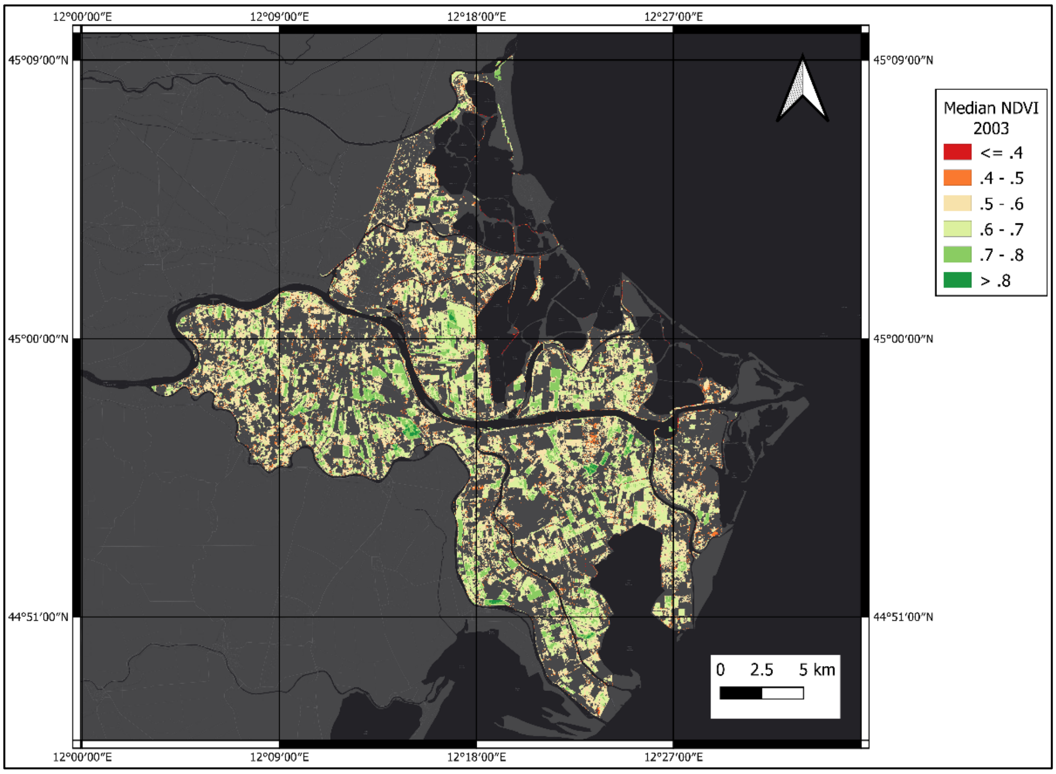


Figure 20 - Median NDVI, 2003

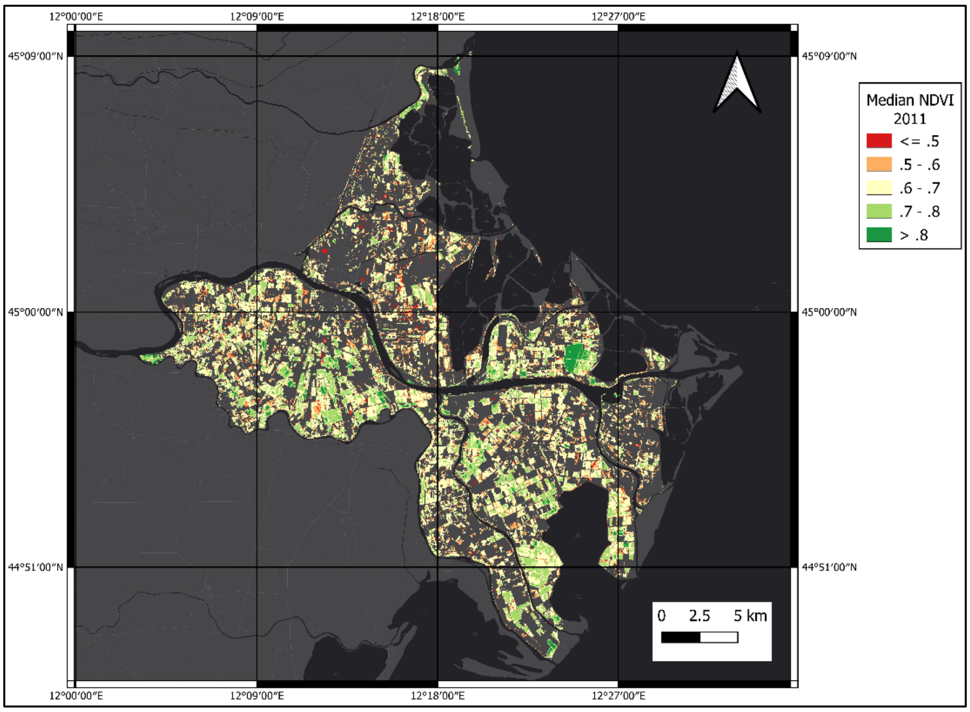


Figure 21 - Median NDVI map, 2011

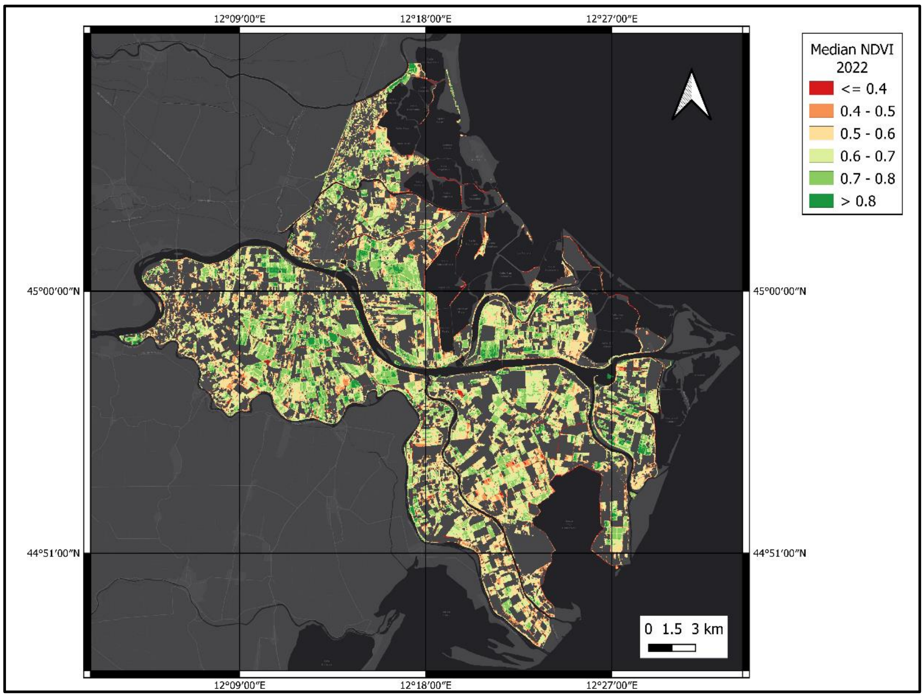
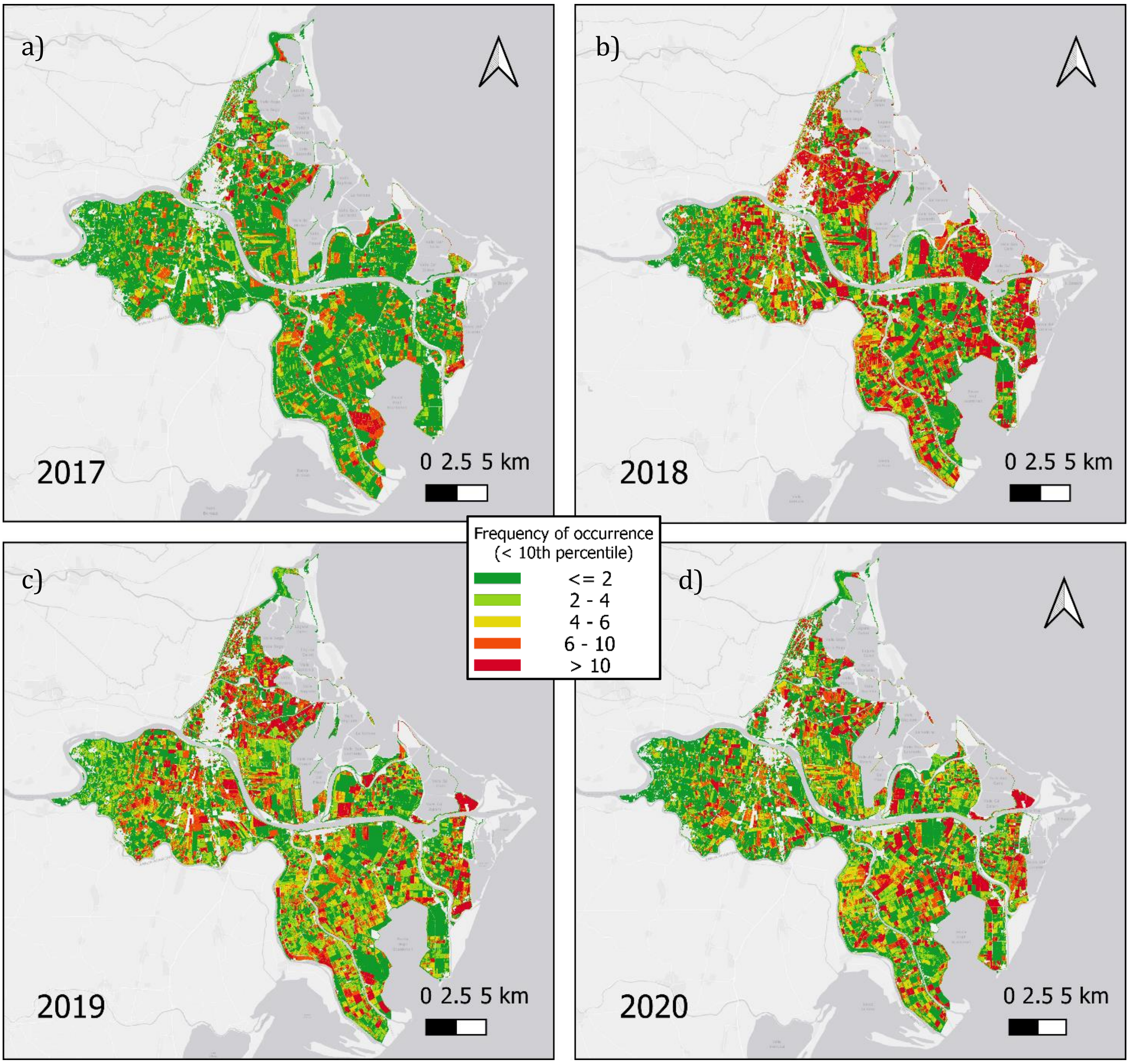


Figure 22 - Median NDVI map, 2022

But, as stated in the Materials & Methods chapter of this paper, the major advantage offered by Landsat satellite imagery is the continuity, making it ideal for long times series analysis, while its disadvantages are the revisit frequency and spatial resolution. The latter of which have both been improved upon in more recently developed satellite products and the reason for which Copernicus Sentinel-2 imagery was used in Method 2. These attributes make it more suitable for identifying hotspots and patterns in spatial distribution. The results of this method will be presented in the following section.

4.2.2. High resolution analysis with NDVI and SI

In Method 2, NDVI and SI values were calculated for the 2017-2024 period. For each year a map was produced (Figure 22 & Figure 23). The values in the output raster represent pixels in the satellite imagery, selected for active cropland in the study area, in the months of June, July, August, and September in which NDVI values were below the 10 th percentile or SI values exceeded the 90th percentile (as determined by the baseline period 2017-2024). Therefore, these year-specific maps can be used to identify fields and areas where NDVI values were frequently low and where SI values were consistently high indicating low crop vigour and high levels of salinization in the upper layers of the soil profile, respectively. Where a shared pattern is observed between these two indices, given the local context, saltwater intrusion is very likely the driving factor behind the observed phenomenon.


a)
2017
0 2.5 5 km
b)
2018
0 2.5 5 km
c)
2019
0 2.5 5 km
d)
2020
0 2.5 5 km
Frequency of occurrence
(< 10th percentile)
<= 2
2 - 4
4 - 6
6 - 10
> 10

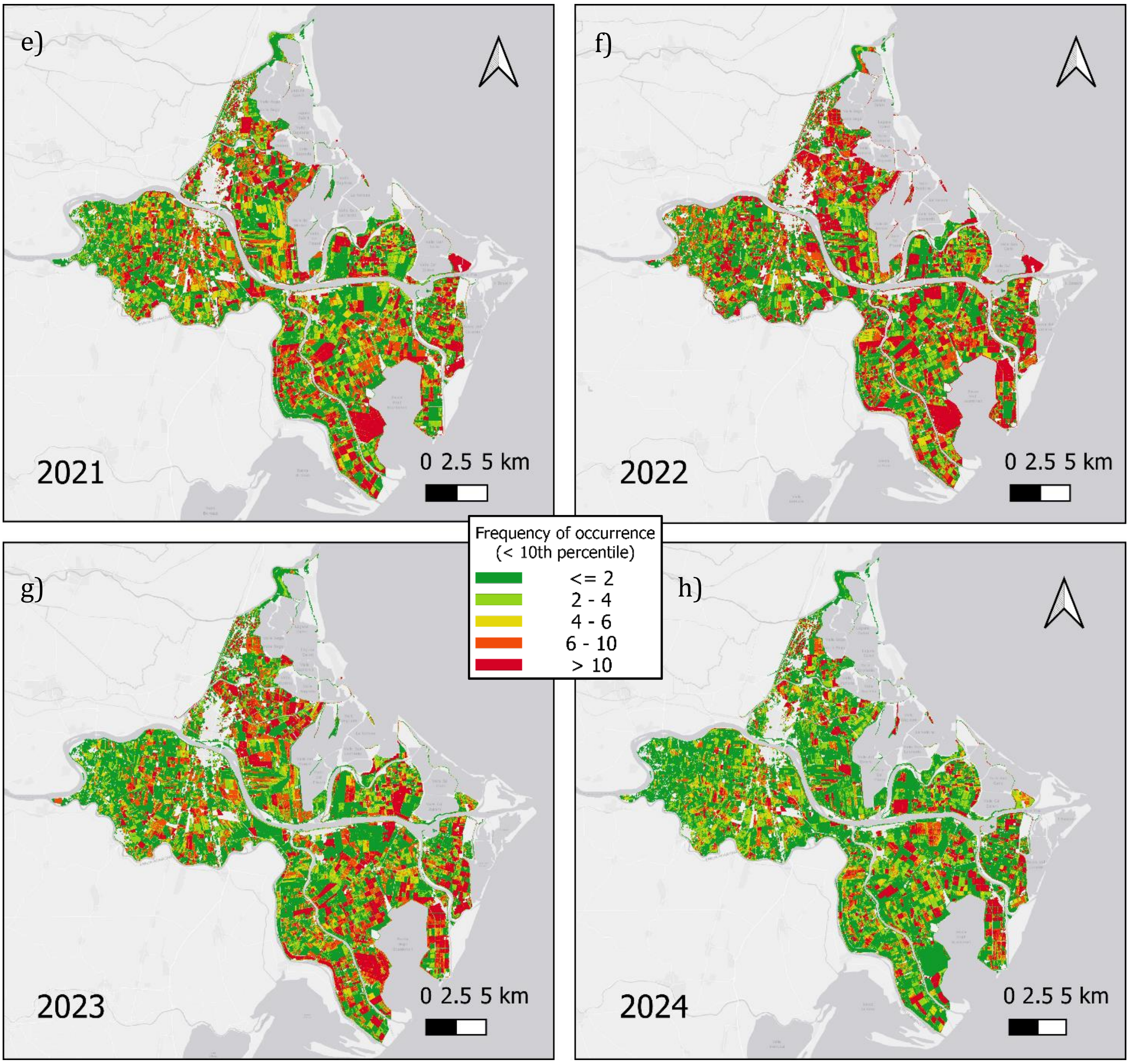
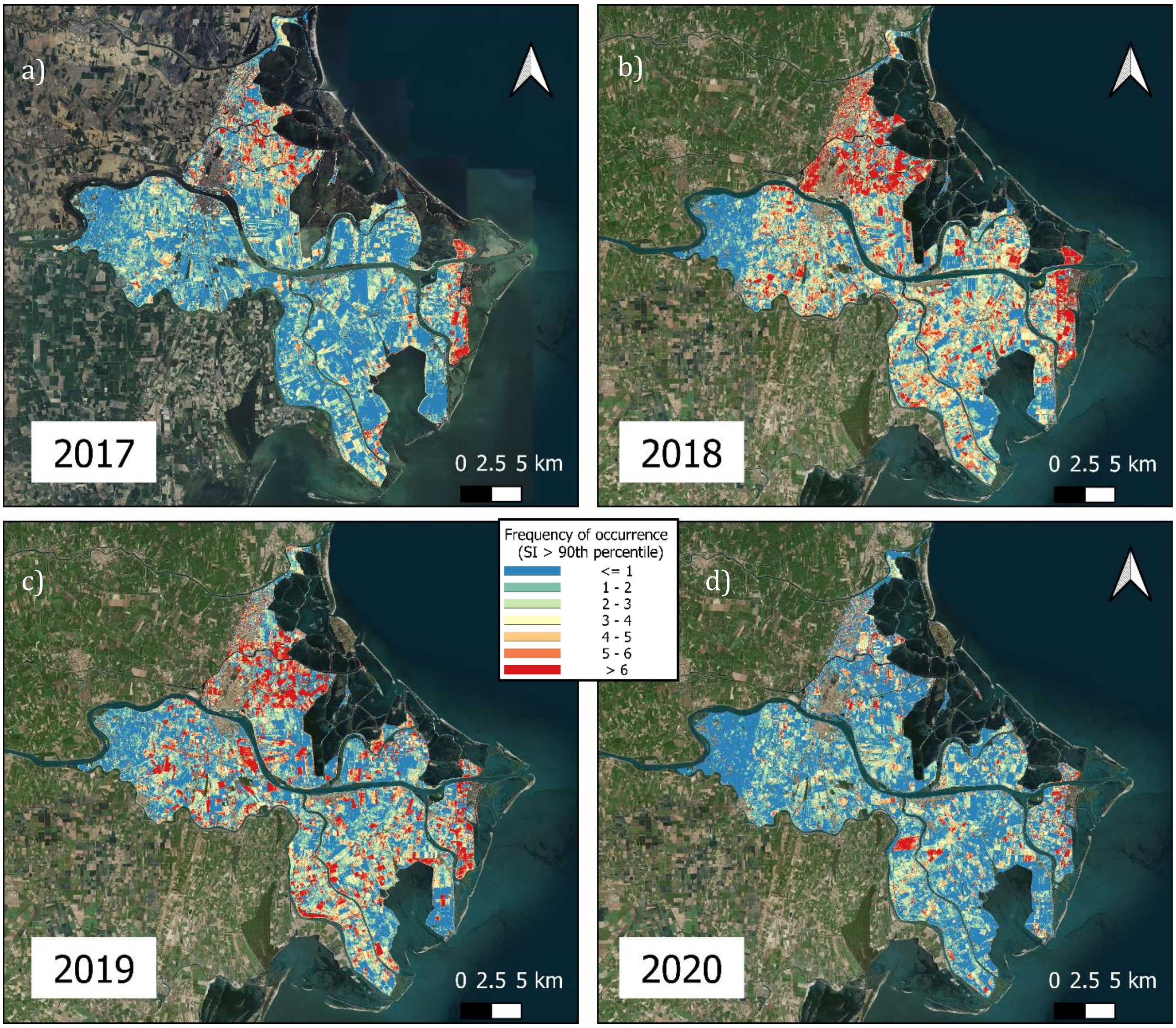


Figure 23 - Low NDVI frequency maps, 2017-2024

The area of cropland which registered low NDVI values most frequently is reported in Table XX for each of the years of the analysis. These are the areas that, in the months of June, July, August, and September of the given year, registered NDVI values below the 10 th percentile more than 10 times (the highest frequency classification, as seen in Figure 22).

Table 5 – Cropland (ha) with high frequency of critical NDVI values

Area of cropland with a high frequency of critical NDVI values (< 10th percentile; >6 times)	
Year	Area (ha)
2017	2,721.19
2018	18,273.34
2019	9,178.98
2020	9,547.95
2021	14,549.08
2022	20,412.38
2023	12,553.46
2024	8,437.09



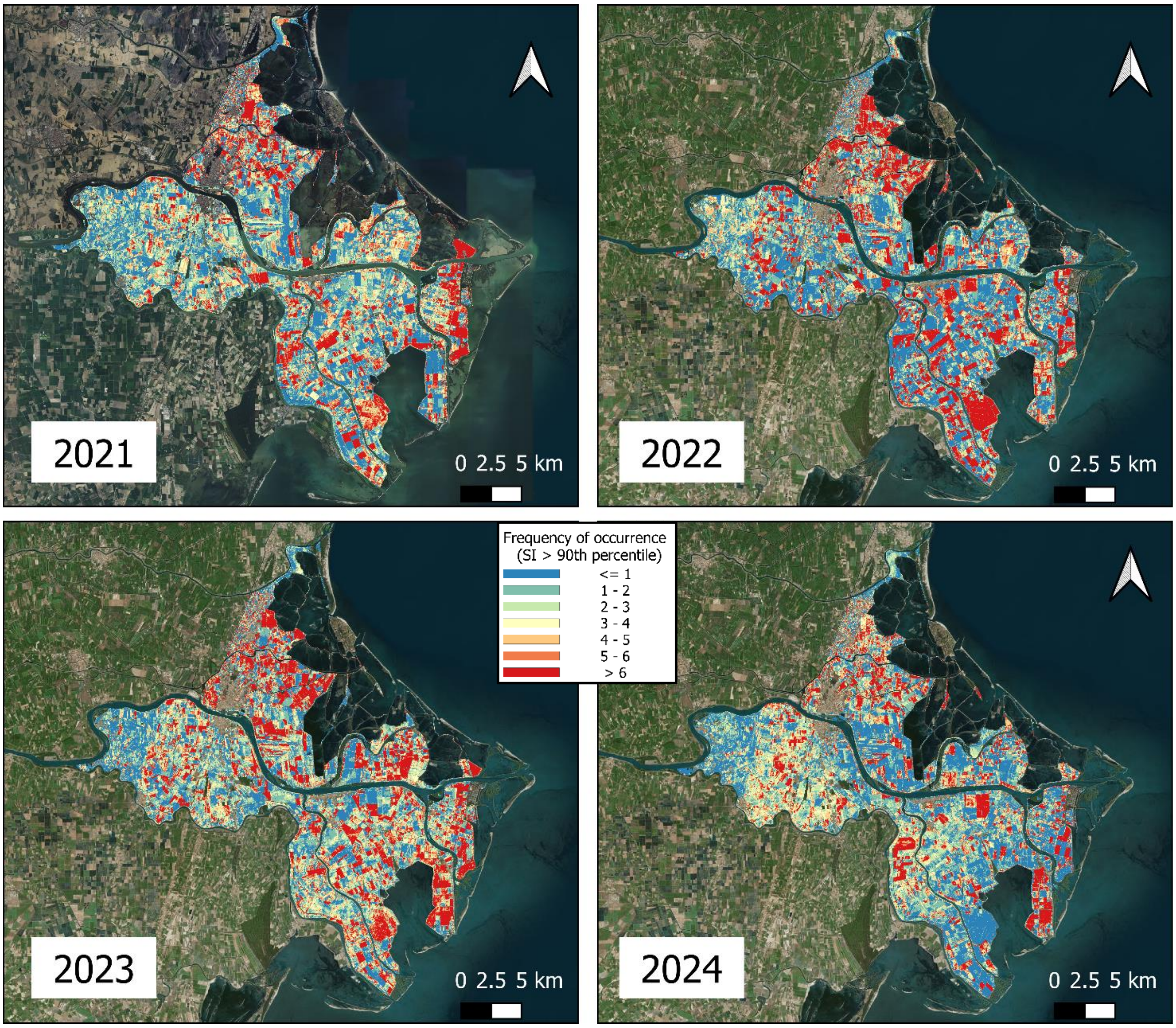


Figure 24 - High SI frequency maps, 2017-2024

The area of cropland which registered high SI values most frequently is reported in Table XX for each of the years of the analysis. These are the areas that, in the months of June, July, August, and September of the given year, registered SI values above the 90th percentile more than 6 times (the highest frequency classification, as seen in Figure 23).

Table 6 – Cropland (ha) with high frequency of critical SI values

Area of cropland with a high frequency of critical SI values (> 90th percentile; >6 times)	
Year	Area (ha)
2017	2,975.43
2018	9,786.09
2019	10,600.72
2020	2,786.42
2021	11,639.69
2022	17,160.99
2023	17,195.82
2024	10,902.01

In order to generate a hotspot map of low critical NDVI values (i.e. below the 10th percentile threshold) for the entire period of analysis (2017-2024), the year-specific maps were summed in QGIS 3.10.10 to produce a new raster. The values in this raster represent the frequency that a pixel's value was, below the 10th percentile across the entire period of 2017 to 2024 in the months of the analysis (Figure 24). This cumulative low NDVI frequency map provides a compelling spatial analysis of which areas frequently experiencing low crop vigour, and the hotspots are evident. The same procedure was followed to produce a cumulative high SI frequency map (Figure 25). This map also revealed clear hotspots where there are frequently critical levels (SI > 90th percentile) of soil salinization in the upper layers of the soil.

As can be seen in Figure 24, there are three evident low NDVI hotspots—in the northern, southeastern, and southernmost regions of the study area. This indicates that, from 2017 to 2024, these were cropland areas whose vegetation was frequently demonstrating low vigour.

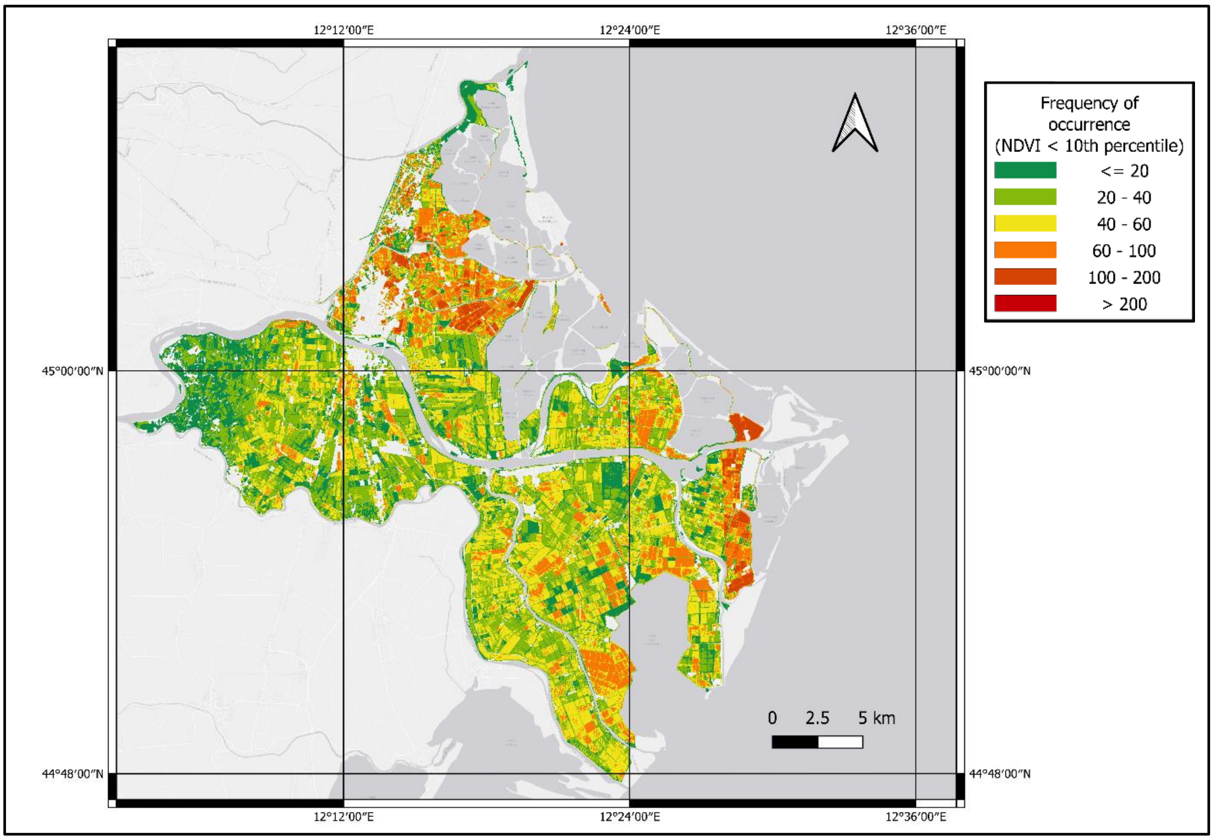


Figure 25 - Cumulative Frequency of Low NDVI values map, 2017-2024

The histogram (Graph 3) for the Cumulative Frequency of Low NDVI values map shows a positively skewed distribution of the values in the study area. The minimum value is 0, the maximum value is 210, the mean value is 41.97, and the standard deviation is 23.96. Thus, on average, in each 10^2 m area of the study area, the NDVI value calculated from the satellite imagery of the growing vegetation was below the 10^{th} percentile threshold approximately 40 times between 2017 and 2024. Given the distribution of the histogram, it can also be said that most areas in the study area registered critical NDVI values (critical being defined as below the 10^{th} percentile) between 18 and 66 times in the period of 2017-2024. The right tail of the histogram does indicate cropland, although representing a small percentage of the study area, which very frequently had crops with impaired growth from 2017-2024. In the following section these hotspots will be considered in closer detail and they will be further discussed in the Discussion of Results chapter of this paper.

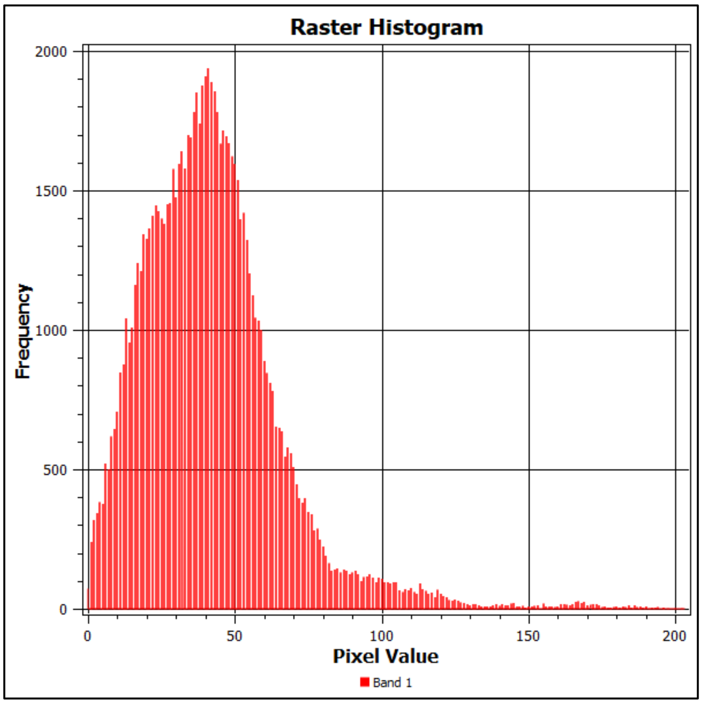


Figure 26 - Histogram of raster values of Cumulative Frequency of Low NDVI values, 2017-2024

As can be seen in Figure 25, there are two apparent high SI hotspots—in the northern and southeastern portions of the study area. This indicates that, from 2017 to 2024, these were active cropland areas with high levels of salinity in the upper layers of the soil profile. These hotspots will be considered together with the low NDVI hotspots in the following section.

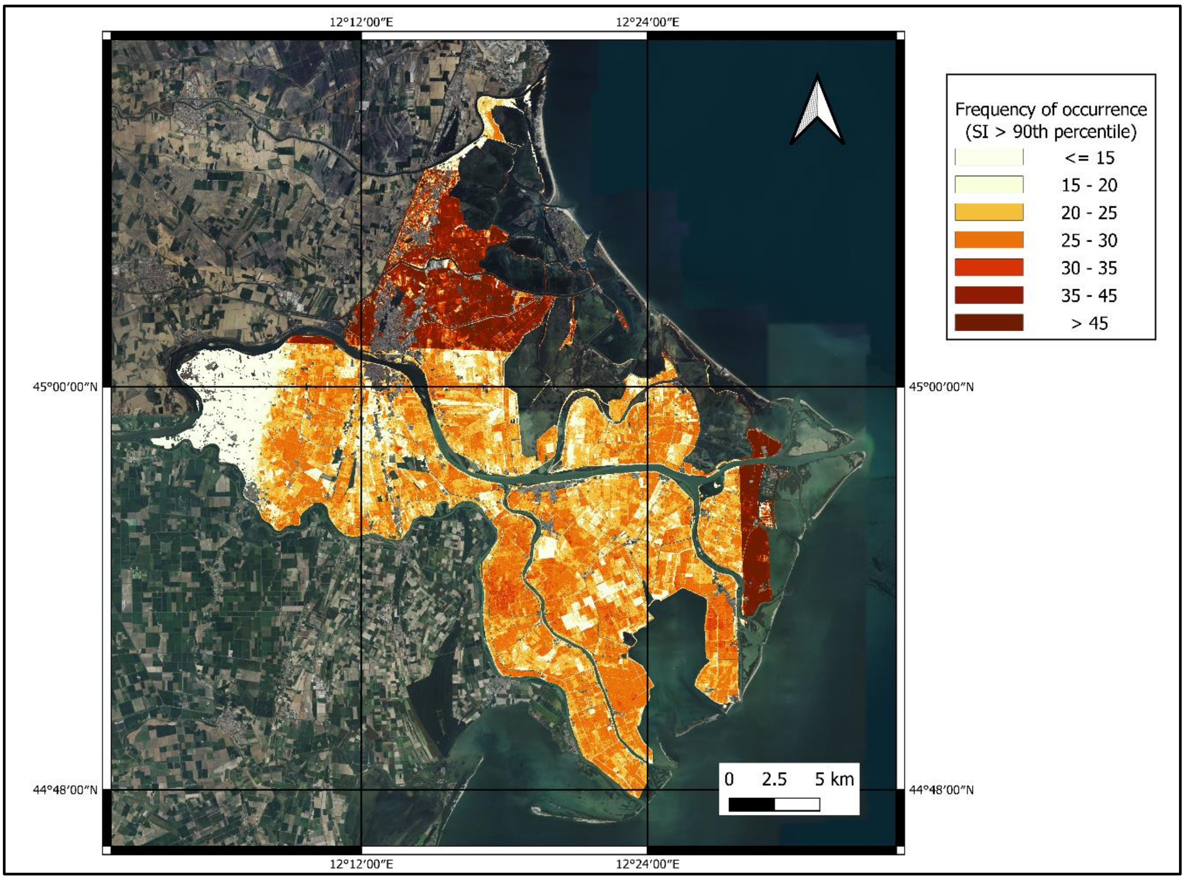


Figure 27 - Cumulative Frequency of High SI values map, 2017-2024

The histogram (Graph 4) for the Cumulative Frequency of High SI values map shows a positively skewed asymmetric bimodal distribution of the values in the study area. The minimum value is 0, the maximum value is 281, the mean value is 26.46, and the standard deviation is 10.85. Thus, on average, in each 10^2 m area of the study area, the SI value calculated from the satellite imagery of the growing vegetation exceeded the 90^{th} percentile threshold approximately 26 times between 2017 and 2024. The values are not widely dispersed and the distribution shows that most areas in the study area registered high SI values around the 26 times in the period of 2017-2024; although a portion registered high SI values more frequently, around 45 times in the 2017-2024 period. Very few pixels had values above 60, meaning that a very small number of 10 m squared areas in the study area registered SI values above the 90^{th} percentile threshold more than 60 times in the period of analysis. In the following section these hotspots will be considered in closer detail and they will be further discussed in the Discussion of Results chapter of this paper.

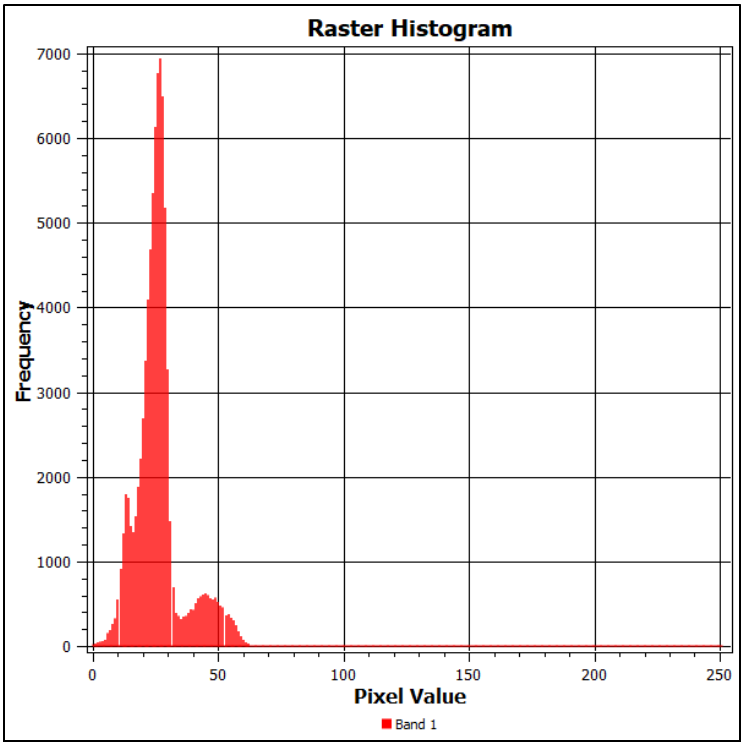
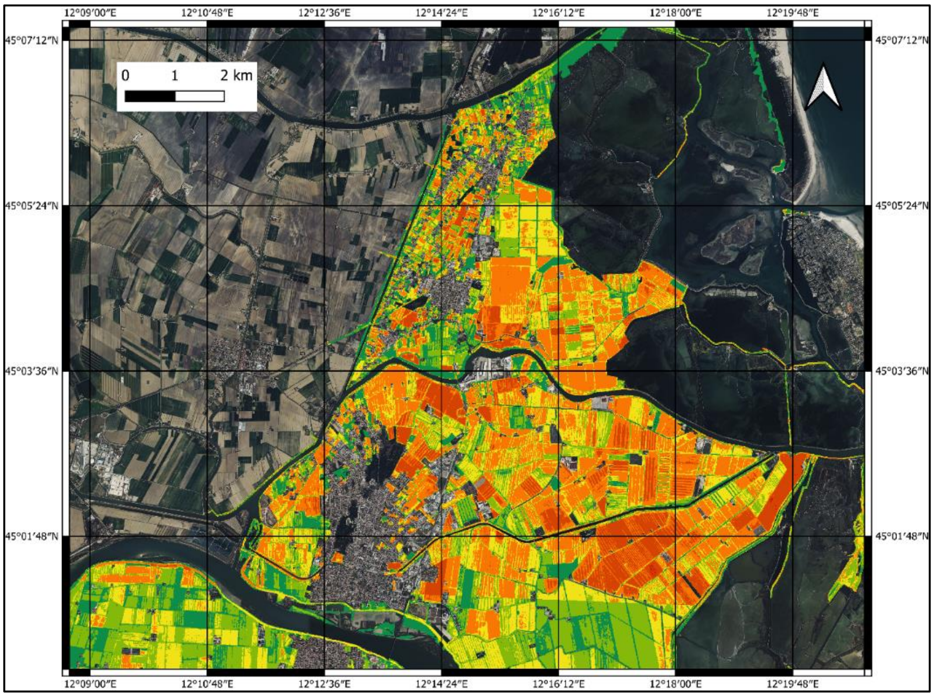


Figure 28 - Histogram of raster values of Cumulative Frequency of High SI values map, 2017-2024

4.2.3. Analysis of frequency and severity

As indicated in the previous section, 3 low NDVI hotspots (Figure 26, 27, and 28) were identified from the Cumulative Frequency of Low NDVI values map and 2 high SI hotspots (Figure 29 and Figure 30) were identified from the Cumulative Frequency of High SI values map. Figure 26 shows Hotspot 1, located in the northernmost region of the study area. Figure 27 shows Hotspot 2, located in southeast portion of the study area. Figure 28 shows Hotspot 3 located in the southernmost portion of the study area. There is evidence of both Hotspot 2 and Hotspot 3 in the low NDVI frequency maps of 2000, 2002, and 2005 derived from the Landsat satellite imagery, as indicated in section 4.2.1. Figures 29 and 30 show Hotspots 4 and 5, respectively, based on frequency of occurrence of high SI values. Hotspot 4 is located in the northern region of the study area. Hotspot 5 is located in the southeastern portion of the study area. There are sharp demarcations of Hotspots 2, 4, and 5, which are not only a result of these areas frequently having low NDVI values/high soil salinity levels, but also suggest an edge artifact, resulting from the satellite tiles covering the study area.



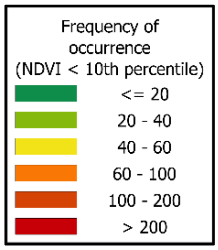


Figure 29 - Hotspot 1, based on high frequency of low NDVI values (< 10th percentile)

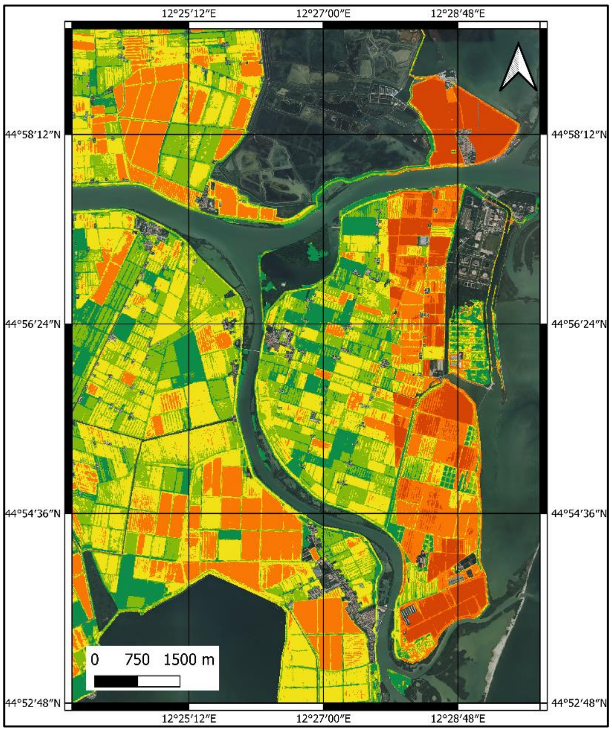


Figure 31 - Hotspot 2, based on high frequency of low NDVI values (< 10th percentile)

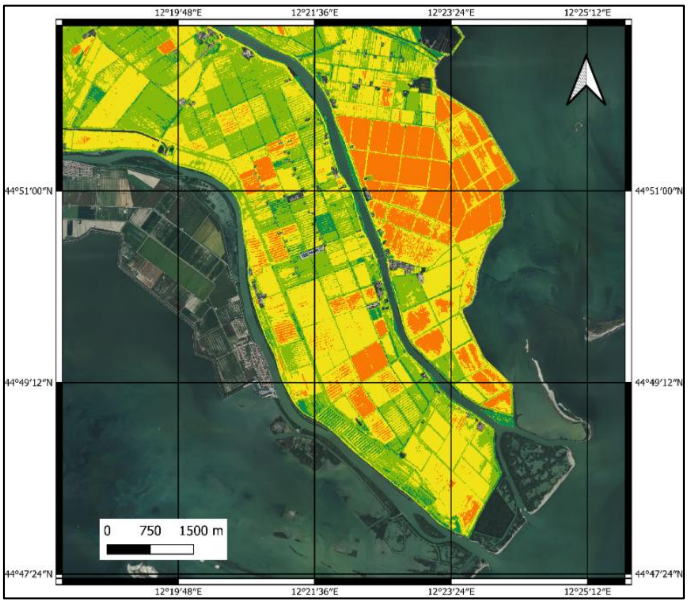


Figure 30 - Hotspot 3, based on high frequency of low NDVI values (< 10th percentile)

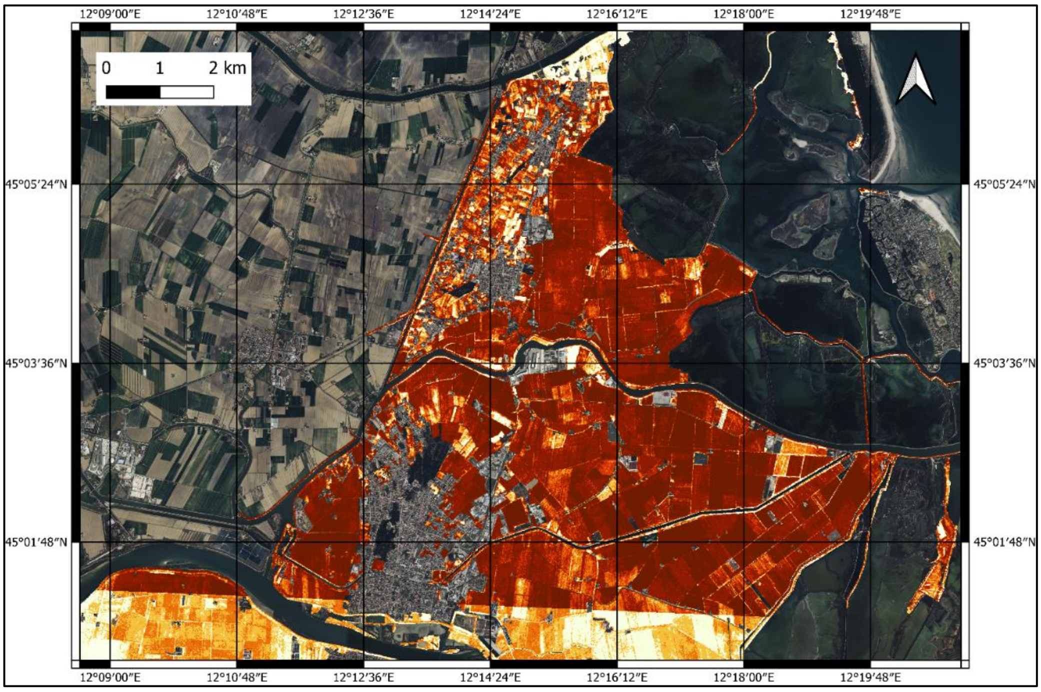


Figure 32 - Hotspot 4, based on high frequency of high SI values (> 90th percentile)

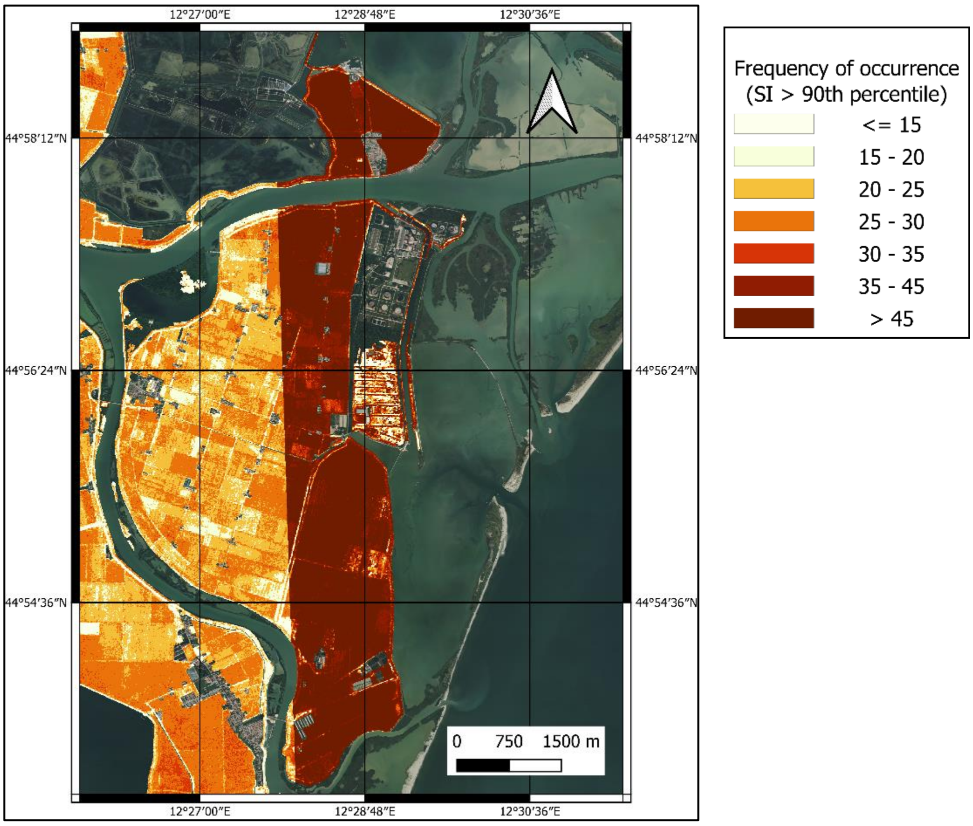


Figure 33 - Hotspot 5, based on high frequency of high SI values (> 90th percentile)

There is a clear overlap of Hotspots 1 and 4, both occupying the northern portion of the study area. There is also evident overlap of Hotspots 2 and 5, both located in the southeastern potion of the study area. The significance of these findings and their utility in solution generation will be discussed in the following sections of this paper.

5. Discussion of results

The value of the results from this transdisciplinary analysis is not only in contributing to the ability to measure and describe the phenomenon of saltwater intrusion on active cropland, but also to use these data to implement effective solutions. This is again why the farmers' personal accounts and demographics are particularly important to consider together with the results from the remote sensing data.

5.1. Sustainability in agri-food systems

This paper takes the position that saltwater intrusion in the Po River Delta will be best addressed when a sustainability lens is applied both in evaluating and solving the problem. Firstly, in any assessment of the sustainability of a system or proposed solution it is important to clearly state the definition of sustainability. One of the most widely recognized and cited definitions came forth at the United Nations Brundtland Commission in 1987. It states sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (IISD, n.d.). Sustainability is further divided into subcategories, most commonly the following three pillars: environmental, economic, and social (UN, 2012). Therefore, a sound analysis of sustainability must consider all three areas of impact. However, in sustainability discourse too often an unbalanced approach is taken with unequal attention given to the environmental pillar; to the point that in many contexts environmental protections and ameliorations have become almost synonymous with "sustainability". While, in reality, sustainability is more synonymous with resiliency–the ability to adapt and return to baseline conditions in the face of adversities. Critical resources for the agri-food system are not only natural resources, but also human resources. When a system does not adequately take into consideration and safeguard the economic and social pillars of sustainability, and the result is abandonment of farms (Subedi et al., 2022; JRC 2018), one cannot consider this a sustainable system in its full and complete meaning.

Thus, especially in this time of transition, the so-named Anthropocene in which we have a heightened awareness of our influence on our environments, and in which there are increasingly frequent extreme weather events as a result of climate change, sustainability is often about meeting people where they are at. For this reason, transdisciplinary approaches and identifying early adopters, also sometimes known as "lighthouse" farms in the agricultural sector, are important pathways to utilize. They are embedded within communities and promote peer-to-peer learning and network building, making them more likely to address all three pillars of sustainability. The following sections of this paper will consider how to utilize such pathways informed by the findings of these analyses.

5.2. Sustainable solutions for saltwater intrusion

Given the devastating impacts of salinization on agriculture, various solutions have been proposed for prevention, remediation, and adaptation. These include constructing natural barriers, restoring and maintaining wetlands, using microbial solutions, increasing water storage capacities, and converting to more salt-resistant cultivars (Tarolli et al., 2024). There have also been a number of national and international conventions and agreements relating to the management of coastal areas, including The Ramsar Convention on Wetlands of International Importance, The Jakarta Mandate, and the Protocol on Integrated Coastal Zone Management (ICZM) in the Mediterranean. These high-level initiatives can serve as important guides, but in order to know which of these solutions is best suited to a local context, quantitative and qualitative data should be used in tandem. For this reason, this paper gives consideration both to the remote sensing data as well as personal accounts of local stakeholders.

Solutions which aim to mitigate the impact of saltwater intrusion on coastal agriculture can be broadly categorized based on which aspect of this problem they aim to address: solutions addressing saline water resources and solutions addressing salt-affected soils.

Solutions focused on saline water resources are in effect dealing with a problem of water availability. Thus, this dimension of solution generation can be further divided into two subcategories: solutions for water quality and solutions for water quantity. Solutions addressing water quality aim to protect or improve water quality or supplement crops' defence mechanisms. Physical barriers can be installed in waterways to slow the rate of saltwater intrusion and protect a greater quantity of waters' quality. The land reclamation authority in the Po River Delta implemented such a barrier in the branch of the Po river, Po di Gnocca, in 1987 (Consorzio, 2021). The mobile salt barrier was an effective measure for many years, and others were built following, but in recent years as the discharge rate of the river has reached unprecedented lows, the mechanical design of the barrier is no longer sufficient under these new conditions (Consorzio, 2021). For this reason, projects have been recently approved for the construction of new barriers that are more adapted to the changing river conditions seen with climate change (Consorzio, 2018).

Figure 34 - Left: mobile salt barrier removed for maintenance; Right view of mobile salt barrier in the Po River

Natural coastal habitats act as natural buffers regulating the movement of saltwater inland and thus their restoration and maintenance is an important strategy to protect inland water quality. Choosing to cultivate halophytic crops offers greater protection of yields in the case of contaminated groundwater by saltwater intrusion or may permit farmers to maintain irrigation schedules and irrigate with brackish waters (Petronia et al., 2011). This can be especially important in drought conditions. Desalinisation and chemical treatments represent a remediation solution. But for large scale agriculture, cost and energy consumption are significant barriers to adopting these strategies and make them less sustainable options compared to other proposed solutions (Rosentreter et al., 2024).

When water quality has been compromised there is a reduction in the quantity of available fresh water, and this often leads to shortages. Thus, solutions addressing this aspect of the problem involve mechanisms which reduce demand or increase the system's resiliency in these periods of water scarcity. Drought tolerant cultivars have a reduced demand for water. Leaving crop residues on the soil surface and mulching are two examples of practices which decrease soil water loss via evaporation, thereby decreasing water demand (Ramos et al., 2024; Currie et al., 2009). Cover crops can also be used to support a good soil structure and thriving microbial communities and along with other practices like low or no till, contribute to a soil structure with a high level of water holding capacity, which reduces demand and increases the system's resiliency (Tarolli et al., 2024). Water storage solutions can also increase a system's resiliency, providing a potentially much-needed supplemental source of freshwater in times of shortage.

In the case that soil is salt affected, an integrated soil reclamation program (ISRP) should be adopted. This is a sustainable agriculture approach which makes use of a number of different strategies and aims to resolve the issue in the short and long term. It takes into consideration the willingness of stakeholders and the available resources. This integrated approach employs physical, chemical, hydrological, and biological solutions (Zaman et al., 2018). The physical mechanisms include levelling, subsoiling, sanding, scraping, and adopting specific tillage practices (Zaman et al., 2018). The intention of levelling is to prep the soil for leaching of the salts. A well-levelled field using a laser land level distributes the water applied for the leaching process in an even manner and results in more homogenous results. Subsoiling involves deep ploughing and deep ripping and is beneficial in the case of sodic soils to remediate the soil permeability. Sanding is a practice typically done on clay soils and is meant to improve the texture and, like subsoiling, improve permeability. The suitability of this solution depends on the availability of sand to carry out this process. Scraping involves manually or mechanically removing any accumulated salts off the top layer of the soil. Adopting tillage practices which alter the soil surface and promote low saline zones on the field is also an effective measure. In these low saline zones crops can be seeded, and in conjunction with specific irrigation practices, can protect germination in a salt-affected soil (Zaman et al., 2018).

Chemical amendments are commonly used for sodic or saline-sodic soils to improve the soil's structure and leach excessive salts out of the root zone (Zaman et al., 2018). These include applications such as lime (CaO), sulphate mineral gypsum ($CaSO_4 \cdot 2H_2O$), acids such as hydrochloric acid, and elemental sulfur, (Zaman et al., 2018). Practices which increase soil organic carbon (SOC) in soils are also effective remediation measures that can promote resiliency in future drought conditions (a condition, as previously discussed, that is closely related to saltwater intrusion in the study area). Xue et al. studied the contribution of various factors to the severe agricultural drought event that occurred in the Po River Delta in 2022 and found that higher SOC levels result in better drought mitigation and that the contribution of soil properties to drought mitigation can be up to 28.3% (2024).

Hydrological solutions to salt-affected soils have the goal of improving water quality or displacing saline waters. The latter is done with leaching saline waters out of the root zone and flushing waters on the soil surface (Zaman et al., 2018). On irrigated lands, depending on the type of irrigation practiced, often these strategies can utilize the existing infrastructure to carry out these processes.

Modifying or constructing new drainage systems is a more intensive solution which can also be used for displacing saline waters from agricultural fields. Other hydrological solutions are related to water management and include smart irrigation and water storages. Smart irrigation can improve water use efficiency, although it is worth noting that affordability and a lack of user-friendly designs are current barriers to wide adoption of these technologies (Bwambale et al., 2022; Zeeshan et al., 2023). Water storage solutions can be an important mitigation strategy when there is saltwater intrusion and there is a reduction in the availability of freshwater. Rainwater harvesting facilities can be an effective method to increase water storage capacities. These facilities can be implemented on different scales—micro or macro storage—with the former being adapted to ensuring greater water security on an individual farm scale, and the latter being suitable for increasing protections on a territorial scale (Tarolli et al., 2024).

A final category of solutions for salt-affected soils includes biological methods. The primary strategies are the addition of organic matter to improve soil health and structure, and the cultivation of salt tolerant crops, the latter which was discussed above (Zaman et al., 2018).

An additional solution should be mentioned which is related to knowledge and alerts. Weng et al. developed an early warning framework for saltwater intrusion in the Pearl River Delta (2023). A frequently made request from farmers in the PHITO focus groups was for more timely and actionable information about saltwater intrusion. As was discussed in the introduction of this paper, saltwater intrusion dynamics are complex and not easily described, but if a real-time or near-real time monitoring and alert system could be developed for the Po River Delta, it would likely have a high adoption rate amongst stakeholders and could prove to be a very valuable tool in decision making and mitigation strategies.

5.3. General use of hotspot map

The hotspot maps' primary uses are to a) contribute to the evidence of the impact of saltwater intrusion on agriculture in the Po River Delta and b) to assist in prioritization of resources and the development of adaptation strategies. Although hotspots were not very evident in year-specific, low median NDVI maps in which there was low spatial variability, patterns were present in years with less confounding variables and the hotspot maps produced from the high resolution, near-real time data clearly indicate croplands more frequently and severely impacted by saltwater intrusion compared to others. Thus, different solutions should be applied to these different areas in order to efficiently use resources. A differentiated approach, in which a territory is separated into smaller management zones, also encourages testing of experimental techniques since the risk is not applied to such large land areas.

As was seen in the Results section of this paper, 5 hotspots were identified between the Cumulative Frequency of Low NDVI values map and the Cumulative Frequency of High SI values map. Hotspots 1 and 4 shared a high degree of overlap, as did Hotspots 2 and 5, so for management purposes the hotspots of interest can be considered in 3 geographical zones: Zone A (Hotspots 1 and 4) in the northern part of the study area; Zone B (Hotspots 2 and 5) in the southeastern edge of the study area along the Adriatic sea; and Zone C (Hotspot 3) in the southernmost area of the study area. Comparing these hotspots to the territorial units of the land reclamation authority we can also place these zones into a relevant technical and organizational context. Figure 32 is a side-by-side comparison of the two cumulative frequency maps (SI and NDVI) and a map of the land reclamation authority's territorial units. Zone A exists within the Rosolina (seen in purple in map 32 a)) and Porto Viro (seen in light blue in map 32 a)) territorial units. Zone B and Zone C both exist within the Porto Tolle territorial unit (seen in yellow in map 32 a)).

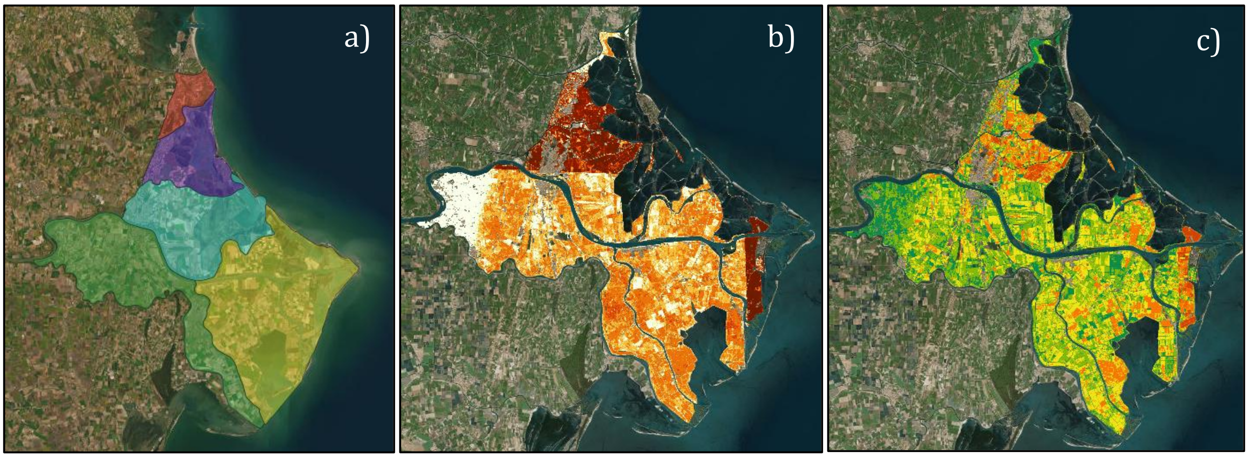


Figure 35 - a) Map of the land reclamation's territorial units (Consorzio.e, n.d.); b) Cumulative Frequency of High SI values map, 2017-2024; c) Cumulative Frequency of Low NDVI values map, 2017-2024

5.4. Indications specific to each hotspot

Based on the remote sensing data analysis of this paper, Zone A, located in the northern part of the study area can be characterized as a zone which frequently had active cropland with low vigour (low being relative to the study area and defined as below the 10th percentile of NDVI values for the period of analysis) and which frequently had high levels of soil salinity (high being relative to the study area and defined as above the 90th percentile of SI values for the period of analysis). Given the local conditions described in this paper and the period of analysis covering the months in which there is the greatest risk of saltwater intrusion in the territory, these findings suggest that saltwater intrusion is one of the main drivers behind these values. Zone B, in the southeastern edge of the study area, can also be characterized as a zone which frequently had active cropland with low vigour and high levels of soil salinity. Agricultural production in this zone is therefore also likely being impacted from saltwater intrusion. Zone C was identified from Hotspot 3, which was determined from the Cumulative Frequency of Low NDVI values map. Saltwater intrusion may also be a driving factor in this case, but without the same pattern emerging from the SI data, other factors may be confounding this influence. As noted by Tarolli & Ghirardelli (2023), water scarcity and high temperatures also induce plant stress and therefore can also be the cause of low NDVI values.

Even for Zones A and B, it cannot be said with certainty the exact mechanisms that link saltwater intrusion to the observed negatively impacted crop growth. A limitation to this study is the lack of in-field measurements to validate the spatial distribution of spectral indices. But it is worth noting, that even with in-field measurements and laboratory experiments, the methods for describing with precision these mechanisms are limited (Werner et al., 2013). Saltwater intrusion can contribute to impaired crop growth in a number of ways, including the interruption of irrigation schedules, irrigation with brackish waters, lateral seepage, and capillary rise. Montanari et al., however found that reduced river flows are the primary driving factor in hydrological droughts in the Po River Delta and that this is part of a long-term trend (2023). They also determined that a reduction in and changes to snowmelt, increasing evaporation due to climate change, and increased demands for water are the main factors which underpin this downward trend in river discharge (Montanari et al., 2023).

Another limitation of this study is that there is landscape heterogeneity which is not accounted for in the remote sensing data. Soil types and irrigation infrastructure may be largely homogenous within each of the identified zones, but heterogeneity of environmental factors such as soil moisture levels and microbial communities, as well as in the management practices of agricultural holdings, including the crop varieties grown, are certainly present. This was seen in the findings from the PHITO project. Taking this into consideration, these zones, identified from remote sensing data, will now be discussed with the findings from farmers' personal accounts.

5.5. Incorporating farmers' personal accounts into research and support systems

The findings from the first round of the user needs assessment of the PHITO project are useful for the insights into the practices of the stakeholders in the region. They not only corroborate the issues explained in the scientific literature but highlight potential solutions and barriers to solution implementation. The participatory methodology utilized is what makes these findings valuable—they are contextualized. It is also worthwhile to note that the findings from the farmer and stakeholders' personal accounts demonstrate their high-level of awareness and ability to describe the issue of saltwater intrusion and that they are also adept at solution generation. This is not the first case of stakeholders and community members proving to have a high awareness of a problem and proving to be valuable source of knowledge. Returning to the history of this territory, it was farmers who sounded the alarm bells about the devastating impacts that methane extraction was having on the lands of the territory; that water availability was being jeopardized and that subsidence was occurring at unprecedented rates. It took extreme events, flooding and the collapse of bridges, and unfortunately the loss of lives for the political and scientific communities to properly address and provide resources to acknowledge and solve the problem. So, while remote sensing and in-field measurements are important tools that can illuminate historical trends in a quantitative way, make quantitative predictions of the future, and provide high levels of precision, the stakeholders who engage with and live amongst the problem on a daily basis are a resource that should not be undervalued.

There should be increased engagement with farmers and other stakeholders within the three identified zones to co-define priorities and develop a strategy for the short and long term. Here more granular data could be collected about farm management practices. Farms in this area could be good candidates to be "lighthouse farms". The findings can be valuable for the participant farm, the surrounding farms in the same zone, and if trends continue, could be implemented in other zones in the future. This brings up another way to think about the zones: temporally in relation to the threat of saltwater intrusion to agriculture. Zones A and B (and potentially C) are likely to be interested in more immediate, potentially more drastic, remediation solutions and mitigation strategies. Whereas other regions of the study area in which there were no identified hotspots can focus on adaptation strategies and be oriented towards longer term solutions. These kinds of considerations are important for public resources which are limited. Of course, all of this is enriched with higher levels of engagement with the stakeholders in these 3 zones.

The scope of the PHITO project was to understand the challenges facing stakeholders on a food system scale. For this reason, as well as to maintain anonymity, the questionnaire did not include a question about the location of farmers' fields. Had the questionnaire been designed with the scope of zone management of hotspots of saltwater intrusion, as has been proposed in this paper, this question would have been necessary to include. Farmer input that can be classified by location can be integrated into a methodological tool (Figure 36) that supports water authorities and policymakers in using a participatory approach to decision-making and resource allocation.

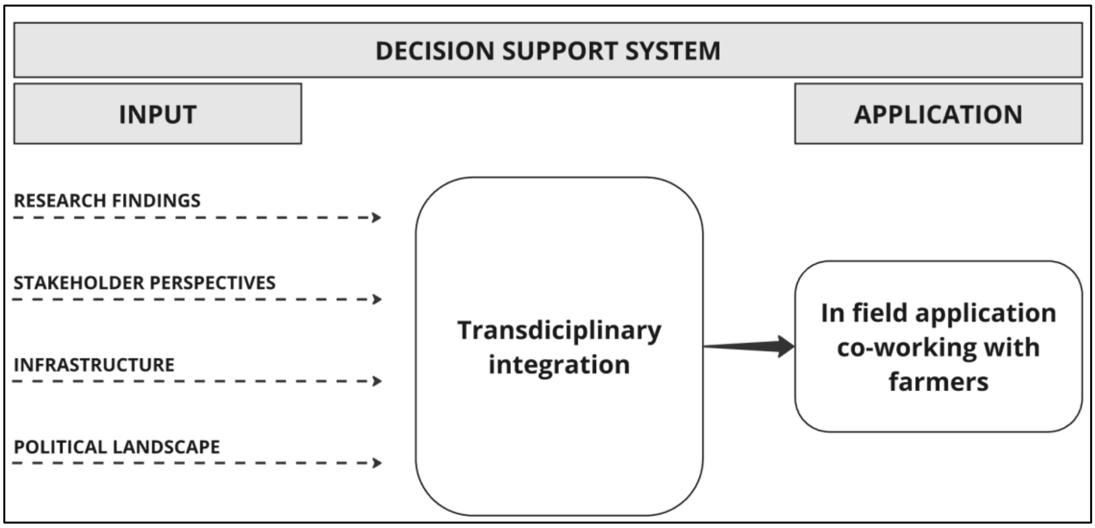


Figure 36 - Methodological tool for water authorities and policymakers

The scope of this tool is to integrate scientific findings, stakeholder perspectives, infrastructure, and political landscape into a decision support system (DSS). For the zone management of agricultural hotspots of saltwater intrusion in the Po River Delta, the remote sensing data analysis presented in this paper is of course just one example of a scientific finding which could be integrated into this tool. As discussed above, the approach taken in the PHITO project represents a way in which to collect stakeholder perspectives and would be appropriate to integrate into this tool if supplemented with reference to locality. An example of relevant infrastructure inputs are the irrigation system and territorial units corresponding to each zone. The political landscape would include regional, national, and European public funds, such as the European-funded National Recovery and Resilience Plan (NRRP), and the respective decision makers at each of these organizational levels. This methodological tool, together with the solutions discussed in section *5.2. Sustainable solutions for saltwater intrusion*, provide a flexible framework for addressing the threat of saltwater intrusion to agriculture.

6. Conclusion

This paper used remote sensing data and two methods to estimate the impact of saltwater intrusion on active cropland. This specific application to this type of land cover was achieved in two ways – with classification training of a GEE script and with the high resolution, near real-time dataset: The Dynamic World V1 Land Use/Land Cover (LULC). This approach takes into account the dynamic nature of salinity processes, heterogeneity in landscapes, and how plant phenology influences salinity indices and is itself influenced by salinization in different ways. The recommendation of the author is that this approach be used in future studies to better understand these relationships and that additional spectral indices are included in the analyses. That said, Landsat satellite imagery, while having lower resolution, is still a valuable resource for longitudinal analyses, as was done in this paper.

This paper also included a case study, from the European Horizon project PHITO: Platform for Helping small and medium farmers to Incorporate digital Technology for equal Opportunity, which served to provide context for the findings from the remote sensing data and to provide an example of how transdisciplinary approaches can support knowledge acquisition and generation of sustainable solutions. While the data from this portion of the paper cannot be applied on a wider scale, the approach, questions, and model for continuous engagement can be integrated into other transdisciplinary work.

As was evident in the introduction, the lack of a universal definition of coastal agriculture makes it difficult to estimate its value and to fully understand the threats it faces on a global scale. But in the absence of this definition, participatory approaches, such as collecting farmer accounts, and scientific research which is linked not only to a process and a study area, but the larger system that it is a part of are important steps to valorising this unique form of agriculture and the communities linked to it. The hotspot maps, management zones, and methodological tool presented in this paper aim to make this contribution to the agricultural territory of the Po River Delta in the face of the threat of saltwater intrusion.

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Appendix 1. Phito Farmer Questionnaire

Phito Farmer Questionnaire

Welcome! The questionnaire will take approximately 35-45 minutes to complete. Your responses and feedback are greatly appreciated. Thank you for your time!

FARMER PROFILE

Please select country / food system of the farmer

Select one only

- ◯ Albania - Albanian Greenhouse
- ◯ SystemAruba & Bonaire
- ◯ Hungary - Great Hungarian Plain
- ◯ Italy - Alpine Foothills
- ◯ Italy - Delta del Po
- ◯ Portugal - Tras-os-Montes e Alto
- ◯ DouroRomania - Moldavian Plateau
- ◯ Spain - Comunitat Valenciana

Please select the gender of the farmer

Select one only

- ◯ Male
- ◯ Female

Please write the year of birth

____

The educational level of the farmer

Select one only

- ◯ No formal schooling
- ◯ Primary - 1-5th
- ◯ Middle school
- ◯ High school - 6th-10th
- ◯ Higher education - Above 10th class, diploma, graduated
- ◯ Other

How many years of experience do you have in farming?

____

Are you currently digitally receiving any agricultural extension services?

Select one only

◯ Yes

◯ No

LAND ASSETS

What is the total land area of your farm?

in hectares (ha)

____

Which of the following enterprises are present in your farm?

Select one or more

☐ Arable Crops ☐ Horticulture ☐ Vineyards
☐ Permanent Crops Mixed Arable and ☐ Permanent or Horticulture
☐ Grazing Livestock (Cattle, Sheep, Goats, Other) ☐ Monogastric (Pigs/Poultry)
☐ Mixed Livestock (Grazing) Mixed ☐ Farming (Crop-Livestock Integration)
☐ Other

Please specify the enterprise

____

» Farm system

Do you cultivate any of the following crops?

Select one or more

☐ None ☐ ☐ Cereals Potatoes and
☐ sugar beet ☐ ☐
☐ Oilseeds ☐ ☐ Fruit Vegetables
Grapes for wine Olives for oil Other

» Crops in the farm

Do you own any of the following livestock animals?

Select one or more

☐ No animals ☐ ☐ Chickens Ducks
☐ Turkeys ☐ ☐ Rabbits Donkeys
☐ Cows ☐ ☐ Sheep Goats
☐ Pigs Horses ☐

» Animal count

Do you implement any of the following agricultural practices or principles?

Select one or more

- [ ] Crop Rotation
- [ ] Agroforestry
- [ ] Intercropping
- [ ] Cover Cropping
- [ ] Precision Farming
- [ ] Integrated Pest Management (IPM)
- [ ] Organic Farming
- [ ] Conservation Tillage
- [ ] Irrigation
- [ ] Drainage & water logging management
- [ ] Soil moisture conservation
- [ ] Management of landscape features (e.g., hedgerows, flower strips, woodland patches)

Do you use services for farm operations (e.g., a contractor for tillage)?

Select one only

- ○ Yes
- ○ No

What kind of services

Select one or more

- [ ] Machine rental
- [ ] Hired labour
- [ ] Technical advice
- [ ] Soil information
- [ ] Drone or satellite services
- [ ] Other

LABOUR

How many people are currently engaged in agricultural activities on your farm, including family members and hired laborers?

____

During peak seasons, how many additional temporary or seasonal laborers do you employ?

____

For which of the following agricultural activities do you employ labor?

Select one or more

- [ ] Land preparation
- [ ] Plowing
- [ ] Irrigation
- [ ] Planting
- [ ] Fertilizing
- [ ] Weeding
- [ ] Pest control
- [ ] Harvesting
- [ ] Pruning
- [ ] Selling

INPUTS

What type of irrigation do you mainly implement in your farm?

Select one only

- ◯ I do not practice irrigation
- ◯ Drip Irrigation
- ◯ Sprinkler Irrigation
- ◯ Subsurface Drip Irrigation
- ◯ Furrow Irrigation
- ◯ Basin Irrigation
- ◯ Border irrigation
- ◯ Other

Please specify the type of irrigation

____

What is the main water source for irrigation?

Select one only

- ◯ Surface rainwater harvesting
- ◯ Underground rainwater harvestingGroundwater from farm
- ◯ Groundwater outside farm
- ◯ Surface water from farm
- ◯ Surface water outside farm
- ◯ Other

Please specify the source of water

____

What types of seeds do you typically purchase?

Select one or more

- ☐ I reproduce my own seeds
- ☐ Improved Varieties
- ☐ Hybrid Seeds
- ☐ Open-Pollinated Seeds
- ☐ Organic Seeds
- ☐ Conventional Seeds
- ☐ Other

Please specify the seed type

____

Do you use any of the following fertilisers?

Select one or more

- ☐ I do not use any fertiliser
- ☐ Synthetic fertiliser
- ☐ Compost
- ☐ Manure (from farm)
- ☐ Manure (off farm)
- ☐ Biostimulants
- ☐ Other

Please specify the fertiliser type

____

Do you use any of the following crop protection products?

Select one or more

- [ ] I do not use any crop protection input
- [ ] Insecticides
- [ ] Herbicides
- [ ] Fungicides
- [ ] Rodenticides
- [ ] Nematicides
- [ ] Bactericides
- [ ] Acaricides (mite control)
- [ ] Antifungals
- [ ] Biocontrol, pheromone traps
- [ ] Plant Growth Regulators
- [ ] Biopesticides
- [ ] Veterinary products
- [ ] Other

Please specify the crop protection product type

____

COMMERCIALISATION STRATEGIES AND MARKET

What is your primary market?

Select one only

- ( ) Individual consumers
- ( ) Network
- ( ) Restaurants / retailers
- ( ) Cooperatives
- ( ) Food processors
- ( ) Other

How do you sell your products?

Select one or more

- [ ] I only sell through the cooperative
- [ ] Direct sale on the farm
- [ ] Direct sale at farmer markets
- [ ] Direct sale through the internet
- [ ] Direct sale to shops, restaurants, or other without intermediaries
- [ ] Direct sale to local processing facilities
- [ ] Sale to farmer cooperatives
- [ ] Sale to small traders
- [ ] Sale to local markets
- [ ] Sale to national markets
- [ ] Sale to international markets

What is the approximate distance, in kilometers, between your farm and your primary market(s)?

____

DIGITALISATION

Do you or anyone in your household have access to the internet?

Select one only

- ( ) Yes
- ( ) No

Do you have access to the internet on the farm?

Select one only

- Yes
- No

Do you use any of the following devices in your personal life?

Select one or more

- Mobile phone
- Desktop computer
- Laptop computer
- Tablet
- Smartwatch

If you use a mobile phone, what kind of phone is it?

Select one only

- Mobile phone, without internet (not a smartphone)
- Smartphone, Android (Samsung, Google, etc.)
- Smartphone, iPhone
- Other

If other, please specify type of mobile phone:

____

Do you use any of the following applications?

Select one or more

- E-mail (Outlook, Gmail, Yahoo, etc.)
- Maps (Google Maps, Bing Maps, etc.)
- WhatsApp
- Telegram

Do you use social media (e.g. Facebook, Instagram, X) for non-farming related activities?

Select one only

- Yes
- No

Which social media applications?

Select one or more

- [ ] Facebook
- [ ] Instagram
- [ ] X (formerly Twitter)
- [ ] TikTok
- [ ] Other

If other, please specify:

____

Do you use any of the following digital tools?

Select one or more

- [ ] Smart Farming Apps
- [ ] Precision Agriculture Tools
- [ ] Remote Sensing
- [ ] Marketplace
- [ ] Satellite images
- [ ] Weather services
- [ ] Geo information (maps)
- [ ] Advice
- [ ] Data Analytics
- [ ] Smart irrigation tools
- [ ] Business management software (e.g., planning, financial, human resources, etc.)
- [ ] Marketing and sales (e.g., e-commerce)
- [ ] Other

Please specify the tool(s):

____

How extensively have you adopted these digital tools and technologies on your farm?

Select one only

- ○ No Adoption
- ○ Limited Adoption
- ○ Moderate Adoption
- ○ Extensive Adoption
- ○ Full Integration

How satisfied are you with the digital tools/apps you currently use for your agricultural activities?

Select one only

- ○ Very dissatisfied
- ○ Dissatisfied
- ○ Neutral
- ○ Satisfied
- ○ Very satisfied

What are the main difficulties you encounter in using digital tools/apps for your agricultural activities?

Select one or more

- [ ] Internet connectivity (e.g., poor signal in rural areas, unstable connection, etc.)
- [ ] Financial reasons (e.g., high costs of services, difficulty in evaluating return on investment, etc.)
- [ ] Digital skills (e.g., difficulty in using tablets, smartphones, and PCs)
- [ ] Existing tools are not optimized for the needs of my farm (e.g., for my crops, for the company structure, etc.)
- [ ] Difficulty in integration with other data, tools, and/or apps
- [ ] Graphical interface, maps, or charts are difficult to interpret
- [ ] Lack of simple, concise, and direct alert systems (e.g., "it's time to irrigate")
- [ ] I believe that currently digital tools are advantageous only for large agricultural companies, not for small farmers Other
- [ ] (please specify)

Please specify:

____

In your opinion, how can digital tools/apps be more useful?

Select one or more

- [ ] Easy and free access to informational material regarding the use of digital tools (e.g., tutorials in native language, video tutorials, etc.)
- [ ] Easy and free access to training courses
- [ ] Technical support
- [ ] More affordable costs for purchasing tools and apps
- [ ] More affordable costs for purchasing subscription-based app services
- [ ] Simpler user interface
- [ ] Easier-to-understand terminology
- [ ] Specific functionalities for different types of cultivation/farms
- [ ] Ability to customize specific digital tools or apps
- [ ] Other (please specify)

Please specify:

____

What would you like to find in an app to agricultural production in your region? Select one only	1 - Insignificant	2 Not useful	3 - Useful 4 - Very useful **support**	
Guidance on irrigation Select one only	○	○	○	○
Information on pest and disease presence Select one only	○	○	○	○
Monitoring of crop vegetative (health) status Select one only	○	○	○	○

Helpful advice regarding sustainable agricultural practices Select one only	○	○	○	○
Advice on improving yield and quality Select one only	○	○	○	○
Weather forecast Select one only	○	○	○	○
Alert systems for critical weather conditions Select one only	○	○	○	○
Potential future climatic conditions of your region (due to climate change) Select one only	○	○	○	○
Marketplace for selling produce, or buying farm input products Select one only	○	○	○	○
Access to labour services Select one only	○	○	○	○
Access to advisory services Select one only	○	○	○	○
Other (please specify) Select one only	○	○	○	○

Please specify:

How do you rate the usefulness of the following information communication methods in an agriculture app? Select one only	1 - Insignificant	2 - Not useful	3 - Useful	4 - Very useful
Georeferenced maps (e.g., map with color scale to indicate vegetation health) Select one only	○	○	○	○
Text messages (e.g., "Field X is experiencing a decline in crop health") Select one only	○	○	○	○
Graphs (e.g., graph showing crop health data over time) Select one only	○	○	○	○
Tables (e.g., table showing crop health data over time) Select one only	○	○	○	○
Other (please specify) Select one only **Please specify:**	○	○	○	○

In your opinion, what are the most useful spatial data (maps) that an app could show to a farmer? Select one only	1 - Insignificant	2 - Not useful	3 - Useful	4 - Very useful

Natural color satellite images
Select one only

Infrared satellite images
Select one only

Vegetation indices derived from satellite products (e.g., green = good vegetation health; red = poor vegetation health)
Select one only

Soil classification data and characteristics
Select one only

Precipitation meteorological data
Select one only

Temperature meteorological data Select one only

Soil moisture data
Select one only

Topographic data (altitude, slope, sun exposure)
Select one only

Hydrological data
Select one only

Maps of drought stress and heatwave risk
Select one only

Soil erosion risk maps
Select one only

Irrigation support maps
Select one only

Other (please specify)
Select one only

Please specify:

In the past year, how many days of training have you invested in learning and understanding new agricultural technologies?
If less than a day, please indicate with 0.5

In your opinion, what is the level of adoption of new digital agricultural technologies in your region?
Select one only

- Very low
- Low
- Moderate
- High
- Very high

In your opinion, which farming activities do you believe can benefit the most from the integration of technology? Select one only

- ◯ Planting and sowing
- ◯ Irrigation
- ◯ Application of fertilizers, pesticides, and other products
- ◯ Harvesting
- ◯ Storage
- ◯ Other

Please specify the benefit

FACED CHALLENGES

Which of the following do you perceived as the main challenge(s)?

Select one or more

- ☐ Climate events
- ☐ Market access
- ☐ Pest and Disease Outbreaks
- ☐ Financial Constraints
- ☐ Input availability (local goods)
- ☐ Rural Infrastructure
- ☐ Land Tenure Issues
- ☐ Policy and Regulatory Issues
- ☐ Labor Shortages
- ☐ High input prices
- ☐ Low products prices
- ☐ Lack of collaboration among farmers
- ☐ Land degradation / soil fertility decline
- ☐ Pollution
- ☐ Biodiversity decline
- ☐ Other

If other, please specify the perceived challenge:

For which of these challenges are you receiving sufficient advice and services?

Select one or more

- ☐ Climate events
- ☐ Market access
- ☐ Pest and Disease Outbreaks
- ☐ Financial Constraints
- ☐ Input availability (local goods)
- ☐ Rural Infrastructure
- ☐ Land Tenure Issues
- ☐ Policy and Regulatory Issues
- ☐ Labor Shortages
- ☐ High input prices
- ☐ Low products prices
- ☐ Lack of collaboration among farmers
- ☐ Land degradation / soil fertility decline
- ☐ Pollution
- ☐ Biodiversity decline
- ☐ Other

If other, please specify the challenge(s):

How do changing weather patterns and climate variability impact your farming operations?

Select one only

- ◯ Insignificant
- ◯ Minimal
- ◯ Moderate
- ◯ High
- ◯ Severe

What are the consequences of these climate changes for your agricultural activity? Select one only	1 - Insignificant	2 - Not important	3 - Important	4 - Utmost importance
Reduced yields Select one only	○	○	○	○
Difficulty in irrigation Select one only	○	○	○	○
Increased pests and diseases Select one only	○	○	○	○
Structural damage to fields Select one only	○	○	○	○
Need to change crops Select one only	○	○	○	○
Other (please specify) Select one only	○	○	○	○

If other, please specify:

____

Have you observed climate variations in your region?

Select one only

- ○ Yes
- ○ No

How long have you noticed these changes?

Select one only

- ○ More than 10 years
- ○ At least 5-10 years
- ○ Less than 5 years

The following is a list of possible consequences from climate change. How do you rate the importance of each in your region and farm? Select one only	1 - Insignificant	2 - Not important	3 - Important	4 - Utmost importance
Increase in temperatures Select one only	○	○	○	○
Heatwaves Select one only	○	○	○	○
Increase in the frequency of intense precipitation Select one only	○	○	○	○

Increase in precipitation intensity Select one only	○	○	○	○
Drought Select one only	○	○	○	○
Water scarcity in water bodies Select one only	○	○	○	○
Hailstorms Select one only	○	○	○	○
Strong winds Select one only	○	○	○	○
Other (please specify) Select one only	○	○	○	○

If other, please specify:

____

The following is a list of possible damages on agriculture from climate change. How do you rate the importance of each in your region and farmer? Select one only	1 - Insignificant	2 - Not important	3 - Important	4 - Utmost importance
Damages due to heatwaves Select one only	○	○	○	○
Damages due to drought Select one only	○	○	○	○
Damages due to saline intrusion Select one only	○	○	○	○
Soil erosion due to intense precipitation Select one only	○	○	○	○
Landslides and hydrogeological risk Select one only	○	○	○	○
Floods and water stagnation Select one only	○	○	○	○
Damages due to strong winds Select one only	○	○	○	○
Reduction in biodiversity Select one only	○	○	○	○
Other (please specify) Select one only	○	○	○	○

If other, please specify:

____

Have you ever had to implement (or do you think you will have to in the future) climate change mitigation measures?

Select one only

○ Yes

○ No

What strategies do you consider most 1 - Insignificant 2 - Not important 3 - Important 4 - Utmost **important**

to ensure adaptation to importance **climate change in your region?**

Select one only

Choosing varieties more resistant to drought

Select one only

Choosing varieties more resistant to heatwaves

Select one only

Modification of the crop calendar

Select one only

Smart irrigation for maximum efficiency (e.g., drip irrigation)

Select one only

Harvesting and reuse of rainwater through reservoirs

Select one only

Conservation agriculture techniques

Select one only

Integration of trees and crops

Select one only

Improvement of biodiversity

Select one only

Precision farming

Select one only

Monitoring crop health through remote sensing techniques

Select one only

Accurate weather forecasts

Select one only

Acquisition of new skills to adapt to climate change through training courses

Select one only

Sustainable agriculture techniques

Select one only

FARMER OPINION

How satisfied are you with your farming activities overall?

Select one only

- Very Dissatisfied
- Dissatisfied
- Neutral
- Satisfied
- Very Satisfied

Are you affiliated with any associations?

Select one only

- ◯ Yes, at the local scale.
- ◯ Yes, at the territorial scale.
- ◯ Yes, at the regional scale.
- ◯ Yes, at the national scale.
- ◯ Yes, affiliated with associations offering incentives.
- ◯ None of the above.
- ◯ Other

Please specify the association

Appendix 2. GEE script for Landsat 8, median NDVI calculation, 2024

```
// Define the date range for 2024 (June to September)
var startDate = ee.Date.fromYMD(2024, 6, 1);
var endDate = ee.Date.fromYMD(2024, 9, 30);

// Load Landsat 8 Collection 2, Level-2 image collection for June to September
2024
var imageCollection = ee.ImageCollection('LANDSAT/LC08/C02/T1_L2')
  .filterDate(startDate, endDate)
  .filterBounds(roi)
  .filter(ee.Filter.lt('CLOUD_COVER', 10))
  .select(['SR_B2', 'SR_B3', 'SR_B4', 'SR_B5'])  // Blue, Green, Red, NIR
bands for Landsat 8
  .map(function(image) {
    // Apply scaling and offset to reflectance bands
    return image.multiply(0.0000275).add(-0.2)
                .copyProperties(image, ["system:time_start"]);
  });

// Calculate median composite for RGB and NDVI
var medianImage = imageCollection.median();

// Define visualization parameters for Landsat 8 RGB
var visParamsTrue = {bands: ['SR_B4', 'SR_B3', 'SR_B2'], min: 0, max: 0.3,
gamma: 1.1};
Map.addLayer(medianImage, visParamsTrue, "Median Landsat 8 RGB (2024)");
Map.centerObject(roi, 8);

// Classification: Prepare training data from manually defined water,
vegetation, and soil classes
var training = water_v.merge(green_vegetation_v).merge(no_green_vegetation_v);
// Merge your defined classes
var label = 'Class';
var bands = ['SR_B2', 'SR_B3', 'SR_B4', 'SR_B5'];  // Bands for classification

// Sample the median image based on the training polygons
var trainImage = medianImage.select(bands).sampleRegions({
  collection: training,
  properties: [label],
  scale: 30
});

// Split the sample data into training and testing sets
var trainingData = trainImage.randomColumn();
var trainSet = trainingData.filter(ee.Filter.lessThan('random', 0.8));
var testSet = trainingData.filter(ee.Filter.greaterThanOrEquals('random',
0.8));

// Train the classifier and classify the median image
var classifier = ee.Classifier.smileCart().train(trainSet, label, bands);
var classified = medianImage.select(bands).classify(classifier);

// Define a land cover palette and add classification layer to the map
var landcoverPalette = ['#0917ff', '#6fff5e', '#996a23']; // Water,
Vegetation, Bare Soil
Map.addLayer(classified.clip(roi), {palette: landcoverPalette, min: 0, max:
2}, 'Classification (2024)');

// Create a mask for green vegetation (Class 1)
```

```
var landMask = classified.eq(1);
Map.addLayer(landMask, {palette: ['lightgreen']}, 'Land Mask');

// Apply the mask to the classification result
var imgMasked = classified.updateMask(landMask);
Map.addLayer(imgMasked, {palette: ['green']}, 'Image, Land Only');

// Transform the mask to NoData values
var NoData = 0;
var imgMasked_nodata = imgMasked.eq(1).updateMask(imgMasked.neq(NoData));
Map.addLayer(imgMasked_nodata, '', 'Green Masked');

// Clip and export the median RGB image
Export.image.toDrive({
  image: medianImage.select(['SR_B4', 'SR_B3', 'SR_B2']).clip(roi).toUint16(),
  description: 'Median_RGB_Landsat8_2024',
  folder: 'Landsat8_RGB_Median',
  fileFormat: 'GeoTIFF',
  region: roi,
  scale: 30,
  crs: 'EPSG:32632'
});

// Calculate NDVI for the median image
var nir = medianImage.select('SR_B5');  // NIR band for Landsat 8
var red = medianImage.select('SR_B4');  // Red band for Landsat 8
var ndvi = nir.subtract(red).divide(nir.add(red)).rename('NDVI');

// Display NDVI and apply mask to NDVI
var ndviParams = {min: -1, max: 1, palette: ['red', 'white', 'green']};
Map.addLayer(ndvi.clip(roi), ndviParams, 'NDVI (2024)');

// Mask NDVI with the green vegetation mask and clip to study area
var green_NDVI = ndvi.multiply(imgMasked_nodata).clip(studyArea);
Map.addLayer(green_NDVI, {palette: ['green']}, 'Green NDVI');

// Export the median NDVI for the specified time period
Export.image.toDrive({
  image: green_NDVI,
  description: 'Green_NDVI_Landsat8_2024',
  folder: 'Landsat8_NDVI_Median',
  fileFormat: 'GeoTIFF',
  region: roi,
  scale: 30,
  crs: 'EPSG:3002'
});
```

Appendix 3. GEE script for Sentinel-2, SI frequency calculation, 2023

```
// Define the baseline period (2015-2024) and target period (2023) dates
var baselineStartDate = '2015-06-01';
var baselineEndDate = '2024-09-30';
var targetStartDate = '2023-06-01';
var targetEndDate = '2023-09-30';

// Load Sentinel-2 dataset and filter by baseline period and study area
var s2Baseline = ee.ImageCollection("COPERNICUS/S2_SR_HARMONIZED")
  .filterDate(baselineStartDate, baselineEndDate)
  .filterBounds(studyArea)
  .filter(ee.Filter.lt('CLOUDY_PIXEL_PERCENTAGE', 10))
  .select('B8', 'B4', 'B3'); // Select bands for SI4 calculation (B8, B4, B3)

// Load Sentinel-2 dataset for the target period (2024)
var s2Target = ee.ImageCollection("COPERNICUS/S2_SR_HARMONIZED")
  .filterDate(targetStartDate, targetEndDate)
  .filterBounds(studyArea)
  .filter(ee.Filter.lt('CLOUDY_PIXEL_PERCENTAGE', 10))
  .select('B8', 'B4', 'B3'); // Select bands for SI4 calculation (B8, B4, B3)

// Function to calculate SI4
function calculateSI4(image) {
  var red = image.select('B4');
  var NIR = image.select('B8');
  var green = image.select('B3');

  // SI4 formula: (red * NIR) / green
  var si4 = red.multiply(NIR).divide(green).rename('SI4');

  return si4.updateMask(si4); // Mask non-SI4 pixels
}

// Apply SI4 calculation to each image in baseline and target collections
var si4BaselineCollection = s2Baseline.map(calculateSI4);
var si4TargetCollection = s2Target.map(calculateSI4);

// Calculate the 90th percentile SI4 threshold for the baseline period (2015-
2024)
```

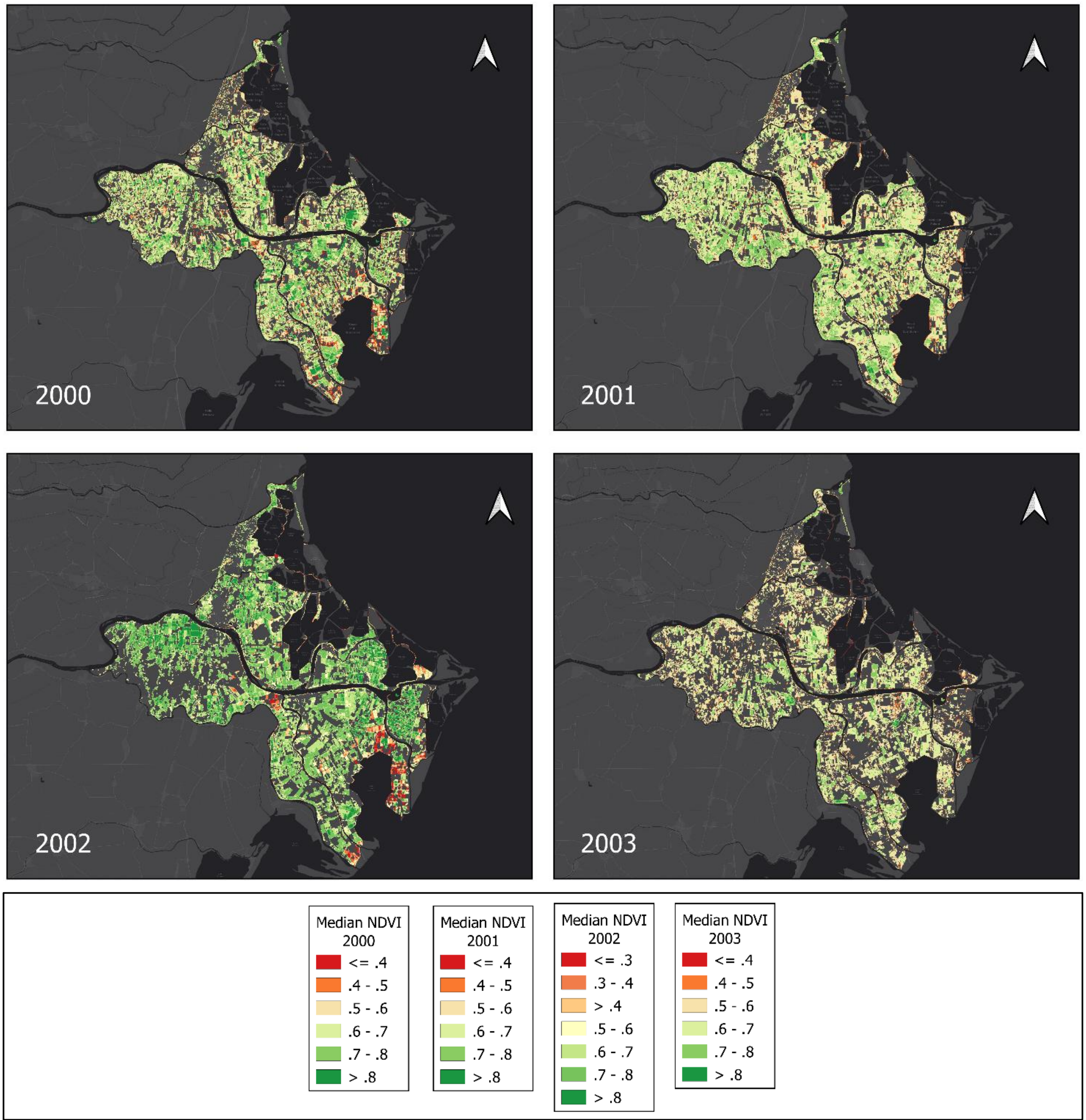
```
var si4Baseline90thPercentile =
si4BaselineCollection.reduce(ee.Reducer.percentile([90]));

// Create a function to identify pixels where SI4 in 2024 is greater than the
90th percentile baseline
function countExceedances(image) {
  var exceedanceMask = image.gt(si4Baseline90thPercentile); // SI4 > 90th
percentile baseline
  return exceedanceMask.rename('Exceedance');
}

// Apply the exceedance mask to each image in the target collection
var exceedanceCollection = si4TargetCollection.map(countExceedances);

// Sum the exceedance masks to calculate the frequency distribution of high
SI4 values for 2024
var exceedanceFrequency = exceedanceCollection.sum().clip(studyArea);

// Display results on the map
Map.addLayer(si4Baseline90thPercentile, {min: 0, max: 1, palette: ['blue',
'green']}, 'Baseline 90th Percentile SI4');
Map.addLayer(exceedanceFrequency, {min: 0, max:
exceedanceCollection.size().getInfo(), palette: ['white', 'red']}, '2024
Frequency of Low SI4 Exceedance');
Map.centerObject(studyArea);

var exceedanceFrequencyDouble = exceedanceFrequency.toDouble();
```

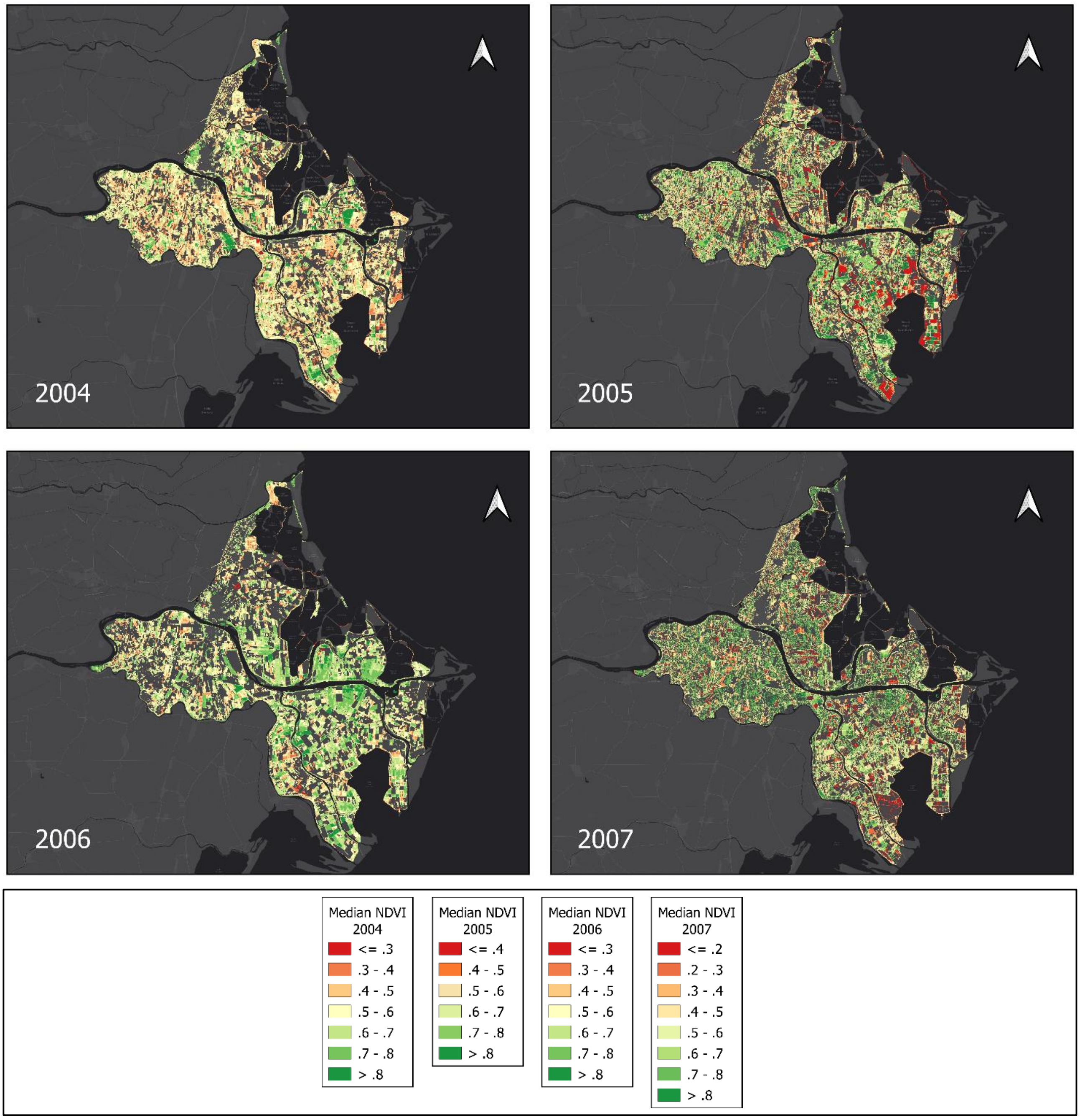
Appendix 4. GEE script for Sentinel-2, NDVI frequency calculation, 2023

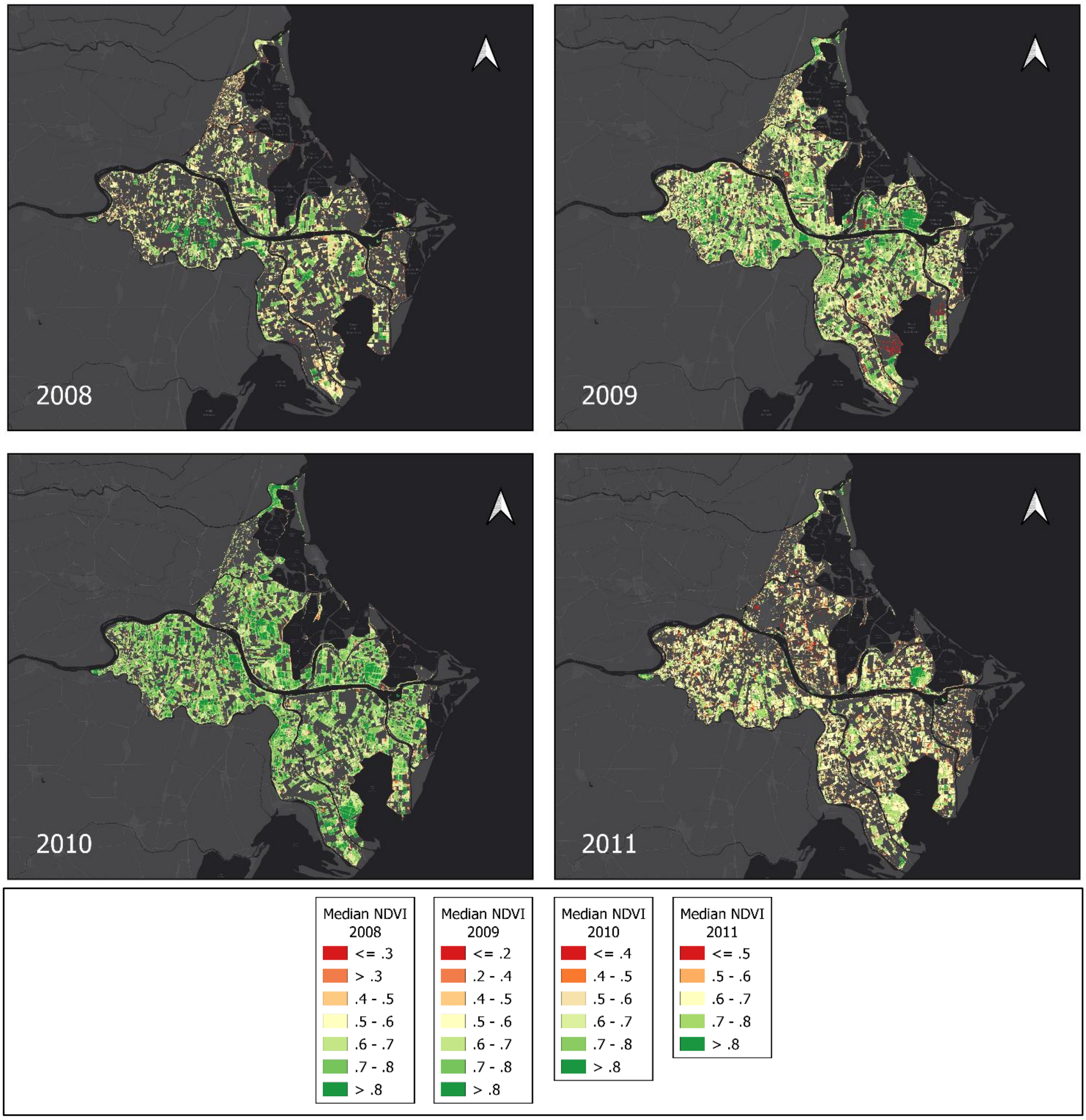
```
// Define the baseline period (2015-2024) and target period (2023) dates
var baselineStartDate = '2015-06-01';
var baselineEndDate = '2024-09-30';
var targetStartDate = '2023-06-01';
var targetEndDate = '2023-09-30';

// Load Sentinel-2 dataset and filter by baseline period and study area
var s2Baseline = ee.ImageCollection("COPERNICUS/S2_SR_HARMONIZED")
  .filterDate(baselineStartDate, baselineEndDate)
  .filterBounds(studyArea)
  .filter(ee.Filter.lt('CLOUDY_PIXEL_PERCENTAGE', 10))
  .select('B8', 'B4'); // Select bands for NDVI calculation

// Load Sentinel-2 dataset for the target period (2024)
var s2Target = ee.ImageCollection("COPERNICUS/S2_SR_HARMONIZED")
  .filterDate(targetStartDate, targetEndDate)
  .filterBounds(studyArea)
  .filter(ee.Filter.lt('CLOUDY_PIXEL_PERCENTAGE', 10))
  .select('B8', 'B4'); // Select bands for NDVI calculation

// Function to calculate NDVI
function calculateNDVI(image) {
  var ndvi = image.normalizedDifference(['B8', 'B4']).rename('NDVI');
  return ndvi.updateMask(ndvi); // Mask non-NDVI pixels
}

// Apply NDVI calculation to each image in baseline and target collections
var ndviBaselineCollection = s2Baseline.map(calculateNDVI);
var ndviTargetCollection = s2Target.map(calculateNDVI);

// Calculate the 10th percentile NDVI threshold for the baseline period (2015-
2024)
var ndviBaseline10thPercentile =
ndviBaselineCollection.reduce(ee.Reducer.percentile([10]));

// Create a function to identify pixels where NDVI in 2024 is less than the
10th percentile baseline
function countExceedances(image) {
```

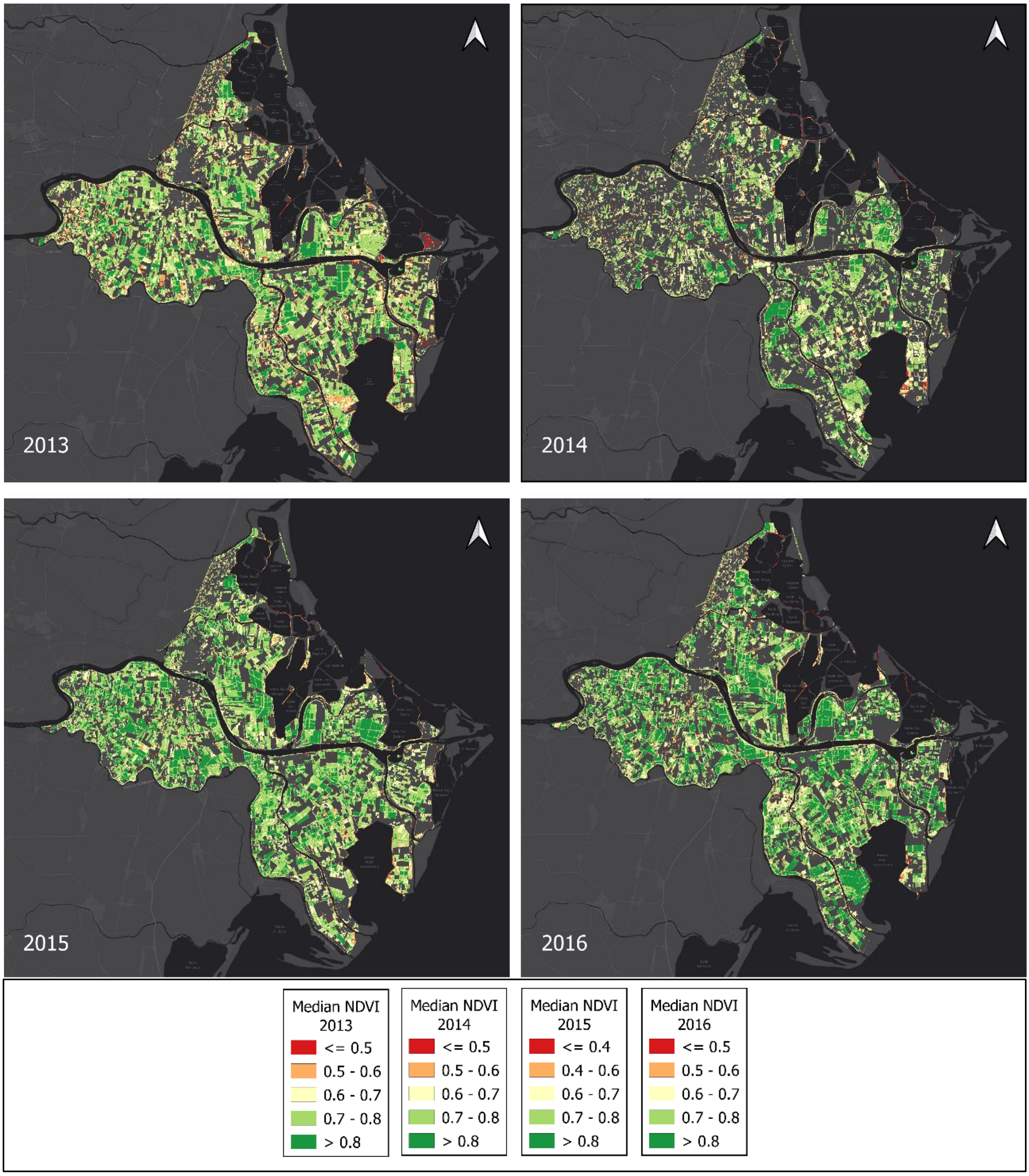
```
  var exceedanceMask = image.lt(ndviBaseline10thPercentile); // NDVI < 10 th
percentile baseline
  return exceedanceMask.rename('Exceedance');
}

// Apply the exceedance mask to each image in the target collection
var exceedanceCollection = ndviTargetCollection.map(countExceedances);

// Sum the exceedance masks to calculate the frequency distribution of low
NDVI values for 2024
var exceedanceFrequency = exceedanceCollection.sum().clip(studyArea);

// Display results on the map
Map.addLayer(ndviBaseline10thPercentile, {min: 0, max: 1, palette: ['blue',
'green']}, 'Baseline 10th Percentile NDVI');
Map.addLayer(exceedanceFrequency, {min: 0, max:
exceedanceCollection.size().getInfo(), palette: ['white', 'red']}, '2024
Frequency of Low NDVI Exceedance');
Map.centerObject(studyArea);

var exceedanceFrequencyDouble = exceedanceFrequency.toDouble();
```

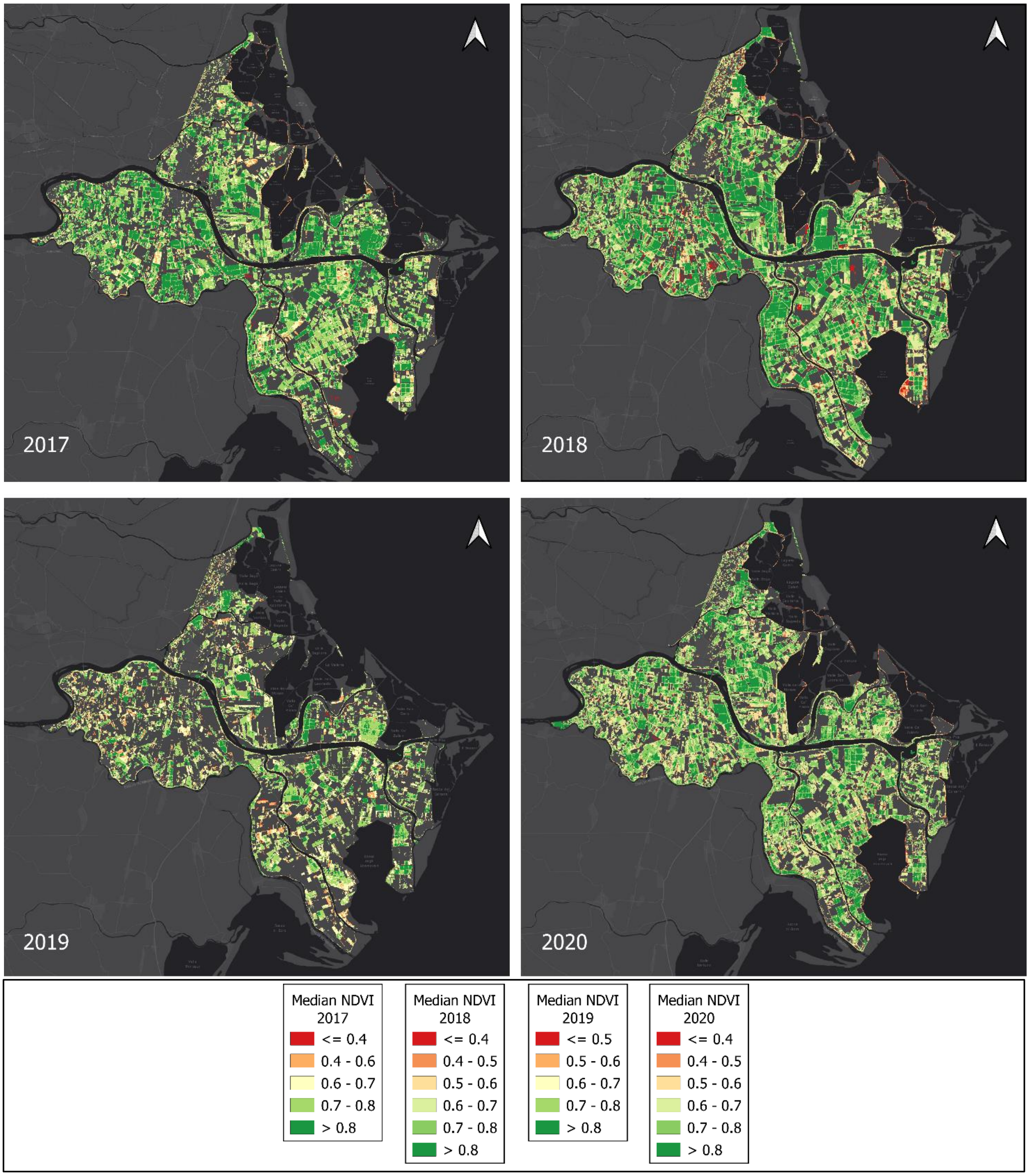
Appendix 5. Landsat median NDVI maps, 2000-2024



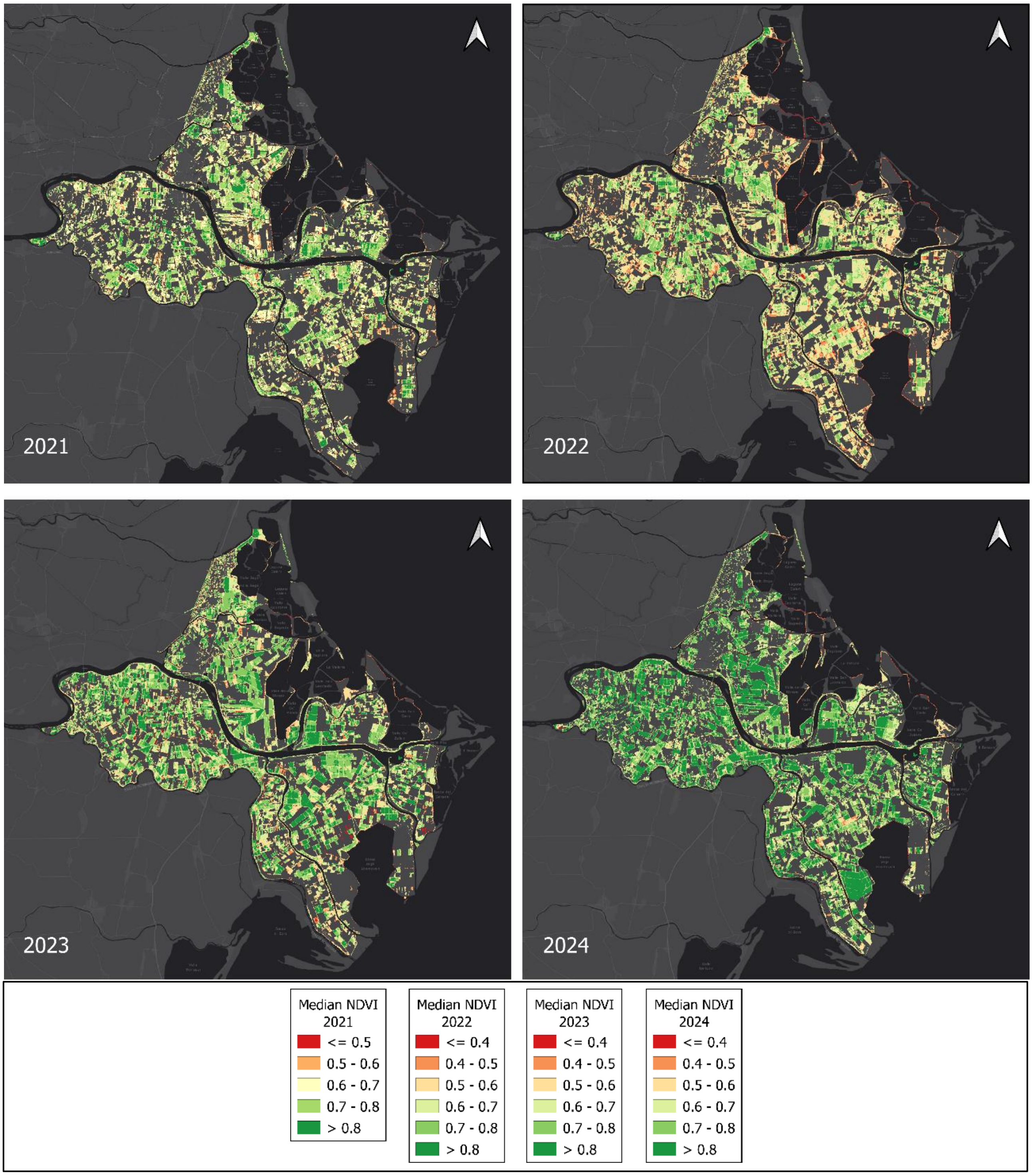

2004
2005
2006
2007
Median NDVI 2004
<= .3
.3 - .4
.4 - .5
.5 - .6
.6 - .7
.7 - .8
> .8
Median NDVI 2005
<= .4
.4 - .5
.5 - .6
.6 - .7
.7 - .8
> .8
Median NDVI 2006
<= .3
.3 - .4
.4 - .5
.5 - .6
.6 - .7
.7 - .8
> .8
Median NDVI 2007
<= .2
.2 - .3
.3 - .4
.4 - .5
.5 - .6
.6 - .7
.7 - .8
> .8


2008
2009
2010
2011
Median NDVI 2008
<= .3
> .3
.4 - .5
.5 - .6
.6 - .7
.7 - .8
> .8
Median NDVI 2009
<= .2
.2 - .4
.4 - .5
.5 - .6
.6 - .7
.7 - .8
> .8
Median NDVI 2010
<= .4
.4 - .5
.5 - .6
.6 - .7
.7 - .8
> .8
Median NDVI 2011
<= .5
.5 - .6
.6 - .7
.7 - .8
> .8


2013
2014
2015
2016
Median NDVI 2013
<= 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
> 0.8
Median NDVI 2014
<= 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
> 0.8
Median NDVI 2015
<= 0.4
0.4 - 0.6
0.6 - 0.7
0.7 - 0.8
> 0.8
Median NDVI 2016
<= 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
> 0.8



2017
2018
2019
2020
Median NDVI 2017
<= 0.4
0.4 - 0.6
0.6 - 0.7
0.7 - 0.8
> 0.8
Median NDVI 2018
<= 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
> 0.8
Median NDVI 2019
<= 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
> 0.8
Median NDVI 2020
<= 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
> 0.8


2021
2022
2023
2024
Median NDVI 2021
<= 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
> 0.8
Median NDVI 2022
<= 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
> 0.8
Median NDVI 2023
<= 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
> 0.8
Median NDVI 2024
<= 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
> 0.8