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OPINION

Saltwater intrusion and climate change impact on coastal agriculture

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1. Coastal agriculture under threats

Coastal agriculture represents a significant food production and socio-economic reality in the world, as millions of people are living in coastal areas. In some regions, the optimal combination between traditions and cultivated coastal land is recognized and protected by UN initiatives such as the Food and Agriculture Organization (FAO), Globally Important Agricultural Heritage Systems (e.g., Kuttanad Below Sea Level Farming System, in India), and UNESCO World heritage (e.g., cultural landscape of the Saloum delta in Senegal, and the Trang An Landscape Complex on the Red River Delta Vietnam). Agriculture in these areas depends on optimal water resource management. Changing climatical conditions is threatening coastal agriculture's preservation and sustainability and its unique role in historical heritage. Freshwater sources close to the sea are at risk of saltwater intrusion [1–3]. This process results from multiple drivers: natural and anthropogenic. Climate change, with the sea-level rise first, and recently also drought, are causing, especially in river deltas, a progressive land degradation, which negatively impacts the sustainable development of agriculture, society, and economy. Droughts are responsible for particularly severe saltwater intrusion events. Indeed, lack of rainfall leads to scarce river discharge and favors marine water inland flow intrusion. The consequences for agricultural production are several: impaired plant uptake of water and essential nutrients, negative effects on crop growth and development, higher weed competition, lower soil microbial activity, and overall crop productivity reduction. Here we present the case of two critical regions that can be considered the world's hotspots of saltwater intrusion phenomenon. We also addressed possible mitigation solutions.

2. The Po River Delta and Mekong Delta: Two world's hotspots of saltwater intrusion

The Po Delta (Italy) is among the main wetlands in Europe, rich in biodiversity, and home to numerous animal and plant species. It also has a strong rural character; agriculture and fishing are major socioeconomic sectors. Over the centuries, the area has been reclaimed for cultivation, including important hydraulic works such as the "Taglio di Porto Viro" built-in 1604 by the Republic of Venice. This region faces a severe threat due to saltwater intrusion [4], an increasingly challenging problem in recent years. Such a process is attributed to a range of

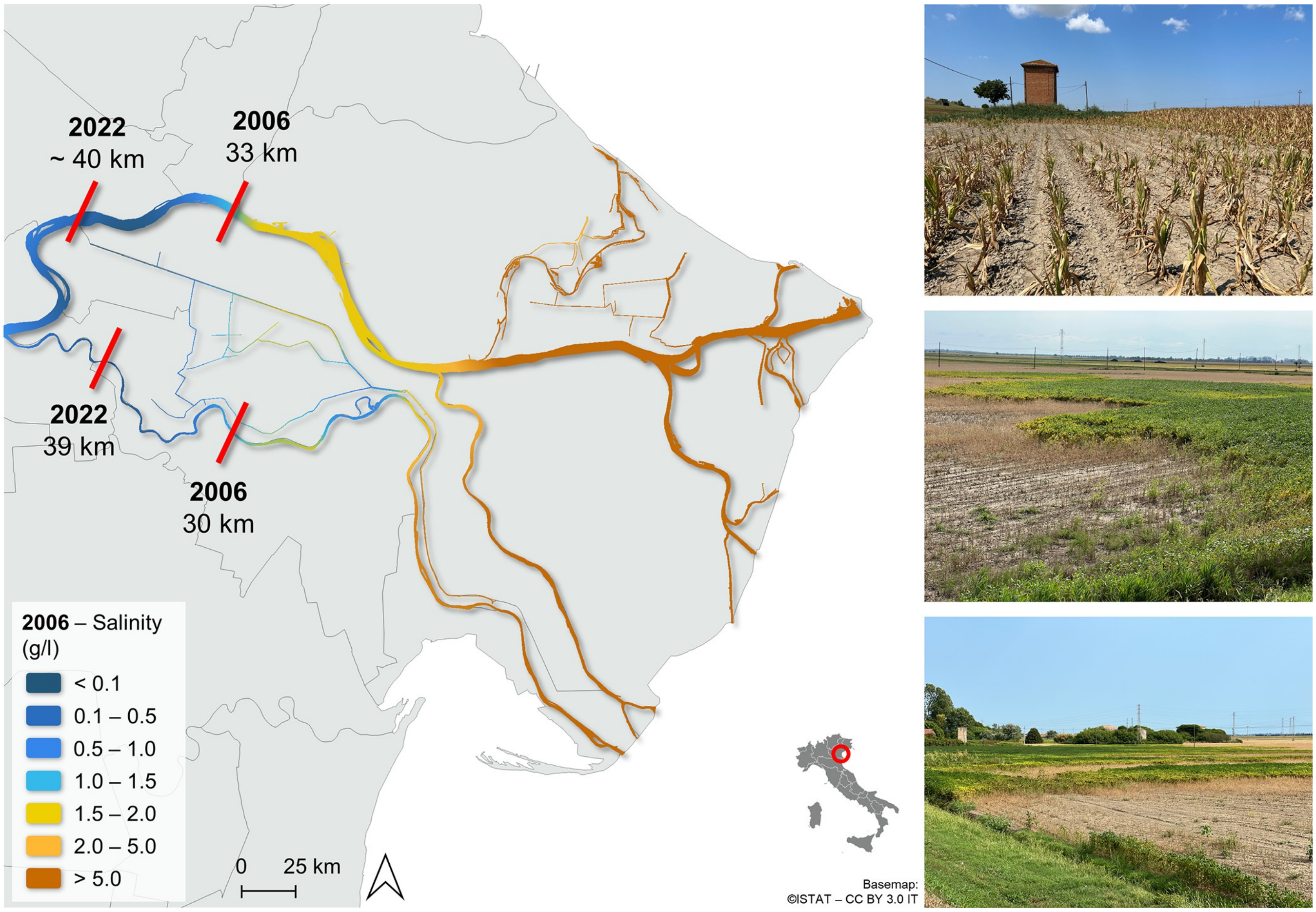

Fig 1. Saltwater intrusion in the Po River Delta during the two major droughts of the summer of 2006 and 2022. On the left is the dynamic of the event in the summer of 2006 (data provided by "Consorzio di Bonifica Delta del Po"). The limits to which water salinity was above the critical threshold for agriculture (2 g/l) and the relative distance from the sea are shown in red. Also shown are the limits of the 2022 drought event, which were even more severe than the 2006 event. On the right, some remarkable effects of saltwater intrusion on crops (maize and soybean) in the delta during summer 2022 (photos: Paolo Tarolli).

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factors, including the pumping of groundwater, the reduced flow of the river due to damming and irrigation, and rising sea levels. Another factor is subsidence; about 40,000 hectares of the Po River delta are below the sea level (in some points, more than -3 m asl). Subsidence mainly occurred in the 1950s and 60s. It was caused by huge extractions of methane from the subsoil. Climate change has significantly worsened these factors, leading to increasingly frequent arid conditions [5]. This has severely impacted the area's natural resources, including soil salinization, habitat loss, and reduced agricultural productivity (Fig 1). In the last two decades, six episodes of drought occurred. They were characterized by low discharge of the Po River (below 450 m^3s^{-1}, a critical threshold indicated to guarantee the river's ecological functionality; the average discharge of the river is about 1500 m^3s^{-1}), favoring the intrusion of saltwater along the tributaries of the delta up to many kilometers from the sea. In all these episodes, the recorded water salinity was more than 2 g/l, the critical threshold FAO indicated for irrigation. One of the most severe droughts ever recorded in Europe occurred in 2022 summer [5]. It dramatically affected northern Italy through water shortages and other indirect processes. During that period, much of the surface of the Po River Delta was exposed to saltwater intrusion, with water salinity peaks in July when the discharge reached the negative record of 104 m^3s^{-1} at

Pontelagoscuro. Critical salinity values of river water were recorded up to about 40 km upstream of the sea (Fig 1) along the main river course and a principal branch (Po di Goro). The event was extraordinarily severe and worse than the summer of 2006, which is remembered as one of the most challenging (critical salinity up to more than 30 km from the sea; Fig 1).

Fig 1 provides an overview of the 2006 drought and compares it to the 2022 drought. An important difference to underline between the two droughts is the long duration of the 2022 phenomenon in terms of exceptionally low river flow and concomitant absence of precipitation (2.5 months of persistent crisis). Freshwater from the Po River is a primary resource for the entire agricultural landscape of the delta, which is used for irrigation through a capillary canal network. When water salinity exceeds the critical threshold, it becomes complex and sometimes impossible to comply with irrigation scheduling, aggravating the severe water shortage. The consequences are dramatic for agricultural production and can manifest as soil fertility deterioration, vegetation loss, and micro desertification of large field portions (Fig 1).

The Mekong Delta region of Vietnam is known as a giant food bowl due to its high rice yield, which has made Vietnam the world's second-largest rice exporter. However, the region has been severely impacted by sea level rise caused by climate change, a problem exacerbated in recent years by the construction of upstream dams along the Mekong River. This phenomenon is driven by four main factors: (a) upstream hydropower dams, (b) land subsidence, (c) the relative sea-level rise, and (d) riverbed sand mining [1, 6]. The intrusion of saltwater has led to the deterioration of soil quality, making it difficult to cultivate rice paddies [1]. The salinity of the water surface rises by approximately 4 g/l as seawater intrudes into the Hau and Tien rivers, extending to 45–65 km and 55–60 km from the coastline, respectively [3]. This fact has called the great attention of domestic and international private and public sectors and scientists. Recently, a method of spatially monitoring soil salinity in the Mekong River (by using a near-infrared channel and Vegetation Soil Salinity Index derived from Landsat 8 OLI data) has been proposed by using satellite data-derived variables to support the management of land resources and to determine the suitable crops to cultivate [7]. According to the National Center for Hydro-meteorological Forecasting, Vietnam Ministry of Natural Resources and Environment, the severity of saline intrusion in the Mekong Delta is expected to increase in the dry season of 2023, further threatening rice supply in the foreseeable future.

3. Future challenges

In the absence of mitigation actions, the frequency of extreme weather events will increase in the following decades [8]. According to Beck et al. (2018) [9], in RCP scenario 8.5, future climate shifts could also affect some important river deltas worldwide. The Po River Delta (Italy) has a temperate climate with no dry seasons and hot summers (Cfa, humid sub-tropical climate). A climate variation toward drier and warmer conditions is predicted (BSh, hot semi-arid climate). Therefore, the process of saltwater intrusion is expected to worsen. Another example is the Saloum River Delta, Senegal's UNESCO cultural landscape. Currently, its southern region is characterized by a tropical savannah climate (Aw). In the future, precipitation may decrease, leading to a hot semi-arid (BSh) climate zone. The new condition could seriously affect the river's flow, impacting the delta's valuable biodiversity and traditional human activities. Also notable is the case of the Ebro River Delta, located on the Mediterranean coast of Spain. It is a wetland area classified as a natural park due to its biological, geological, and cultural importance. Part of the delta is devoted to agriculture. Rice is among the most implemented crops. The area is characterized by a cold semi-arid climate (BSk). Here, climate change could lead to higher temperatures with hot summers, shifting to a hot semi-arid climate zone (BSh). Therefore, it could experience an intensification in the frequency of heat waves, with potential impacts on agriculture. Given the severity of the problem in several deltas worldwide, it is essential to adopt a collaborative approach involving local communities, policymakers, scientists, and other stakeholders to develop and implement effective solutions. We propose a focus on four critical aspects, from actions to be taken with immediate urgency (short-term intervention to preserve the existing agricultural system) to a long-term mitigation plan (remediation and adaptation):

(i) physical mitigation of seawater intrusion: providing shallow mobile barriers that can act when the river's discharge reaches critically low levels, stopping the inland flow of saltwater. This solution should be adopted to mitigate the phenomena during extreme conditions and only for short periods, minimizing any impact on coastal ecosystems. Indeed, even in the most onerous conditions—hence with the barrier in full operation—there will never be confinement of two ecosystems. This will guarantee the continuity in the flow of the river and the interchange between faunal species. The benefit of this solution is immediate: preserve the agricultural production (and indirectly the local economy) for that year.

(ii) promoting and optimally designing rainwater harvesting facilities. During drought conditions, low-impact water storages (e.g., built according to modern Natural Water Retention Measures criteria) guarantee fresh water that could be used for irrigation and public supply. Such solutions create multiple benefits: a) collect rain during intense rainfall events to be reused for emergency irrigation; b) contain the flood that can form from increasingly intense rainfall events; c) reduce groundwater exploitation with wells that could irreversibly damage the entire water storage in soil with negative impact even on water that can be used for a public purpose; d) establish wetlands that could offer a refugee for birds and amphibia; e) improve biodiversity and ecosystem services.

(iii) implementing soil remediation strategies: the higher organic carbon content in soils can improve soil structure, increase water holding capacity, and promote beneficial microbial activity, leading to better ecosystem functioning [10] and overall increasing the resilience of the soil. The purpose is to remediate those soils affected by the micro desertification phenomenon, reestablishing organic content and microorganisms.

(iv) adaptation of coastal agriculture to extreme conditions: promoting more tolerant crops to drought and salinization of soil, also focusing on potential breeding and genetic modification strategies for improving salt tolerance or preferring autumn/winter crops instead of summer crops [11, 12].

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