

Discussion

Sustainability of Coastal Agriculture under Climate Change

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Abstract: Climatic and non-climatic stressors, such as temperature increases, rainfall fluctuations, population growth and migration, pollution, land-use changes and inadequate gender-specific strategies, are major challenges to coastal agricultural sustainability. In this paper, we discuss all pertinent issues related to the sustainability of coastal agriculture under climate change. It is evident that some climate-change-related impacts (e.g., temperature and rainfall) on agriculture are similarly applicable to both coastal and non-coastal settings, but there are other factors (e.g., inundation, seawater intrusion, soil salinity and tropical cyclones) that particularly impact coastal agricultural sustainability. Coastal agriculture is characterised by low-lying and saline-prone soils where spatial competition with urban growth is an ever-increasing problem. We highlight how coastal agricultural viability could be sustained through blending farmer perceptions, adaptation options, gender-specific participation and integrated coastal resource management into policy ratification. This paper provides important aspects of the coastal agricultural sustainability, and it can be an inspiration for further research and coastal agrarian planning.

Keywords: climatic stressors; sea-level rise; salinity intrusion; agricultural adaptations; coastal urbanisation; climate change impacts

1. Introduction

Climate change is an inevitable and urgent global challenge with long-term consequences for the sustainable development of all nations. It is widely documented as a key environmental issue that is affecting natural and human systems on a global basis. According to the Fourth Assessment Report (AR4) by the Intergovernmental Panel on Climate Change (IPCC) [1], coastal systems and low-lying areas are projected to be increasingly at risk throughout the 21st century and beyond due to global climate change. Major risks coming from the shoreline are waves, winds, currents, tides and storms. The outcomes of these natural actions and interactions on the shoreline and near-shore seabed are known as coastal processes [2], and include erosion and deposition, dune motion and longshore drift. Coastal areas are particularly exposed to a range of climate-related hazards (e.g., rising sea levels, higher flood levels and storm surges, accelerated coastal erosion, seawater intrusion and increasing ocean acidity and surface temperatures). These hazards may lead to a series of socio-economic impacts in the coastal zones (e.g., reduced agricultural productivity, loss of property and coastal habitats, loss of tourism, recreation, transportation and industry and harbour activities) [3,4]. There is also evidence

across the globe that non-climate stressors, such as urban growth, population migration, land-use change, pollution and gender issues, have been powerful drivers of changes in coastal agriculture. These would ultimately have an impact on the sustainability of food security in coastal areas [5–7].

Oceans cover approximately 72% of the surface of the Earth in total with 620,000 km of coastline [8,9]. Climate change unquestionably poses complex challenges to coastal communities. Over 40% of the global population (around 2.4 billion people) reside in coastal areas or within 100 km from the coast, amid extremely productive deltas, coral reefs, mangrove biomes and the adjacent land-based estuaries [10]. Many inhabitants of these environmentally heterogeneous regions embrace blended livelihoods based on natural resources, including agriculture and artisanal fishing [11]. Climate change and agriculture are interdependent and occur globally [12]. Climate change is expected to have negative impacts on the production of crops and livestock worldwide that could impact food security [13,14]. The uncertain impacts of climate change will further enhance the production risks of the agricultural sector. In view of these facts, priority must be given to the notion of sustainable agricultural development and global food security [15]. Both precipitation and temperature will change as a result of climate change and affect agriculture everywhere. Coastal agriculture will also face added impacts from sea-level rise (SLR), inundation, seawater intrusion, rising salinity, storm surges, tropical cyclones and flooding [16].

Coastal agricultural practices are less stable than upland agriculture because they need to cope with frequent changes in salinity, tidal processes, water stresses and waterlogging [17]. Coastal ecosystems are greatly impacted by location-specific land use [7]. Projections of the precise magnitude, frequency and regional patterns of the impacts from climate change on coastal agriculture are uncertain. However, the implications of these impacts will change the destiny of many generations to come and affect coastal communities in particular if no suitable action is taken. Given this growing concern, it is urgent that appropriate adaptation policies and strategies are developed and applied to mitigate the vulnerability of coastal agricultural systems to climate change [18].

Sustainable management of natural resources in coastal regions is, therefore, of utmost importance to ensure the stability of this system of production. Hence, it is vital to investigate how agriculture may change under the influence of climate change in the dynamic and resource-rich coastal regions. While the impacts of climate change on agriculture and food security are well-established, its cascading impacts on the sustainability of coastal agriculture have not been adequately resolved. Given the key role that agriculture plays in the livelihood of coastal communities, we aimed to investigate the sustainability of coastal agriculture in the face of changing climate. In this paper, we review and discuss the pertinent issues related to coastal agricultural sustainability, differences between coastal and inland agriculture and key climatic pressures on coastal agriculture. We also discern the factors, such as perception, adaptation and gender issues, which are related to coastal agriculture under climate change. While some issues, such as gender in agriculture and rapid urbanisation in coastal regions, are not directly climate related, we have included them as they are connected to coastal agricultural sustainability. They are central to any discussion on mitigation and adaptation in coastal agricultural settings. This review and discussion paper synthesises pertinent information that is essential for researchers and policymakers. It will help identify alternatives in the sustainability of coastal agriculture in the wake of climate change and serve as a basis for similar studies in the future.

2. Identification of Stressors of Coastal Agricultural Sustainability

Coastal agricultural systems, sandwiched between land and sea, are particularly under threat from increasing climate and non-climate related hazards [5]. Coastal farming is more susceptible to climate change compared to inland farming because, along with the rainfall and temperature changes, they also have to deal with frequent changes in coastal ecosystems [17]. Furthermore, coastal agriculture is experiencing increasing anthropogenic disturbances through land degradation and encroachments of agricultural lands [6]. In a broader sense, there are two types of stressors: climatic and non-climatic.

2.1. Climatic Stressors

Climatic stressors are likely to have significant impacts on coastal agriculture, challenging food security in the future [19]. Crop productivity is highly vulnerable to climate variability, including increases in temperature, changing patterns of rainfall, tropical cyclones and extreme events, as well as the associated impacts of sea-level rise, floods and coastal inundation. The climatic stressors are identified here.

2.1.1. Temperature

According to the report from the IPCC [20], anthropogenic warming has reached approximately 1 °C (likely between 0.8 °C and 1.2 °C) above pre-industrial levels and continues to increase at a rate of 0.2 °C (likely between 0.1 °C and 0.3 °C) per decade. If the current rate of warming continues, it is likely to reach 1.5 °C between 2030 and 2052. In addition, heat waves are likely to occur more frequently and last longer.

2.1.2. Rainfall

A key factor in the sustainability of coastal agriculture is rainfall. According to the IPCC AR5 [21], changes in precipitation will not be uniform throughout the world with the current warming trend. Mean precipitation is likely to decrease in many mid-latitude and subtropical dry regions, while it is likely to increase at high latitudes, in the equatorial Pacific and in many mid-latitude wet regions by 2100 under the representative concentration pathway (RCP) 8.5 scenario. Overall, precipitation in the area affected by monsoon is likely to increase under all RCPs, as the variability in regional-scale precipitation is associated with the El Niño–Southern Oscillation (ENSO) [21].

2.1.3. Sea-Level Change

The IPCC AR5 [21] reported that the global mean sea level rose by 19 cm between 1901 and 2010 and was projected to rise by 52 to 98 cm under the RCP8.5 by the end of this century compared to the 1986–2005 period. With greenhouse gas concentrations continually rising, the rate of global mean SLR over the 21st century is likely to exceed the rate observed during 1971–2010 for all RCP scenarios [22].

2.1.4. Tropical Cyclones (TCs)

Cyclones are disturbances that occur in low latitudes and in particular atmospheric environments, with distinct names for each type based on their place and strength. There are two types of cyclones: tropical and non-tropical cyclones (mid-latitude or extra-tropical) [23]. Coastal regions are particularly vulnerable to the impacts of any cyclones compared to inland regions. According to the IPCC AR5 [21], the global mean precipitation rates and maximum wind speeds of TCs are likely to increase in the future. Models predict that rainfall rates associated with TCs would increase with global climate change [24]. Seneviratne et al. [25] indicated that the frequency of TCs will either decrease or stay unchanged, and the poleward track of TCs may be converted into extratropical cyclones. These cyclones have distinct features compared to their tropical originators and can impact areas distant from the tropics [26].

2.1.5. Climate-Change-Induced Stressors

A few stressors (e.g., floods, inundation and saltwater intrusion) are not directly climatic in nature but can be caused or accelerated by climate change. Coastal floods are caused by heavy rainfall, particularly when rainwater cannot discharge through the nearby rivers and creates waterlogging conditions. Coastal inundation occurs when coastal areas are submerged by a large amount of seawater brought by, for example, sea-level rise, tidal surges and cyclones. Coastal saltwater intrusion is a global issue that threatens soil productivity, and it is estimated that by 2050, salinity will affect 50% of all arable soil worldwide [27]. Droughts can increase the uses of groundwater for irrigation. Furthermore,

intensive use of groundwater for irrigation depletes the water table and makes it possible to leach even more salt into the soil and further impede coastal farming [28].

2.2. Non-Climatic Stressors

Agriculture is a weather-dependent practice that is grounded in the climatic conditions of an area. However, it is also influenced by several non-climatic factors. Broad examples include urban growth and population [29,30], population migration [31], land use [32] and pollution [7]. Rapid urbanisation for increasing populations in the coastal areas is competing with agricultural lands, polluting the farm areas and changing the pattern of land use. Millions of people currently rely on being within proximity to the coast for the provision of favourable livelihoods [33] and economic and trade opportunities. Migration to coastal cities and modifications to land use and physical construction (such as offshore airports, wind-energy parks and land reclamation) are increasing as a result of enhanced human demographics and the intensified use of coastal areas [5]. Tourism and other capital-intensive activities may make the land tenure fragile for smallholders with a limited capacity because they may be highly tempted to sell productive agricultural land for non-agricultural purposes [32,34]. Furthermore, gender as a non-climatic stressor [35] has become an issue of increasing concern for coastal agricultural sustainability. This is because different gender roles and responsibilities, along with unequal access to resources, make men and women vulnerable to the impacts of climate change differently [36].

3. Impact of Stressors of Coastal Agricultural Sustainability

3.1. Impact of Climatic Stressors

3.1.1. Impact of Temperature

Increasing temperatures may favour agriculture in some parts of the world but the effect will be negative in others. At high altitudes, rising temperature can increase the yield and variety of crops grown, and at high latitudes, the productive potential of crops would increase with a poleward shift of the temperature limits for agriculture [37]. For example, an increase in the temperature of the temperate climate zones of China has caused a significant increase in the rice yield and allowed a northward expansion of rice planting [38]. However, an overall increase in temperature will most likely have more negative than positive impacts on crop yields [21,39,40].

The ranges of minimum and maximum temperatures are different for each crop species at different stages of development, beyond which all processes of growth are inhibited. The reproductive stage (flowering and pollination) is the most sensitive stage of development to heat stress [41–43]. Heat stress can significantly affect plant respiration, photosynthesis, stability of leaf membranes, quality of seeds and overall crop production [41]. Increasing temperature also affects crops indirectly; examples include increasing evaporation rates, depletion of surface and groundwater resources, increasing drought duration and intensity and an increase in the spread of pests and diseases [44–46]. Prolonged warmer temperatures will alter the timing of crop cycles, which in turn may coincide with the proliferation of pests. For example, the frequency of spring frosts declines with increasing temperature. This prolonged frost-free period increases the intensity and length of insect outbreaks. At the same time, to take advantage of this changing climate, farmers are also expected to plant earlier. These crops will then be available for crop pests, enabling an even faster growth of insect populations and possibly adding extra generations of these pests during a typical growing season [47]. High temperatures can also suppress the defence responses of plants, resulting in the enhanced severity of diseases [48,49].

Here, we can use the example of rice, which is considered to be one of the most important food crops in the world, and is cultivated on over 163 million ha in more than 100 countries [50]. It is the most common crop cultivated in the coastal lowlands of the world. Asia contributes about 90% of the global rice consumption and production [51]. In most of the current rice-growing regions, the temperature is already close to the optimum for rice production. Hence, any further increase in temperature or

exposure to high temperatures, even for short periods, during the sensitive development stages could easily impede the rice yield [52]. A temperature change of 1.5 °C would affect the rice production [53] and a local increase of 2 °C or above would impose significant impacts on rice production in both tropical and temperate countries [54]. The negative impacts of rising temperature on rice production are well documented [39,52,55–57]. A 10% decline in grain yield is reported with a temperature increase of 1 °C [58,59]. As Asia plays a key role in global rice production, these impacts on rice crops will be a major threat to the sustainability of global food security.

The changes in soil water balance will impact soil evaporation and plant transpiration. Plants exposed to extreme heat will lose the capacity to extract sufficient water from the soil to meet the demand of increased temperatures [60,61]. Even though these changes are common in both coastal and inland agriculture, when combined with other coastal climatic stressors, the cumulative impacts are diverse and devastating. For instance, water scarcity is identified as one of the major threats to coastal agriculture compared to inland agriculture since the increased temperature and fluctuating rainfall are likely to reduce the availability of water for crops, consequently reducing the yield. Such water scarcity in the coastal areas can also increase saltwater intrusion into the aquifers.

3.1.2. Impact of Rainfall

Coastal agriculture is particularly vulnerable to changes in rainfall for many reasons. The heat contrast between diurnal land and sea circulation is the primary and fundamental cause of coastal precipitation. Ogino et al. [62] studied the climatological characteristics of precipitation in the coastal regions of the tropics and found that total precipitation tends to peak around the coastline and decreases rapidly away from coastal areas. Approximately 34% of the total precipitation over the tropics occurs within the coastal region (defined as within 300 km of the coastline). A study by Curtis [63] also reported a decline in rainfall from the coast to the interior, with approximately 911.5 mm yr⁻¹ of precipitation within 50 km of the coast and 727.2 mm yr⁻¹ between 100 and 150 km from the coastline in south-eastern USA. High-intensity or prolonged low-intensity rainfall can trigger shallow landslides in mountainous coastal regions [64–66]. In addition, coastal regions orientated alongside mountain chains also receive orographically enhanced extensive rainfall [63]. Mountains also block and slow down the monsoonal flow in countries such as Myanmar, Thailand, the Philippines and the western coast of India, resulting in intense precipitation at the coast [67].

Rainfall variations significantly affect coastal agriculture by influencing germination, plant size, seed production, invasive weeds, water quantity and quality, erosion rates and cropping patterns [55]. Heavy rainfall can cause waterlogging conditions that result in a reduction in the amount of land available for agriculture. Riverine and/or flash floods in river deltas and estuaries can exacerbate coastal flooding and sedimentation. This occurs when the outflow is limited and the riverine flood water reinforces coastal surges by increasing the height and duration of the flood [68].

3.1.3. Impact of Sea-Level Rise

Potential major physical impacts of SLR on agriculture include coastal flooding and shoreline recession, which produce a loss of coastal soil; intrusion of seawater into surface and groundwater; decline of coastal vegetation, such as mangroves and salt marshes; and increase storm surge events [69]. Physical impacts of SLR, combined with their associated socio-economic consequences, directly or indirectly impose substantial negative implications on the sustainability of coastal agriculture [69]. Chen et al. [70] reported that the global rice production has decreased by 1.6–2.7%, resulting in welfare losses of up to US\$10.6 billion from 1961–2005 due to SLR. Countries such as Myanmar, Vietnam and Egypt are identified as being more at risk and are expected to change from rice exporters to importers under an extreme rise in sea level. Sugarcane is another crop that is commonly grown in low-lying coastal areas and is therefore also vulnerable to SLR [71]. Any increase in sea level would lead to the abandonment of many significant regions in which sugarcane is grown, and a major loss is therefore expected, especially in Australia and South Florida, USA [72].

Deltas are renowned for their fertile and highly productive agricultural lands, and they are known to be more fragile and vulnerable to SLR. Close interactions between the land and sea results in highly complex agricultural systems, where rain-fed and irrigation systems are practised alternatively with the changes in season, with much attention paid to the quality of the water to be used in irrigation (salinity), and to the removal of salt by rain before the planting of crops. An example can be seen in Vietnam where nearly 70% of rice is produced in two deltas, namely the Mekong and Red River delta. Any coastal disturbances will therefore significantly impact the economy [73]. Another study in the Yangtze delta area in Shanghai identified that increases in the groundwater table, and the subsequent shortage of arable land and freshwater, will be unavoidable in coming decades due to the projected SLR. This problem is expected to have a profound impact and become a major threat to the sustainability of peri-urban agriculture in the Yangtze delta region [74].

Most immediate secondary threats caused by SLR are the increasing salinity in soil and groundwater resources along with coastal erosion (Box 1). Saline environments tend to impede agriculture by reducing crop yields, often substantially [75,76]. The diverse impacts of salinity on crops are well reported [77–79]. In Bangladesh, coastal soil salinity from the SLR in agricultural lands has been found to have a profound effect on crop revenue and the internal migration of farmers [80]. Southern coastal areas of Bangladesh are projected to lose 40% of productive land due to SLR inundation over the next 120 years [81]. Both coastal erosion and shoreline recession are caused by alterations in the relationship of the shore profile to the water level by the rising sea. This shrinks the availability of land and its suitability for agriculture [82]. However, this is also induced by the removal of coastal vegetation, such as mangroves, which act as barriers and buffers against increasing sea levels and more frequent storms [83,84]. For example, Baharuddin et al. [85] suggested that oil palm plantations would not be feasible in areas that are severely affected by erosion by the 21st century, such as Carey Island, Malaysia, according to local sea-level predictions.

Box 1. Inundation in Jaffna Peninsula, Sri Lanka.

Jaffna Peninsula, located in the northern tip of Sri Lanka, is identified to be extremely vulnerable to inundation due to its geomorphology and anthropogenic influences. The landscape is nearly flat, with 96% of the land lying below an elevation of 5 m and all the peninsula lies within 10 km from the coast. Having no perennial surface water resources or permanent water supply systems, the inhabitants are completely dependent on groundwater for their daily needs. Rice is the most common and widely grown crop in the coastal lowlands on Jaffna Peninsula.

Figure 1 shows the total land area that is likely to be inundated by a mean SLR of 98 cm under the RCP8.5 scenario by 2100. This amounts to an area of approximately 447.9 km², which is nearly 38% of the total land area of Jaffna Peninsula. In addition, approximately 4.5 km² of the current paddy lands (which is about 43% of the total paddy land area) will be lost by the end of this century under the above scenario, solely by direct inundation. This will be even more significant with the associated impacts of SLR, such as seawater intrusion, rising salinity, the contamination of underground water resources, coastal erosion and an increase in coastal flooding events. Therefore, SLR will have a significant impact on the livelihood and agriculture of the inhabitants of Jaffna Peninsula.

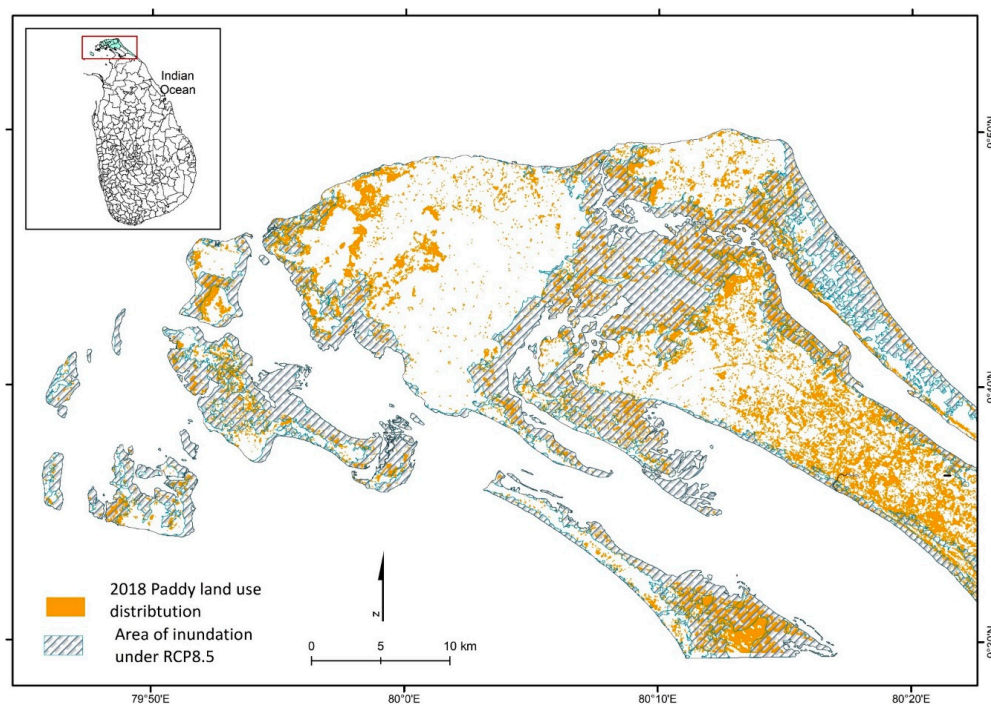


Figure 1. Map of total land area of Jaffna Peninsula, Sri Lanka, that is likely to be inundated under the Intergovernmental Panel on Climate Change (IPCC) representative concentration pathway (RCP) 8.5 projection for the global mean sea-level rise (SLR) (98 cm) by 2100.

3.1.4. Impact of Tropical Cyclones

Tropical and non-tropical cyclones are significant causes of the removal of forest canopies, destruction of mangroves and landscapes close to coastal areas, demolition of sand dunes and widespread erosion along the coast of many nations [86]. A hurricane is a tropical cyclone occurring in the Atlantic Ocean and the north-eastern Pacific Ocean, and a typhoon happens in the south-eastern Pacific Ocean. Similar storms are simply referred to in the South Pacific or the Indian Ocean as “tropical cyclones (TCs)” or “severe cyclonic storms” [87].

TCs trigger a range of destruction in the coastal areas of many countries and have a significant impact on lowland farming and coastal aquaculture [88]. High rain, strong winds, large storm surges near landfalls and tornadoes are the main effects of TCs. TCs cause irreversible damage to coastal farms and forests by destroying vegetation, crops, orchards and livestock; damaging irrigation canals, wells and tanks; and causing the long-term loss of soil fertility from saline deposits on seawater-flooded land [88]. Cyclones, storms and floods can lead to livestock loss, an increase in the susceptibility of livestock to disease, the contamination of water bodies, wind and water erosion, land degradation and the destruction of agricultural infrastructure, such as roads and fences [89]. For example, it is estimated that TC Debbie caused US\$308 million of widespread damage to the Queensland sugarcane industry in March 2017, resulting in production losses of 25–30% across the coastal region [89]. Cyclones can also cause a potential reduction in the amount of coastal land suitable for agriculture [90]. Some studies, however, have shown that TCs also have beneficial effects on agriculture, as TCs often reduce coastal drought in the summer. While the beneficial effects on agriculture and fisheries due to TCs may be trivial [88], further studies are needed to estimate the positive effects of cyclones, as such knowledge can be used to formulate adaptive measures to maintain sustainable coastal agriculture.

Similar to TCs, strong winds and hail storms cause considerable damage to crops, pastures and infrastructure, resulting in the loss of animals and crops and a reduction in overall agricultural production [91]. Coastal forests are easily affected by climatic perturbations, and severe hurricanes can cause extensive losses in these ecosystems [92]. The physical impact from the extreme events results in

erosion, subsidence, coastal deformation, soil/water contamination and widespread debris, contributing to the degradation of agricultural fields and the boundaries of fish ponds, water management systems and seed stocks needed for both aquaculture and agriculture [93,94].

3.1.5. Impact of Climate-Change-Induced Stressors

The following paragraphs discuss the impacts of climate-change-induced stressors, such as floods, coastal inundation and salinity related issues.

The vulnerability of coastal and delta areas has been accentuated because of a decrease in the supply of fluvial sediments to the coasts [95] and higher rates of land subsidence in the face of extreme climate conditions [96]. Flooding generates the intrusion of saline water, increasing the salinity in agricultural land and resulting in a salt-encroachment fragmentation of the land. In particular, high salt levels in agricultural soil or irrigation water makes it difficult for salt-sensitive plants, such as rice, to absorb water and the necessary nutrients, thereby reducing plant growth and significantly reducing crop yields in coastal farming systems [97]. Increases in salinity and the frequency of flooding due to the increase in sea-level reduces tree growth and regeneration, including mangroves, which will also negatively limit the supplementation of green manure and fodder to agricultural practices [97]. The conditions caused by flooding are linked to a deterioration in the health of crops and livestock due to waterborne diseases [98]. Flooding can also lead to delays in harvesting or other field operations or can have plurennial effects by altering the crop rotation of coastal agricultural land [99]. Agricultural runoff accelerates the removal of nutrients from the soil, together with agrochemicals and other substances that ultimately end up in nearby terrestrial and aquatic ecosystems [98,100]. Furthermore, the amount of water suitable for irrigation in coastal agronomic practices can be reduced by flooding [90].

Agriculture is one of the most vulnerable sectors to inundation by saltwater, particularly in low-lying coastal areas. In addition to SLR and rainfall, changes to the patterns of evapotranspiration and an increase in the occurrences of extreme weather have intensified the inundation process in coastal areas [1]. Coastal inundation will shift the coastline landward, erode beaches, damage crop lands, degrade some coastal habitats and potentially damage coastal infrastructure [101,102]. In addition to the effects from SLR, the salinisation of the groundwater in many coastal areas is primarily induced by over-extraction. For example, in the western and southern coastal areas of South Korea, the intensive removal of groundwater has been identified to be the main driver for increasing seawater intrusion, threatening the sustainability of the agriculture. Nearly 41–50% of coastal groundwater was identified to be affected by contamination from seawater, and 42.6% exceeded the recommended limit of 2000 $\mu\text{S}/\text{cm}$ of electrical conductivity for agriculture [103]. Many nations currently face groundwater inundation and it is a serious issue as it contaminates groundwater aquifers and surface water, leading to the unavailability of water resources for agricultural use [104]. Furthermore, the constant use of water with high salt concentrations as a source of irrigation causes salts to accumulate in the soil and ultimately damages the productivity of cultivated lands in coastal regions [105]. Excessive sodium can replace necessary nutrients, such as calcium and magnesium, in soil particles, leading to poor plant growth and development [106]. Saltwater inundation also alters the soil chemistry and mobilises nutrients that add to the loading in adjacent water bodies, reducing the water quality and damaging coastal agricultural plants. In Vietnam, for example, more than 30% of the sugarcane plants have been either destroyed or significantly damaged by the inundation and intrusion of saltwater into the Mekong Delta, resulting in significant financial loss [107].

3.2. Non-Climatic Stressors

3.2.1. Urban Growth, Population and Rural Out-Migration

Approximately 10% of the world's population lives in coastal areas of less than 10 m elevation above sea level and nearly 40% of the world's population live within 100 km from the coast [8,9]. Coastal areas contain a sizeable portion of the population since over 90% of cities are found in coastal

areas, based on the above definition [108]. A substantial number of people migrate to the coastal cities because they are regarded as “happening places” [109]. The result of this increased population is the urban growth of cities and the associated built-up areas, such as roads, houses and industries, that ultimately cause an increase in the pollution of the soil, water and air [110]. Dramatic population growth in coastal cities also results in a concentration of people and businesses that are producing waste that remains mostly untreated prior to its release into the water and soil. Excessive extraction of groundwater from geologically young sedimentary coastal cities can cause subsidence, which in turn can also enhance the relative rise in sea level [111]. Population and economic growth alongside the coast (i.e., littoralisation) is changing the coastal morphodynamics [112], limiting the sustainability of coastal ecosystems [110] and agriculture. Furthermore, migration from rural areas causes imbalances in the labour supply and skill mix in the rural areas [113]. Eventually, it becomes difficult for coastal agriculture to sustain production despite the increased viability of genetic improvements to crop varieties that renders them more suitable for growth in coastal areas.

3.2.2. Land-Use Change

Major dynamic uses of coastal lands include settlements, agriculture, seaport and harbour, industries and tourism [114]. Differences in the activities and their changes for which land is used in coastal areas have a significant effect on coastal ecosystems [7]. The expansion of urban land/settlement and non-agricultural use, such as industry, can supersede agriculture [32]. Coastal grasslands are changed into agricultural lands and both grass- and crop-lands are converted into built-up areas [115]. Agricultural lands are lost due to urban growth and the construction of roads, factories, amusement parks and tourist attractions, which is concerning in terms of coastal sustainability [116]. Tourism inhibits fisheries and the related sustainable infrastructure of the fishing industry [109]. Agricultural lands become a target for non-agricultural purposes (Box 2). Such competing changes in land use in coastal areas pose a threat to coastal agricultural sustainability.

Box 2. Land-use change.

Based on the images obtained from Google Earth Pro (version 7.3.2.5776), three regions are shown in Figure 2 that represents land-use changes in Ghana, Indonesia and Japan. In Gomoa East (Ghana) and Bali (Indonesia), croplands have been replaced with houses and roads, and in Choshi, Japan, croplands have been replaced with buildings and car parks (Figure 2).

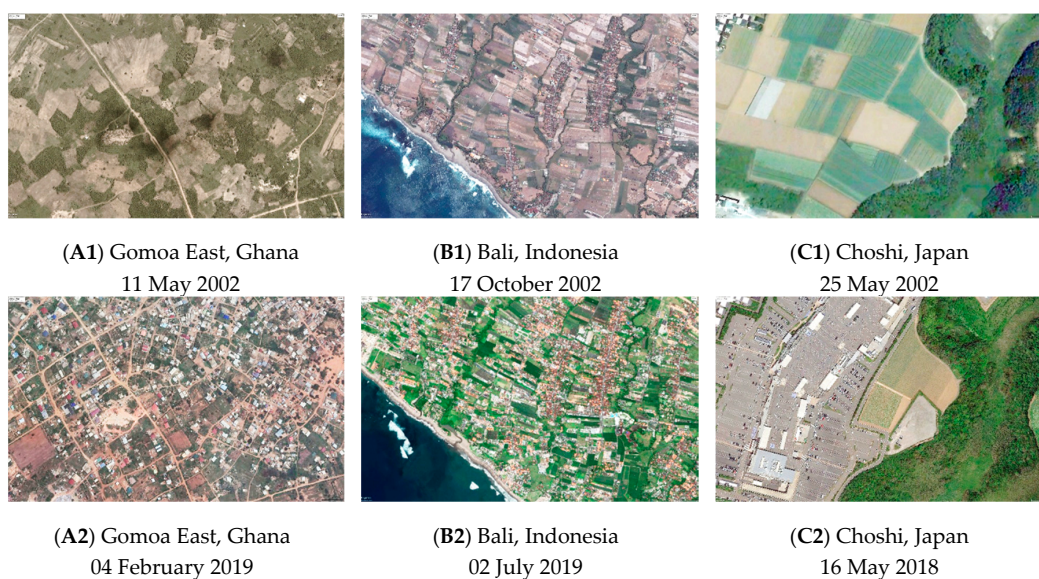


Figure 2. Changes in the land use in different coastal agricultural areas.

3.2.3. Pollution as a Constraint for Sustainability

Agricultural activities are heavily constrained by polluted soil, water and air. Human activities (both agricultural and non-agricultural) and weather events can cause soil and water pollution, salinisation and riverbank and coastal erosion, as well as the deposition of nutrients, pesticides and sediments in the geologically unstable coastal areas [7,115,117]. Coastal sediments, wetlands and other coastal ecosystems retain more than 90% of all chemicals, garbage and other material entering the ocean [32], causing the degradation of coastal agricultural lands. Soils are being depleted due to inadequately planned agricultural systems. Globally, 20 million tons of potential grains cannot be produced because of an estimated 12 million hectares of land degradation each year [118].

The coastal water is notoriously polluted in areas with high population and excessive tourism [7]. It was found that in Accra (Ghana), heavily polluted water from the city was being used for irrigation. Farmers used this untreated water for growing vegetables to be consumed by both the farmers and the inhabitants of the city. The rising urban demographic and industrial growth produces an increased volume of untreated wastewater [30]. Eutrophication near the coast is usually more prominent where the population is dense and agriculture is more intensive because sewage disposal, laundry waste and unutilised fertilizers end up in the sea [119]. Waste from agriculture and livestock is of significant concern in coastal areas [120]. Intensive agricultural activities, such as the excessive use of fertilizers and pesticides, also add toxic pollutants to the water that ultimately decrease the fish yield [7].

Shrivastava et al. [121] found that in the delta plains of West Bengal, heavy rainfall and monsoon flooding accelerated the infiltration of arsenic from the deep soil to the shallow underground water table. The arsenic then moved back into the soil during the winter via the underground water irrigation of rice. This resulted in arsenic contamination of the rice grains beyond the acceptable limit (1.6 mg/kg against 1.0 mg/kg). In south-east China, sulfur from a coal-based thermal plant trapped cadmium and lead in the topsoil, which subsequently accumulated in the rice grains, again leading to concentrations beyond the acceptable limit [122].

3.2.4. Gender Issues

The main issue that arises from climatic impacts on gender roles is the out-migration of rural people to city areas in the aftermaths of natural disasters. Regarding migration, males are more likely to go to cities to earn money from labour-intensive and non-agricultural jobs. The nature of non-agricultural jobs in the cities itself attracts mostly the men and the caring role of women restricts them from migrating to cities. Consequently, females tend to stay at home to raise children and take care of household activities. The migration of men in the face of climate change and poverty are the main reasons for the increase in women in agriculture, both as cultivators and labourers [123]. However, women from male-migrant families face difficulties when trying to continue farming in a sustainable way. It was observed that women face exclusion from extension services and found it difficult to prepare land and seed beds, irrigate land, spray pesticide and haul rice; duties that are usually performed by men in the coastal Mekong Delta in Vietnam [124]. In a changing climate, agriculture is not capable of sustaining the livelihood in coastal areas alone due to its low productivity. In coastal Tanzania, women have been forced to undertake subsistence agriculture (the rearing of small livestock, home gardening and beekeeping) to produce food for survival because of the insufficient income of the men from fishing activities [125].

4. Pathways Forward to Improve Coastal Agricultural Sustainability

Coastal agriculture faces both climatic and non-climatic stresses. Some of the stressors are long-term (e.g., temperature, rainfall, urban growth and pollution) while others are short-term or seasonal (e.g., salinity, coastal floods and migration). Multiple stresses are affecting coastal agriculture in a complex manner [115]. There is, therefore, no easy solution to this challenging problem. In this paper, we emphasise pathways for adaptation that are more relevant to the farmers in coastal areas.

The focus of agricultural adaptation is to perform better under the stresses, while mitigation tries to reduce the sources or enhance the sinks of greenhouse gases (GHGs) [21]. Mitigation is clearly the best option, but it is generally outside the scope of farmers because it needs to deal with both agricultural and non-agricultural GHG emission sources. The causality of CO₂ emission sources is complex and comprises multiple stakeholders [126]. Therefore, adaptation to the stressors by the farmers is the second-best choice. If it can be achieved together with the mitigation of stressors by all the stakeholders, it will be the most effective strategy for sustaining coastal agricultural activities.

Farmers are adaptive by nature as they continuously struggle against enormous environmental challenges. They depend primarily on their traditional knowledge and indicators of seasonal forecasts in making farm management decisions [127]. In many parts of the world, examples can be found of farmers adapting to climate change. For example, farmers in Bangladesh are practising self-made sorjan or floating methods of cultivating vegetables to tackle salinity and waterlogging. In the sorjan method, alternate ridges and furrows are made. The ridges remain above the water level and water remains in the furrows. Salts from the ridges can leach down to the furrows by rainwater. These farmers are also cultivating multiple stress-tolerant crop varieties that can withstand salinity and submergence [128]. In Pakistan, farmers are undertaking adjustments in sowing times, cultivating drought tolerant varieties and shifting to new crops as major agricultural adaptations [129].

Climate-smart agriculture (CSA) has been adopted in many parts of the world to cope with climate shock and minimise greenhouse gas emissions while sustaining crop yields [128,130]. Examples of such CSA include soil nutrient management through cultivating stress-tolerant crop varieties, composting manure and crop residues, urea deep placement, water harvesting and use, efficient harvesting and reducing post-harvest loss, altering cropping patterns and planting dates, diversifying the production system, cultivating vegetables in floating beds, crop rotation, minimum tillage and efficient water management [128,131,132].

Maintaining progressive agriculture and an unaltered environment is obviously the best solution, but this may not always be possible. Mitigation efforts place a major burden on carbon-intensive farms, which emit GHGs and accelerate the process of climate change [133]. Carbon dioxide emission is a complex social problem [126]. Despite the inconsistency in the findings of eco-efficiency, cost-effective GHG emissions are rare in industries [134]. Individual pollution reduction behaviour is influenced by incentives, the spread of pollution risk messages and pressures from markets and communities [135,136]. Regarding the farmer perspectives, organic farming, integrated pest management and zero-tillage can minimise agricultural pollution and improve market values of the commodities, but the amount of yield that is compromised by using these practices needs to be better understood. The possible trade-off between agricultural output and environmental stewardship needs to be empirically quantified and both economically and financially analysed [115]. Landowner incentives are important to motivate them to protect environmental resources, such as forests and water [114]. A short-term costly effort towards sustainable agriculture can bring long-term environmental benefits. Thus, the central philosophy of sustainable agriculture mimics the old saying “short-term pain, long-term gain”, as opposed to “short-term gain, long-term pain”.

In order to enhance adaptation and mitigation, appropriate actions are necessary at different levels, such as the micro-level (individual-household tier), meso-level (community-society tier) and macro-level (national-international tier), which are presented here.

4.1. Micro-Level: Farmer Perceptions, Awareness and Education

The response to climate change through agricultural adaptations depends on the understanding of climate change by the farmers [137]. Their recognition of climate change may not always be accurate as scientific information is not always properly communicated [138]. Global climate change occurs over a lengthy period, while individual experiences of climatic events are based on short-term local variability. This leads to a diversified response to climate change by different farmers. Therefore, it is important to understand the perception of coastal farmers before motivating them to adopt practices

for adaptation in a sustainable fashion. Box 3 shows how farmers understand climate change, which does not necessarily include only scientific indicators of climate change, e.g., temperature change. They use a set of proxy indicators, such as rainfall, cyclone, flood and salinity, to perceive climate change. Hasan and Kumar [139] found a significant correlation between the perception of climate change and the adoption of adaptation practices among the coastal farmers in Bangladesh where erratic rainfall, coastal flooding, seasonal droughts and salinity are usual climatic events. In this area of Bangladesh, the adoption rate of climate-smart agricultural practices was 48%, which could be enhanced through involving the farmers in farming associations and training programs [128,139].

Box 3. Farmers knowledge about climate change and adaptation.

Farmers sense climate change through changing temperature, rainfall and other indicators (Figure 3), which is mostly consistent with meteorological records [139]. In general, economically better-off farmers are more clustered in the good climate-change-perception group [140]. The sensing of climate change is significantly different from methods used by scientists since farmers do not use sophisticated instruments for measuring climate variables. Figure 3 shows that the change in tidal cyclones is the predominant indicator used by 24.6% of the farmers ($n = 118$) in the Kalapara sub-district of Bangladesh to understand climate change; they perceive that the climate is changing because the frequency of tidal cyclones has increased. Another important indicator used by farmers to understand climate change is temperature. According to the opinion of farmers, temperature is related to rainfall as an increase in temperature is linked to a decrease in rainfall, and an increase in drought affects soil moisture. Farmers always need to assess soil moisture to decide which crops to cultivate. One in five farmers perceive changes in the climate by observing two or more of the traditional climate change indicators.

Farmers identified salinity intrusion, tidal inundation, waterlogging, diminishing arable land, lack of fresh water for irrigation, yield loss and plant varieties with inadequate saline tolerance to be the major problems caused by climate-change-induced SLR. As a response to these threats, farmers perceived that using the sorjan and floating methods of vegetable cultivation, embankment cropping, rice–fish mixed farming and river-side and coastline mangrove afforestation would be sustainable pathways to improve coastal agriculture [141].

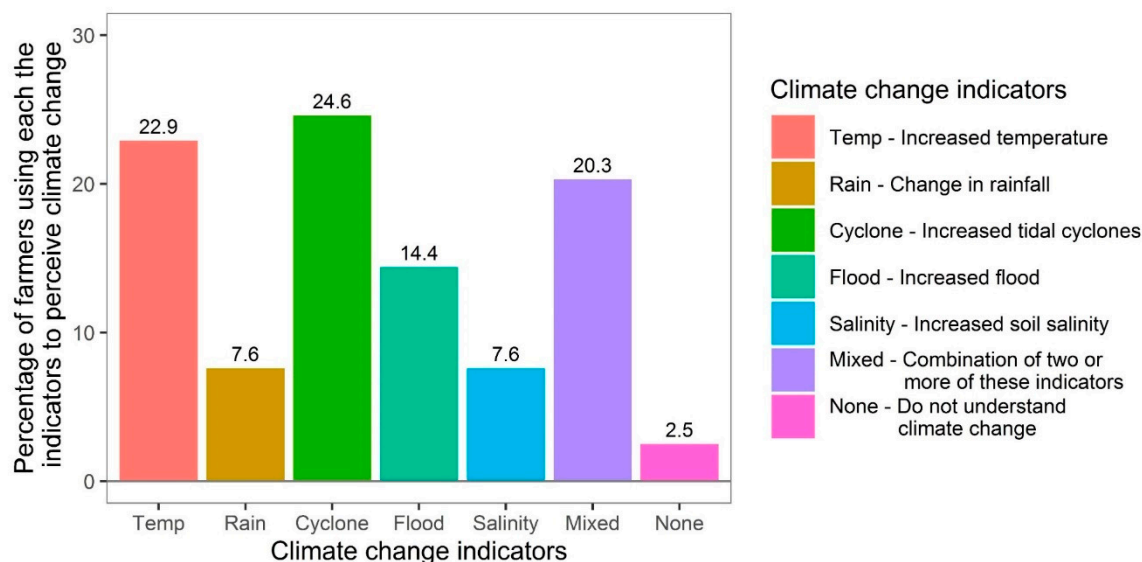


Figure 3. Percentage of farmers using traditional indicators to perceive climate change in a coastal region of Bangladesh (adapted from Hasan and Kumar [139]).

Knowledge concerning climate change is a crucial factor in making farmers aware of climate change, which in turn will help to increase their adaptive capacity and make informed decisions about the changing climate. Awareness of climate change acts as a vehicle for coping with climate change as local farmers can choose appropriate technologies and thus increase their adaptive capacity [142,143]. Education positively impacts on the growing awareness of climate change among farmers and enhances the probability of adaptation to climate change [144]. Farmers in coastal areas rarely receive scientific

information about climate change and adaptation due to the complexity of the content and the structure of information dissemination. A major challenge for raising the awareness of climate change and motivating farmers to adopt measures for adaptation to climate change is the dissemination of scientific information that is understandable to the layman [145]. To communicate more effectively about climate change, the use of bottom-up, participatory and context specific communication should be initiated. Emphasis should be given to key aspects of the communication process, such as goals, audience, message, messenger, channels and effects [146].

While communication alone is not sufficient to bring change in the awareness and behaviour of farmers regarding climate change, changes in policy support, economic conditions and infrastructure need to be ensured [147]. However, farmers from developing countries are sometimes incapable of using climate science in their farming decisions. This is why Caron et al. [148] stressed the need for educating both farmers and the public to obtain a better adaptive capacity and policy. Needs-based, timely and adequately packaged information concerning the weather and climatic trends, along with improved economic conditions, will help farmers to change farming systems as the climate changes [132,149].

Agricultural extension departments in many countries are operating farmer field schools (FFSs) through which farmers are receiving updated information regarding agricultural adaptation to climate change. The FFS farmers in coastal Jamaica were found to have a greater awareness, non-fatalistic behaviour and an improvement in the capacity for adaptation to climate change than non-FFS farmers [150]. Involving more farmers in FFS in developing countries will ensure sustainability in agriculture through enhancing adaptive capacity. Farmer-to-farmer communication is preferred by farmers for obtaining farming information. Therefore, such communication can complement government extension services used for the dissemination of adaptation strategies [132,149,151]. Therefore, providing knowledge about climate change by educating farmers or opinion leaders, along with providing incentives, could be a cost-effective option for communication about climate change.

The promotion of information about climate to coastal inhabitants is therefore important to improve their preparedness against disasters regarding agricultural activities. It was found that early warning systems for climatic hazards in coastal areas save lives and agriculture, as well as improving adaptive capacity [152]. Information about climate change can be sent through several types of social networks in coastal communities, ensuring a greater exchange of climate change information [153]. This will increase climate change awareness and participation in adaptation programs [154]. Understanding social networking and designing climate change communication will help to meet the knowledge and information gap between climate science and coastal farmers.

4.2. Meso-Level: Protective Measures

There is no panacea for climate-induced threats to coastal agriculture, so a holistic approach is needed to provide enhanced protection. To sustain the productivity of coastal agriculture, climatic threats need to be adequately addressed. In 2009, after cyclone Aila hit Bangladesh, the polder area was tidally inundated for two years due to a breached embankment, which hindered crop cultivation in one direction, while in the other direction, it raised the polder land by up to 40 cm over the two years through sedimentation [155]. Protection from the intrusion of saline water can be provided through the introduction of freshwater to drying rivers and waterways from active, fluid rivers by building barrages in low-lying delta plains [156]. Coastal agriculture in active deltas can, therefore, be protected from SLR, tidal surges and saltwater intrusion using controlled embankments with improved drainage facilities in the polders through the emplacement of appropriate sluiceways. With a rising sea level, these embankments and dykes should allow non-saline tidal water to enter at appropriate times of the year to raise polder lands with sediments [156]. It should be noted that the construction of embankments may not be possible in all deltaic areas.

Since coastal land erosion and degradation cannot be fully prevented by dykes, there is also a need for coastal afforestation. Coastal mangroves protect the land from erosion, conserve biodiversity

and act as a wind barrier against cyclones. However, the over-exploitation of mangroves with the rise in coastal population, along with the effects of cyclones, has led to the destruction of mangroves around the world at a rate of 0.66–1.04% per annum [157–159]. Extending the community-based coastal buffer zones along the coastal belt will not only prevent coastal erosion, but also minimise the force of tropical cyclones hitting the hinterlands [157]. The creation of green belts and windbreaks through coastal afforestation can also protect crops from strong winds (Figure 4). Effective protection for coastal agriculture may be achieved by incorporating context-specific research results into participatory and climate-responsive land use policy. This is necessary for sustainable coastal resource planning and management in a rising competition for coastal land use among the coastal fishing industry, crop farmers, forest loggers, industrialists, realtors and new settlers.



Figure 4. Mangrove afforestation along the coastal areas in Jaffna, Sri Lanka.

4.3. Macro-Level: Policymaking

The management of pressures affecting coastal agriculture is difficult. Many countries follow multidisciplinary integrated approaches involving governments, private sectors, non-government organisations and individuals [160]. In many areas, integrated coastal management has been effective but conflict over the utilisation of resources still exists. Conflicts arise when specific resource users think that distributions are unfair. Therefore, the acceptable and efficient distribution of resources by appropriate institutions is a prerequisite to sustainable coastal development [161]. Agricultural development has advanced tremendously since the “green revolution”, but environmental concern is more prominent in the planning level than found in the actual implementation. Transformation of coastal agricultural practices by individual farmers without supervised planning may not always be environmentally friendly. For example, sustainable fisheries can define the survival capability of many coastal communities; nevertheless, unplanned and excessive shrimp culture that requires ponds of saline water may not be sustainable and may be a concern regarding salinity intrusion [162,163]. In fact, coastal agriculture in Bangladesh has been undergoing a major shift from cereal production, especially paddy, to vegetable production [164] and shrimp farming because climate change and market demand have changed the economic incentives of different farming practices. Farmers are not willing to stick to the existing practices if changes in farming systems offer a higher income [165].

The sustainable management of coastal agriculture in polluted ecosystems is difficult. Major sources of pollution are agriculture, urban disposals and industrial wastes [166]. The implementation of policy is required to minimise pollution from both agricultural and non-agricultural sources. To bring sustainability into agriculture, investment in restoring degraded ecosystems and supporting infrastructure has been suggested by the Commission of Sustainable Agriculture [118]. The stakeholders who are directly vulnerable to climate change should take a role in preparing and implementing strategies for adaptation. Other relevant action should include the provision of necessary counselling regarding the sustainability of coastal agriculture [167]. Local communities are likely to contribute to developing and implementing sustainable agricultural strategies if their immediate needs are fulfilled without damaging the ecological carrying capacity [168]. Individual adaptation is motivated by self-interest that may not be beneficial for all. Therefore, joint adaptation is required through government interventions in training and market-based incentives [114,169,170].

Policies concerning the sustainability of coastal agriculture involve several stakeholders, such as administrators, policymakers and farming and non-farming communities living in the coastal areas. Policymaking and its implementation in coastal areas involving many countries can be a lengthier process than for an individual country [171]. Integrated coastal area management plans can be tailored prior to the implementation of country-specific capacity and requirements [32]. Integrated coastal management was found to be effective in the coastal cities of China regarding governance, the coastal environment and socio-economic aspects [116]. In addition, the raising of awareness to promote coastal management is necessary to render the current patterns of coastal management sustainable [172]. Education and voluntary incentive-based programs to improve the adoption of conservation practices can perform better than regulatory tools at controlling pollution in the case of industrial pollution in coastal areas and to promote sustainable agricultural land management [7].

Land-use planning is at the heart of sustainable agriculture. Different countries, as well as different farming communities (e.g., subsistence farming, family farming and capitalist farming) in an individual country, should be recognised and addressed differently in the integrated management policies [167]. Public policies need to diversify off-farm activities and to improve rural services with special attention being paid to the adoption of sustainable agricultural practices by smallholders. This would help to minimise the out-migration of rural farmers [113]. Though Bhutan is not a coastal country, its land use policy could be an imitable example of limiting the conversion of agricultural land for other uses. According to Sections 166–171 of the Land Act of Bhutan, landowners are required to submit a written application to the appropriate authority to use their land for different purposes [173]. Such prior-approval initiatives can protect against unplanned changes in land use in the coastal areas to promote agricultural sustainability.

From the perspective of sustainability science and feminist literature, the adaptation and mitigation to climate change should address the role of gender in strategic decision-making and in the access to the use of and control over resources [174]. In such a scenario, women's capacity building, along with the integration of participatory approaches in the management of natural coastal resources, is required to promote agricultural sustainability [175]. Besides cultural and economic barriers, the limited access to resources and inadequate policy support are the constraints faced by women in coastal areas that need to be minimised for attaining sustainability [176]. It is evident that traditional gender roles, social norms and unequal access to knowledge create differences in climate change perceptions between men and women [177,178]. The perception of climate change influences women more than men while selecting adaptation strategies [179]. In such a scenario, ignoring half of the population (women) in coastal planning and management may not help adaptation programs to become successful [180].

5. Conclusions

The sustainability of coastal agriculture is influenced by both climatic and non-climatic factors, of which SLR is the most influential factor. SLR is a consequence of climate change and will mainly affect coastal zones. Apart from SLR, climate change has the potential to affect coastal areas in several

ways, such as through increases in temperature, and changes in the frequency and intensity of rainfall and storms. Additionally, coastal areas are already stressed by littoralisation, human activity and pollution and climate change is likely to magnify these problems. Coastal agricultural problems are intermingled with each other, such as heavy rainfall in the up-side and SLR from the down-side, which creates a “double whammy” problem. Rising sea levels combined with storm surges are likely to cause accelerated erosion and increase the risk of inundation, and coastal agriculture is likely to be at the forefront of these impacts from climate change. The coasts will bear the brunt of the impacts from rising sea levels, increased salinity levels, storm surges, coastal erosion, floods and an increase in the frequency of extreme events, such as tropical cyclones. Many parts of the world are already reeling under such impacts. Increasing soil and water salinity caused by climate-change-induced rising sea levels is already driving coastal farmers inland. Apart from economic incentives, frequent flooding with saltwater is pushing farmers in countries, such as Bangladesh and Vietnam, to shift from growing rice to raising shrimp and other seafood, intensifying the issue of sustainability and food security of staple food crops in many parts of the world.

As the discussion and examples in this paper show, the sustainability of coastal agriculture has many dimensions and is an issue of immense importance. There are many factors that affect coastal agriculture, and climate change has the potential to exacerbate many of these. Increasing coastal population and urban growth are compounding this issue. The opportunity of jobs in the ever-expanding urban areas attracts farmers, mainly male farmers, to the cities, thereby leaving female farmers to take increasing responsibility for farm-related activities. Such gender issues have not been adequately addressed in terms of climate change. The perception of climate change and the information available or used by farmers for this is also an important topic to be addressed. There is also the issue of coastal agricultural adaptation to climate change, the failure of which can make further adaptations necessary that are beyond the reach of the experience of ordinary farmers. Each of these issues is a part of a complex puzzle. While the sustainability of coastal agriculture is a very complex issue and is affected by many inputs, both climatic and non-climatic, it needs to be addressed for future societal viability and food security. Integrated coastal resource management and proper land-use planning are of foremost importance. The inclusion of farmers in the planning and implementation of the policies is necessary. However, policymaking is more effective when education and communication work in a synergistic manner. Therefore, the gap between farmer perceptions and scientific records of climatic information must be minimised to increase their participation in adaptation actions concerning coastal agricultural sustainability.

This work showed that there is a dearth of papers on coastal agricultural sustainability and climate change. Since coastal agriculture will be majorly affected by climate change, there needs to be a concerted effort to undertake more targeted studies in these regions, addressing the individual stressors of agricultural sustainability. This paper has highlighted some of the pertinent issues that can lead to positive actions for the sustainability of coastal agriculture in the face of a changing climate.

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