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Review

Inland dry season saline intrusion in the Vietnamese Mekong River Delta is driving the identification and implementation of alternative crops to rice

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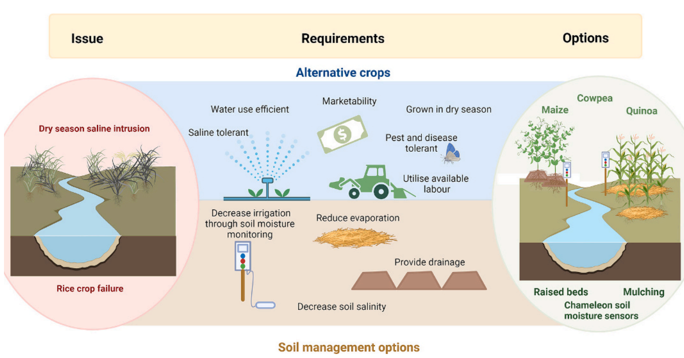
HIGHLIGHTS

- Inland saline intrusion is causing substantial rice losses during the dry season of the Mekong River Delta, Vietnam.
- Alternative crops and management practices need to be identified to supplement the loss of rice income.
- Numerous biophysical, environmental, and socioeconomic factors are identified that determine alternative crops suitability.
- Mulching, raised beds and soil water monitoring can decrease salinity stress and improve water use efficiency.
- Combining alternative crops and management practices provide farmers with options for saline affected areas.

GRAPHICAL ABSTRACT

Dry season saline intrusion in the Mekong River Delta is requiring the identification of suitable alternative crop and soil managment options for farmers.



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Inland saline intrusion is causing substantial rice losses during the dry season of the Mekong River Delta, Vietnam
Alternative crops and management practices need to be identified to provide farmers with options to supplement the loss of rice income

ABSTRACT

CONTEXT: Inland saline intrusion is occurring during the dry season in the Mekong River Delta (MRD), Vietnam. Rising sea levels, tidal fluctuations, drought, and changes to upstream flow contribute to extensive salinisation of rice producing areas of the MRD, leading to substantial rice crop losses.
OBJECTIVE: The identification, evaluation and implementation of alternative crop and soil management solutions are required to complement on-going rice production in the region.
METHODS: A review of scientific and grey literature was conducted regarding the nature and extent of salinisation in the MRD and the adoption and management of alternative crops to rice.

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Numerous biophysical, environmental, and socioeconomic factors are identified that help determine an alternative crops suitability
Management practices including mulching, raised beds and soil water monitoring can decrease salinity stress and improve water use efficiency
Combining alternative crops and management practices provide farmers with production options for saline affected areas during the dry season

RESULTS: Familiar crops in Vietnam (e.g., maize, soybean), as well as novel crops to the MRD (e.g., quinoa, cowpea) were explored as potential options to replace dry season rice. Management options including surface soil mulches and plastic coverings help maintain soil moisture and reduce salinity damage to plants, and the use of drainage and seed preparation techniques can improve plant establishment and yield. Factors contributing to the success of alternative crops include salt tolerance, timing and efficiency of water use, ability to grow in the dry growing season, tolerance to pests and diseases, labour intensiveness and the crops' marketability.
SIGNIFICANCE: The identification of suitable alternative crops to replace dry season rice in saline affected areas of the MRD, combined with management practices like mulching and soil moisture monitoring, could provide farmers with income opportunities to offset rice losses. Documenting the factors contributing to successful crop diversification can assist with decision-making and support initiatives among farmers, agribusiness, and government agencies.

1. Introduction: The Mekong River Delta and the central role of rice cropping

This review focuses on the increasing salinisation of the Mekong Delta in Vietnam and the search for alternative crops to rice. Focusing on the primary bio-physical aspects, the review has sections on: the Mekong River Delta and the central role of rice cropping, saline intrusion, alternative crops to rice, and in-field management practices to mitigate the impacts of saline intrusion.

The Mekong River Delta (MRD) is in the south of Vietnam where the Mekong River flows through a network of distributaries before reaching the East Sea (Fig. 1). The Mekong is the longest river in Southeast Asia and originates in the Tibetan Plateau before flowing through China, Myanmar, Laos, Thailand, Cambodia and Vietnam; it provides an important water source for over 70 million people (Räsänen et al., 2017). Fertile alluvial soils have been deposited along the Mekong River, but the presence of anaerobic conditions in subsoils means that acid sulfate soils are widely present throughout the Delta (Nguyen et al., 2020b). The 40,000 km^2 of MRD productive land mass sits marginally above sea level (<5 m) (Anh et al., 2019) and is dominated by rice production (Nguyen et al., 2020b).

Approximately two-thirds of the MRD is dedicated to agricultural production. Agriculture has been estimated to account for approximately 40% of regional GDP and to provide for the livelihoods of over 75% of people, leaving the economy of the MRD particularly exposed to negative impacts on agricultural production arising from saline intrusion (Mackay and Russell, 2011). Rice production is fundamental to the economic function and livelihoods of the people of the MRD (Nguyen et al., 2020c). With an average annual production of 24.9 million tonnes, Vietnam is the fifth largest rice producing country in the world and a net exporter of rice (CGIAR, 2016). The MRD accounts for 12% of the total area of Vietnam but provides >50% of the total paddy area planted in Vietnam (General-Statisitcs-Office., 2019). This contributes to 56% of the total rice produced and provides income for up to 80% of the MRD population. Rice yield varies from year to year largely due to a range of climatic factors. For example, in 2019 the paddy rice production was 0.6 Mt. less than average due to a combination of drought and hot weather.

Flood control measures (Marchand et al., 2011), advancements in fertiliser use, implementation of mechanisation and the adoption of high yielding rice varieties saw the rice production area increase from 52% to 91% of the Delta area (Nguyen et al., 2020b). A combination of climatic, soil and hydrological conditions allow farmers to produce up to three

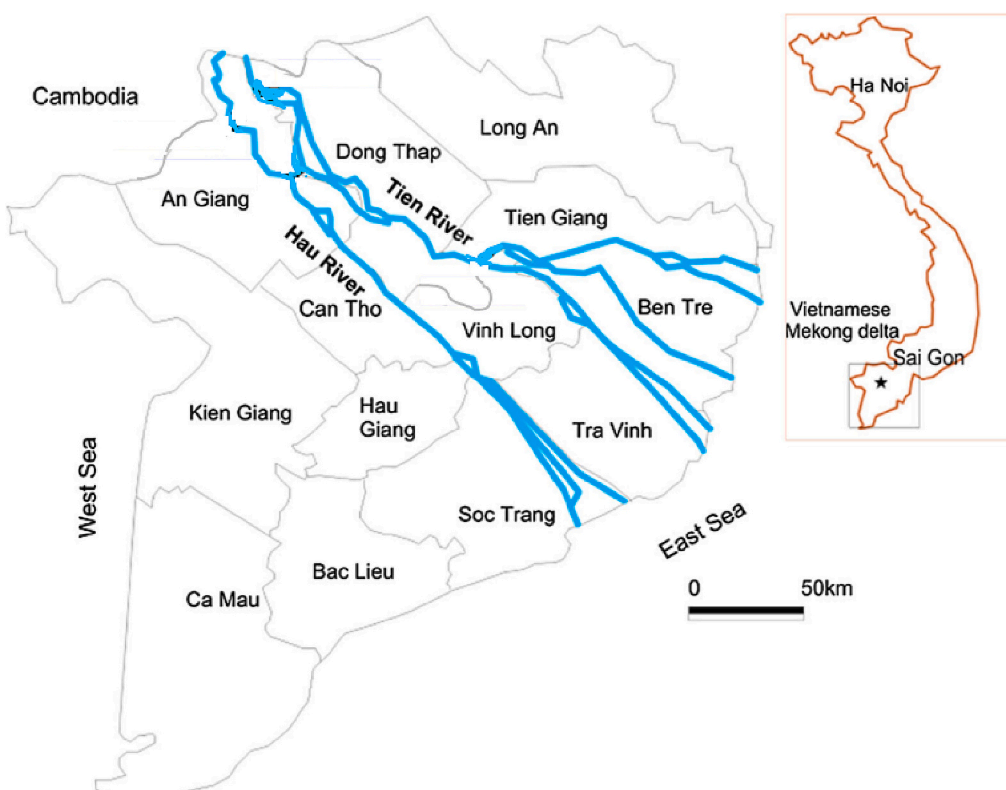

Fig. 1. Map of the Vietnamese Mekong Delta, its provinces, and its location within Vietnam (insert) (map adapted from Trieu and Phong (2015).

rice crops a year. The climate of the region is tropical monsoonal, with two distinct seasons (Fig. 2); 90% of the average rainfall (1860 mm) occurs in the rainy season (Dang et al., 2020). The timings shown in Fig. 2 are typical for the MRD, however they may vary between different parts of the region.

2. Saline intrusion

While the development of irrigation infrastructure in the 1970's (Wassmann et al., 2004; Van Kien et al., 2020) allowed for the intensification of rice production (Nguyen et al., 2020b), it also created a link between the ocean and agricultural regions. Because the MRD has a marginal elevation above sea level, it is vulnerable to oceanic saline water intrusion. This is exacerbated by changes to upstream river flows and a changing climate causing rising sea levels, tidal influxes, and drought (Wassmann et al., 2004; Trieu and Phong, 2015; Hoa et al., 2019). The contributing factors to dry season saline intrusion and the associated effects these have on the MRD are highlighted in Table 1.

Salinity has been identified as the most prominent hazard to agricultural production for farming households (Renaud et al., 2015) with national authorities suggesting the irrigation threshold for salinity regarded as being detrimental to rice production is 4 g L^{-1} (Le et al., 2007). Saline intrusion has damaging effects on agricultural production, farmer livelihoods and economic stability (Phung et al., 2020). In 2000, the Vietnamese government recognised the need to diversify agricultural production in order to meet food security demands and thus changes were made to the land use policy (Nguyen et al., 2020c). This allowed for the diversification into rice shrimp farming along coastal areas that utilised saline water and provided high economic returns, however at the adverse cost of rapid soil salinisation. Over 1.2 million ha of the southernmost point of the MRD is now classified as salt affected as a result of rice shrimp farming (Thi Nhung et al., 2019). Increasingly worrisome is evidence of saline intrusion occurring in inland provinces further up the Mekong traditionally not affected by salinity (Fig. 3) (Phung et al., 2020). Despite the installation of over 21,000 sluice gates along the 92,000 km of canals of the MRD (Marchand et al., 2011), saline water is impacting rice production and decreasing long-term productive capacity as soil salts accumulate over time (Renaud et al., 2015). In 2020, parts of the MRD including Soc Trang and Tra Vinh Provinces declared emergencies with drought and salinity affecting over 100,000 ha of rice crop production as salt water intruded ~60–70 km inland (MARD, 2020).

Table 1
The contributing factors causing dry season saline intrusion and the consequential effects on the Mekong River Delta, Vietnam.

Contributing factor	Effect on MRD	Reference
Increasing sea levels	• Average sea level rise of 3 mm yr^{-1} • Forecast sea level rise from 0.3 to 0.8 m by 2081–2100, affecting 75% of land area and 70% population inundated	Stocker et al., 2013 IPCC, 2021 Minderhoud et al., 2019
Land subsidence	• Occurring at a rate equal to and/or faster than sea level rise (average 1.1–2.5 mm yr^{-1}) • Land subsidence combined with tidal fluctuations exacerbate saline intrusion	Minderhoud et al., 2019 Hoa et al., 2019
Drought	• Dry periods are becoming longer, hotter and have increasingly sparse rainfall causing salt to accumulate in the soil • Acute drought in 2016 (215,000 ha of rice loss and 320 million USD in damages) and in 2020 (loss of 460,000 ha of rice.	Pang et al., 2010; Phan et al., 2020 Lee and Dang, 2019 WorldBank, 2017 IFRC, 2020
Upstream flow variations	• Upstream hydrological dams have changed river flow and sediment delivery • Lack of sediment deposition has increased riverbed incisions (~3 m) causing the rapid intrusion of saline water	Räsänen et al., 2017 Binh et al., 2020 Eslami et al., 2019

The extent of saline intrusion over time is summarised in Fig. 4 where intrusion occurred prior to sluice gate control (1998), was constrained to coastal areas in 2010, however breached sluice gate control measures in 2016 and 2020 and intruded far into inland provinces affecting over 2 million ha (Loc et al., 2021). It has been predicted that salt concentrations in 2050 will exceed 4 g L^{-1} up to 60 km upriver from the ocean (Vu et al., 2018), meaning that inland areas like Can Tho will be subjected to the same severe salinisation currently observed in coastal areas.

In response to inland saline intrusion, farmers have varied the time of sowing based on seasonal predictions (Phung et al., 2020) in an effort to advance crop development and avoid salinity damage at the critical stages of anthesis and grain filling (Fig. 4). Efforts have also been made

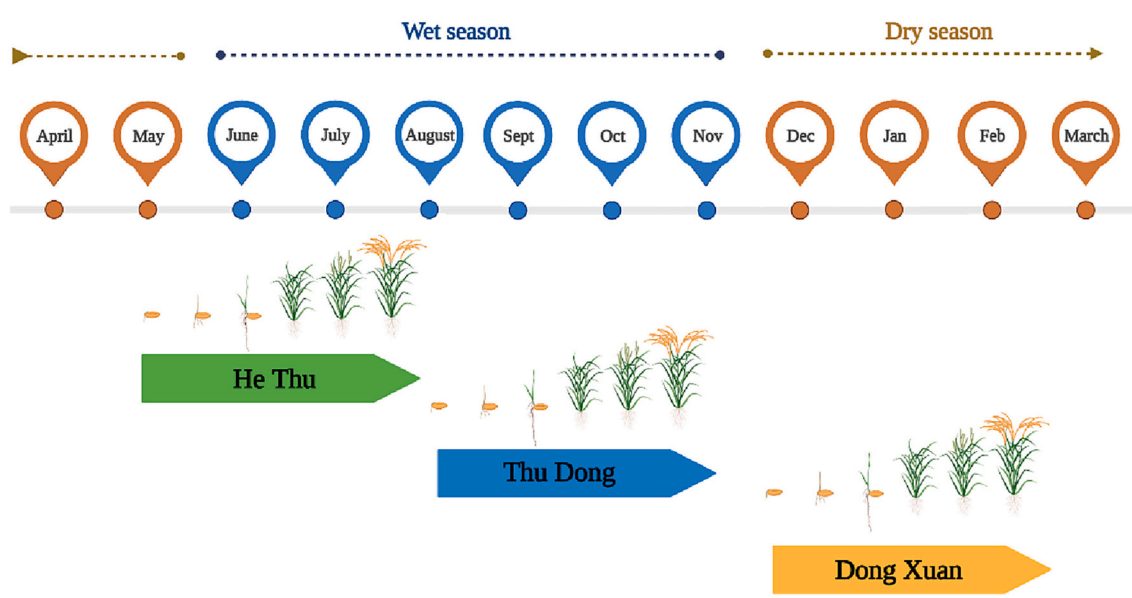

Fig. 2. The three phase (He Thu, Thu Dong and Dong Xuan) rice cropping calendar of the Mekong River Delta. Also shown are the months of the rainy and dry seasons.

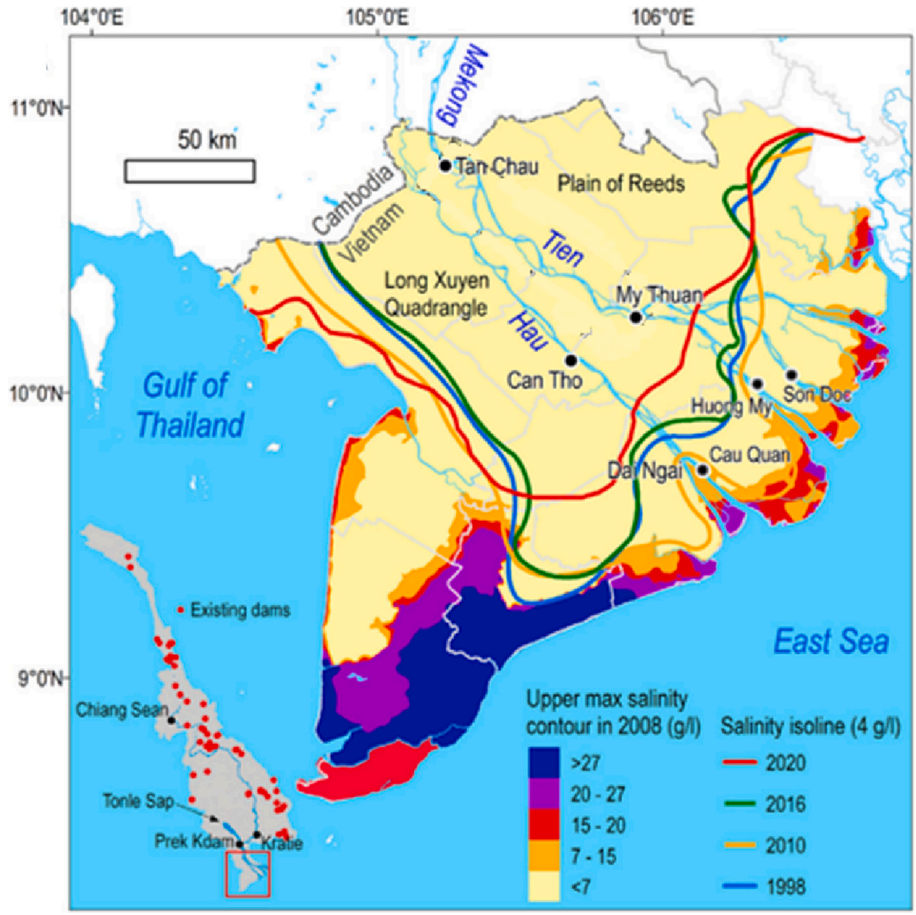

Fig. 3. Maximum areas of the MRD affected by dry season saline intrusion with isolines in the rivers and water distributaries set at the threshold 4 g L^{-1} (Figure adapted from Loc et al. (2021)).

by the Consortium for Unfavourable Rice Environments (CURE) to encourage farmers to adopt the use of salt tolerant rice varieties to reduce salinity damage. In some areas including Ca Mau and Soc Trang, over 80% of households have implemented the use of salt tolerant rice varieties (Paik et al., 2020) even though market prices for these varieties are lower (Manzanilla et al., 2017). Despite attempts to use earlier sowing dates and salt tolerant varieties as a method to reduce salinity damage, substantial crop losses including complete crop failure have continued to occur (CGIAR, 2016; MARD, 2020).

Rice grown in the Dong Xuan season is most susceptible to the effects of saline intrusion where salt stress effects the development and growth of rice. In addition, He Thu season rice is dependent on the onset of a sufficient wet seasonal break to leach salts from soil to a level acceptable for the transplantation or sowing of rice. In response to the early onset of the extensive saline intrusion event in 2020, farmers were instructed not to grow rice in areas that could be impacted by saline intrusion and were urged instead to grow drought tolerant crops (MARD, 2020). In the absence of adequate research-based solutions to saline intrusion, farmers in areas traditionally growing three rice crops a year have also been advised to limit production to two crops a year (Nguyen et al., 2020b). To supplement the loss of income incurred from decreased rice production, there is a requirement for alternative crops with a higher tolerance to salinity and lower water use that are suitable for growth in the Dong Xuan period.

3. Alternative crops

To identify and successfully grow alternative crops to rice in the MRD dry season, criteria must be developed that encompass the suitability of a plant to fit into the production system. These include suitability for growth in saline or water limited conditions, appropriate growing duration and correct temperature range for the Dong Xuan season, tolerance to diseases and pests, an ability for the crop to be grown and processed using existing labour, and the overall profitability of and market availability for the alternative crop. The complexities of combining plant adaptation, with social and economic imperatives in finding a suitable alternative crop for adoption in a rice-dominated landscape should not be under-estimated. Whilst six alternative crops are investigated in this review, they are not the only options that may be suitable, and thus emphasis should be placed on the method of identifying and determining alternative crops. This allows for assessment in areas outside of the MRD that may need alternative crops for similar reasons.

3.1. Salt tolerance

Crops have varying degrees of tolerance to salinity (Maas and Hoffman, 1977; Steppuhn et al., 2005) and respond physiologically in different ways to salt exposure (Greenway and Munns, 1980; Munns, 2005). High salt concentrations cause osmotic stresses that impede the ability of roots to take up water, and ionic stresses from absorbed Na^+ and Cl^- can affect plants metabolic pathways (Munns and Tester, 2008). An additional important elaboration on crop physiological responses is that waterlogging (soil saturation, an important soil constraint in Vietnam) under saline conditions can increase Na^+ and Cl^- uptake and decrease K^+ uptake by crops, which can substantially decrease crop growth and commercial yields (Barrett-Lennard, 2003; Barrett-Lennard and Shabala, 2013). In the MRD, salinity increases throughout the dry

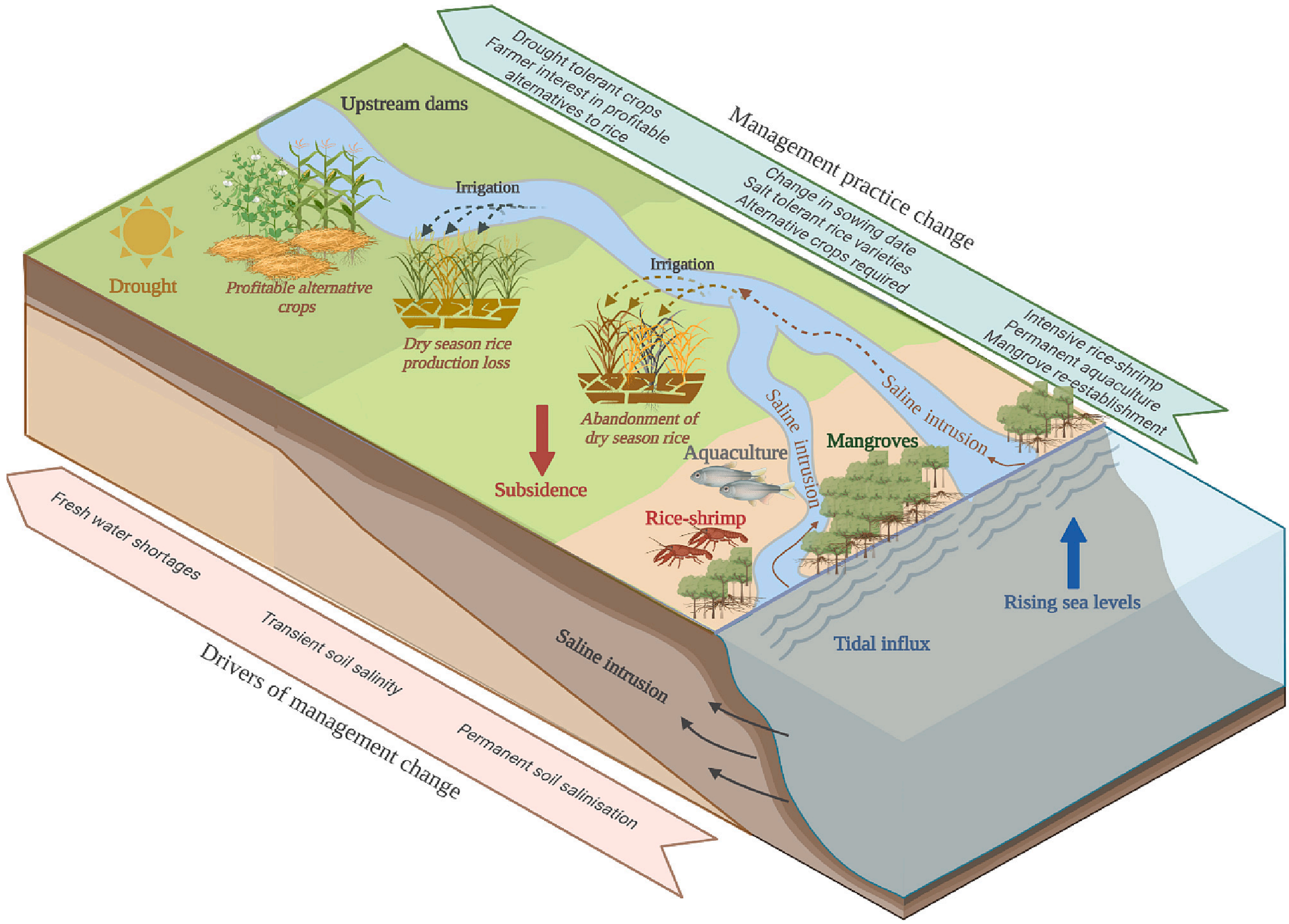

Fig. 4. The contributing factors causing saline intrusion and consequential dry season rice production loss in the Mekong River Delta Vietnam, including the progression and drivers of changing management practices.

season with canal water salt concentrations exceeding the 4 g L^{-1} rice producing threshold in lower elevations of the delta (Phung et al., 2020), sometimes reaching ~15 g L^{-1} towards the end of the dry season (Eslami et al., 2019). Rice will start to incur yield losses at 2 g L^{-1} (Grattan et al., 2002) and even salt tolerant varieties will suffer grain quality defects at 3 to 4 g L^{-1} (Qin et al., 2020). Consequently, plants that can either tolerate salinity during the reproductive stages of growth, or plants that can be harvested early will be more suitable as alternative crops.

Are there prospective salt tolerant crops for the MRD? Field trials of possible crops are just starting, but there are promising and notable alternative crops of whom demonstrate various cellular physiological mechanisms for tolerating salinity exposure. Salt-tolerant varieties of cowpea (*Vigna unguiculata*) appear to osmotically adjust by accumulating greater concentrations of Na^+ in their roots during vegetative stages to minimise salinity damage (Le et al., 2021). The upregulated production of proteins involved in photorespiratory pathways also occurs in cowpea plants exposed to salinity (De Abreu et al., 2014). Quinoa *(Chenopodium quinoa)* can withstand high levels of salinity due to its halophytic nature and efficiency in excluding Na^+ from its leaves (Cai and Gao, 2020). In fact, quinoa has shown to have increased biomass and yield production under saline conditions compared to non-saline conditions (Hariadi et al., 2011; Jacobsen et al., 2003). Characterisation of the salt overly sensitive gene *(SOS1)* involved in salt sensory mechanisms has occurred in quinoa (Maughan et al., 2009) with the plant demonstrating the ability to rapidly sequester salt into the vacuole to prevent the accumulation of cytoplasmic Na^+ (Cai and Gao, 2020). An overexpression of the *SOS1* gene was also found in saline tolerant mustard greens *(Brassica juncea)* that was associated with an increased sequestration of Na^+ in roots (Singh et al., 2019). Proline is an osmoprotectant that plays a critical role in counteracting osmotic stress and increased concentrations of proline have been found in salt-stressed maize (*Zea mays*) plants (Kaya et al., 2010).

Whilst alternative crops have differing cellular physiological salt tolerance mechanisms, salinity also affects the agronomy and consequential yield in different ways. Seedlings are generally sensitive to salt exposure; however, seedlings of alternative crops are planted when soil salinity levels are low. For this review, germination and seedling tolerance is irrelevant and will not be further investigated. Priority lays with an alternative crops ability to withstand salinity exposure during vegetative and reproductive growth. Ultimately, the precedence is a crops ability to produce marketable yield in a saline environment. Table 2 summarises the yield response of alternative crop options at varying salt concentrations including a relative ranking.

Quinoa proves very salt tolerant and successfully produces grain (Hussain et al., 2020) at similar concentrations recorded in canals during extreme salinisation events in the MRD (Eslami et al., 2019), whilst cowpea and mustard greens demonstrate high tolerance. The successful inoculation of cowpea played a significant role in the crops ability to withstand increased salt concentrations (Manaf and Zayed, 2015). The reproductive phases of maize are affected by salinity with decreased kernel set and grain weight (Kaya et al., 2010) and consequentially, is ranked lower than cowpea and mustard greens. Soybean has a low tolerance and ranks similarly to rice, although salt-tolerant soybean varieties can increase photosynthetic rates to generate ~47% greater grain yields than salt-sensitive varieties (He et al., 2016). Salinity stress in soybean can also greatly affect grain quality including the oil and

Table 2
The effect of salt concentrations on the yield response of various alternative upland crops and rice compared to their non-saline treatments. The mean % yield loss per unit salinity for each species was used to rank plant tolerance to salinity.

Crop	Salt conc. (g L^{-1}) *	Yield response	Reference	Relative ranking
Quinoa	16	60% yield ↓	Hussain et al. (2020)	**Very high tolerance**
	8	45% yield ↓		
	9	48% yield ↑	Jacobsen et al. (2003)	
	25.5	32% yield ↓		
	2.9	14% yield ↓	Nguyen et al. (2016)	
	17.5	51% yield ↓		
Cowpea	3	23% yield ↓	Manaf and Zayed (2015)	**High tolerance**
	3.8	47% yield ↓	Düzdemir et al. (2009)	
	2	48% yield ↓	Mshelmbula et al. (2015)	
	2.9	9% yield ↓	Taffouo et al. (2009)	
	3.3	8% yield ↓	Sohrabi et al. (2008)	
	5	20% yield ↓		
Mustard greens	4.1	14% yield ↓	Singh and Panda (2012)	**High tolerance**
	3.3	13% yield ↓	Shanker et al. (2014)	
	5	21% yield ↓		
	6.8	28% yield ↓		
Maize	2	13% yield ↓	Feng et al. (2017)	**Moderate tolerance**
	3.4	17% yield ↓		
	2.9	14% yield ↓	Baghel et al. (2019)	
	5.8	36% yield ↓		
	1.6	33% yield ↓	Rodrigues et al. (2020)	
	2.7	45% yield ↓		
Rice	1	8% yield ↓	Zhang et al. (2022)	**Low tolerance**
	2	18% yield ↓		
	1.6	13% yield ↓	Saidy and Arslan (2022)	
	5.6	100% yield ↓		
Soybean	3.8	42% yield ↓	Papiernik et al. (2005)	**Low tolerance**
	3.3	58% yield ↓	Ghassemi-Golezani et al. (2009)	
	5	76% yield ↓		
	3	29% yield ↓	Sadak et al. (2019)	
	6	72% yield ↓		

* concentrations are approximate due to conversion.

protein content (Ghassemi-Golezani et al., 2009).

3.2. Efficiency of water use

A plant with efficient water use will assimilate more biomass or grain per unit of water. During the dry season in the MRD there are infrequent rainfall events (Dang et al., 2020) which need to be offset by the increased use of irrigation water. Where this irrigation water contains salt, these salts can accumulate in the soils during the growing season. Alternative crops that have a high-water use efficiency (WUE) or low water requirement may minimise the dependence on irrigation to complete their lifecycle. A plant's WUE is dependent on physiological processes, and anatomical and morphological adaptions that control water movement (Liu et al., 2005). Decreased stomatal conductance will reduce transpiration rates, however there can also be decreased yields from concurrent decreased CO_2 assimilation. A suitable replacement crop will need to have elevated WUE without significant adverse effects on yield. Fig. 5 compares the WUE of a range of crops with potential for growth in the MRD. In general, higher WUE can be achieved with the application of less irrigation water. Of the six crops listed in Fig. 5, soybean, and quinoa both use less water throughout the growing season to achieve the highest levels of WUE in this dataset (~8 kg ha^{-1} mm^{-1}). By contrast, rice was a profligate user of water and had a far lower WUE. Cowpea was more water efficient in the post-rainy season and more resilient to water limited conditions that promoted high evapotranspiration rates (Oumarou et al., 2015). Studies by Kang et al. (2000) show that the WUE of maize is improved when plants experience drought stress at the seedling stage. These seedlings were better adapted to water deficiency at stem-elongation and experienced no negative effects on yield. Similarly, the WUE of soybean was improved by incurring mild water deficits before and after anthesis (Liu et al., 2005). The highest WUE for mustard greens was observed to be the treatment with relatively moderate water inputs (190 mm) compared to treatments with higher irrigation (225 mm) (Kumar et al., 2020).

Factors contributing to a plant's WUE are also intrinsically linked with the physiological effects of salinity induced osmotic stress. Thus, WUE and a plant's ability to withstand saline conditions are often examined together. The saline-tolerant quinoa variety Utusaya maintained a higher stomatal conductance in saline conditions up to 12 g L^{-1} NaCl with only a 25% reduction in CO_2 assimilation compared to the 67% reduction in the salt-sensitive variety 'Titicaca' (Adolf et al., 2012). Stomatal conductance of salt-tolerant maize plants was unaffected by salinity at NaCl concentrations up to ~6 g L^{-1} mM and the variety BR5033 maintained its leaf water potential at this concentration despite there being a reduction in root hydraulic conductivity (Azevedo Neto et al., 2004). Cowpea was found to be tolerant of salinity induced water stress by decreasing transpiration rates without significant adverse effects on yield (Düzdemir et al., 2009).

Alternative crops with a low water use and high WUE are more suited for growth in the MRD dry season to suit the minimal rainfall (Fig. 5). The development and weakening of the monsoon system control the

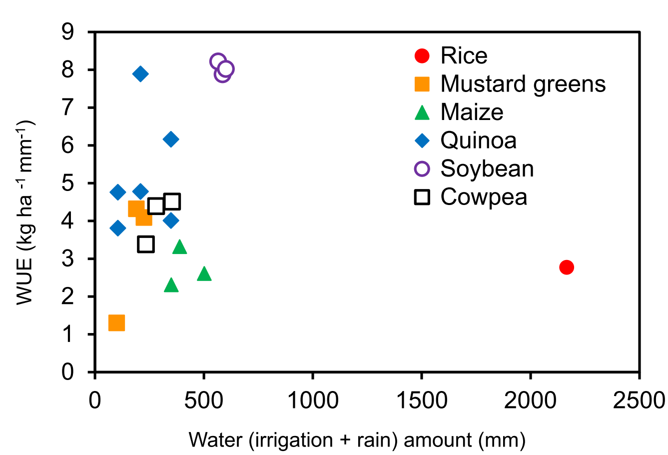

Fig. 5. Water use efficiency (WUE) of alternative crops with potential for growth in the Mekong River Delta. WUE was calculated as the ratio of commercial yield (kg ha^{-1}) to water applied via irrigation and/or rainfall (mm) for a range of crops including rice (Materu et al., 2018), mustard greens (Kumar et al., 2020), maize (Kang et al., 2000), quinoa (Telahigue et al., 2017), soybean (Irmak et al., 2014) and cowpea (Souza et al., 2019).

onset of the rainy and dry seasons. The MRD dry season rainfall averages 107 mm; this falls in an unpredictable pattern from December through to April, although totals of between 411 and 512 mm have been recorded (Dang et al., 2020). Soybean and maize can provide high yielding crops with efficient water use, however they both require >350 mm of growing season moisture to achieve this (Fig. 5). Supplementary irrigation is therefore likely to be required which has the potential to increase salinity exposure and soil salinisation. Alternatively, quinoa and mustard greens can complete their life cycle with just over 100 mm of water, and cowpea with a little over 200 mm, making these crops a more suitable replacement for rice regarding water use.

3.3. Crop duration and temperature suitability for Dong- Xuan

In general, the dry season starts in December and continues until May where salinity levels are highest (Fig. 6). Whilst this allows for a potential 150-day growing period in which an alternative dry season crop can be grown, a shorter duration variety might be more desirable. Canal water increases in salinity and soil salinisation peaks in the later months of the dry season (Kotera et al., 2014). Fig. 6 shows that crops with a shorter growing period may have the potential to complete their life cycle before the salinity concentrations peak at the end of the dry season. By contrast, longer duration crops need to have high salt tolerance during their reproductive phase because this aligns with the highest salinity concentrations (Fig. 6). Therefore, an ideal alternative crop needs to have a shorter duration than the current 120-day rice crop, but also needs high salt tolerance during reproductive phases. Fig. 6 shows that cowpea, mustard greens and quinoa all have shorter crop durations than maize, soybean and rice. All crops are likely to experience some salinity stress regardless of growth duration, although the longer duration crops will be exposed to high salinity levels at both vegetative and reproductive phases. Maturity will be reached for the shorter growing crops before the second peak of salinity occurs (Fig. 6).

Temperatures remain relatively consistent all year round with maximum daytime temperatures ranging between 30 °C and 35 °C and minimum temperatures ranging between 24 °C and 28 °C. Therefore, a suitable replacement crop must be adapted and suitable for growth in warm conditions with a relatively low rainfall. Crops that require a vernalisation period or a cool growing season are not suitable. Maize is a C4 plant that has already been successfully produced in the MRD as farmers diversify from rice to provide supplementary income and additional household provisions. Over 16,000 ha of maize has been sown across the An Giang, Dong Thap and Can Tho provinces (Smith, 2013). Maize can tolerate high temperatures with a photosynthetic inhibition not occurring until ambient temperatures reach 37.5 °C (Crafts-Brandner and Salvucci, 2002). However, access to irrigation would be critical for the successful growth of maize due to its high growing season water requirements. Unfortunately, peak irrigation demand during the low rainfall months of January to March coincides with high salinity concentrations in the canals (Fig. 6).

Soybean is another alternative crop that can tolerate high temperatures but requires irrigation. Soybean can tolerate a range of growing temperatures (20–40 °C) (Alsajri et al., 2019), although a water requirement of up to 600 mm is needed (Irmak et al., 2014). Irrigation would be required to supplement the low dry season rainfall for the successful growth of soybeans in the MRD. Farmers became familiar with growing soybean and maize in the MRD as popular vegetable crops (Khai and Yabe, 2011) after the Ministry for Agricultural and Rural Development (MARD) developed a land-use plan (2014–2020) to encourage the shift from intensive rice production to alternative cropping systems (Nguyen et al., 2020b). However, the higher water requirement of maize and soybean may limit the crops suitability for larger scale growth as an alternative to rice.

Another possible alternative crop is quinoa; this tolerates a wide range of temperatures (5–35 °C) (Oveisi, 2017) and is highly drought resistant with a low water requirement (Algosaibi et al., 2017; Telahigue et al., 2017). Whilst its growth is not common in Vietnam, it has been successfully grown in conditions similar to the MRD dry season (Choukr-Allah et al., 2016). However, quinoa's sensitivity to waterlogging (González et al., 2009) would require careful management following its growth after a rice crop. Implementation of raised bed systems might successfully alleviate waterlogging issues (Bakker et al., 2010).

Mustard greens is affected by heat stress (35/15 °C) at early flowering stages although biomass production is unaffected at moderate temperatures (day/night) of 28/15 °C (Angadi et al., 2000). Cowpea has been successfully grown in the dry season of Niger where temperatures

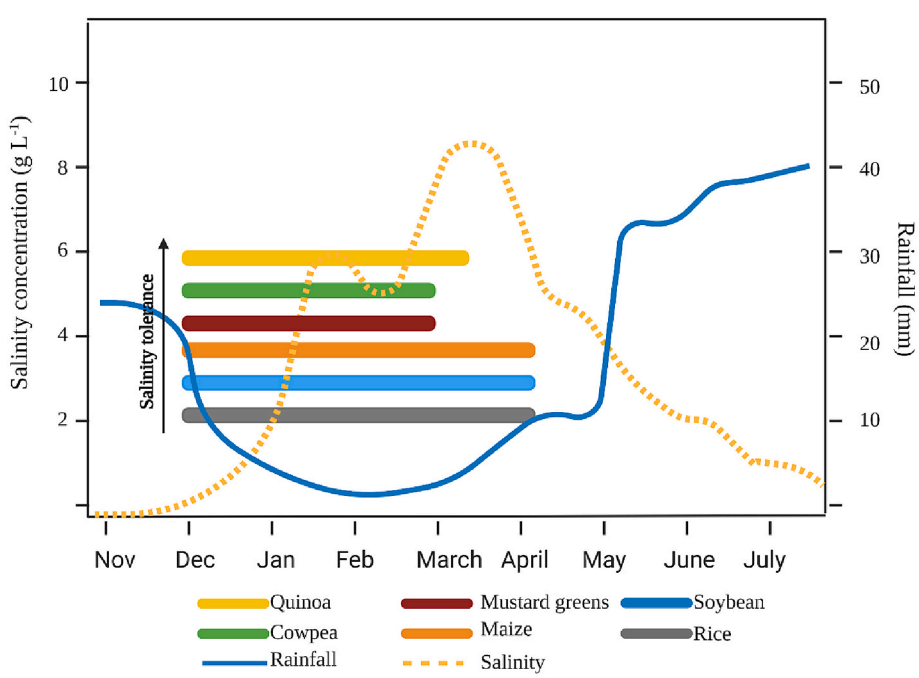

Fig. 6. An overlay of dry season canal salinity concentrations (average of Soc Trang and Dai Ngai) with average monthly rainfall and crop growing duration for quinoa, cowpea, mustard greens, maize, soybean and rice (Salinity data from Ratering Arntz (2018).

ranged from 31 to 44 °C (Oumarou et al., 2015).

Alternative crops with a shorter growing duration like quinoa, cowpea and mustard greens that would mature before the peak in salinity occurs may be a more suitable option as a replacement dry season crop. Additionally, tolerance to the high temperatures that occur throughout the dry season is essential for a plant to successfully grow as an alternative to rice.

3.4. Tolerance to disease and pests

Disease and pest susceptibility refers to the risk of a plant being likely to be affected by diseases or pests. This can have implications for yield and profitability and thus an alternative replacement crop for rice should have a relatively low susceptibility. Diseases and pests can often be controlled by integrated pest management (IPM) options involving either chemical application or biocontrol methods, although the cost for implementing these must be considered when considering alternative crops.

High disease and pest pressures exist in MRD rice systems because of continuous cropping. Rice blast (Fukuta et al., 2020) and brown plant hoppers cause extensive damage to rice crops (Phan et al., 2010) and consequently, farmers are familiar with the use of chemical control methods. A farmer survey conducted in the MRD identified 64 different chemicals that were used in rice-shrimp farming systems (Berg, 2001). Of these, 25% were herbicides, 25% fungicides and the remaining 50% were insecticides. The survey also identified a strong understanding and implementation of IPM. Whilst an ideal replacement crop would have low pest and disease pressures, the identification of crops that have well established knowledge regarding the management and control of prominent pest and diseases could also be favoured.

Good environmental conditions exist for pathogen growth during the rainy season although conditions in the MRD dry season do not favour fungal spore development. Despite a lower disease pressure in the dry season, the identification of alternative crops that have undertaken advanced breeding through the selection of disease tolerant traits will help reduce disease impacts. Fungal diseases like downy mildew, stalk rot and sheath blights have been identified as some of the major diseases in Vietnamese grown maize (Sharma et al., 1993). Downy mildew is a prominent fungal disease in quinoa (Testen et al., 2012) with considerable yield losses incurring from infection (Danielsen and Munk, 2004). The breeding of downy mildew tolerant quinoa varieties have significantly decreased fungal impacts in these production systems (Colque-Little et al., 2021). Soybean is also affected by fungal diseases with up to 20% yield reductions occurring in plants infected with powdery mildew (Dunn and Gaynor, 2020) although breeding of tolerant Vietnamese soybean can reduce disease susceptibility (Ho Manh et al., 2016). Powdery mildew has also been identified in Vietnamese Indian mustard greens (Tam et al., 2016) with evidence of tolerance in Indian cultivars (Nanjundan et al., 2020), although more work needs to be done to breed disease tolerant varieties in Vietnam. The combination of IPM and use varietal selection may help reduce the losses or costs of production incurred from pest and diseases.

3.5. Ability to be sown and processed using available labour

Farm mechanisation has improved over the last decade in the MRD in response to labour shortages and developments in the availability of small farm machinery. Mechanisation reduces labour time and improves efficiency, however the equipment available to MRD farmers is generally specific to rice crop production and small farm sizes can hinder uptake (Nguyen et al., 2020a). Ideally, alternative dry season replacement crops would be capable of being grown using the same rice-producing equipment already available to farmers, without major modification, although there will be limits to this. Unlike rice which requires anaerobic soil conditions (Rauf et al., 2019), alternative crops will generally require aerobic soil conditions for growth. Bed formation may become a critical part of field preparation prior to sowing for some alternative crops, particularly those with limited waterlogging tolerance like quinoa (González et al., 2009). In 2010, the use of mechanisation to prepare land in the MRD was 70% of rice farm production area and over 60% of rice was harvested using a combine harvester (Takeshima et al., 2018). The seeds of identified alternative crops can be sown via direct placement into the soil, either by hand or implement. These crops do not require transplanting like rice, and this reduces one labour component from the system. For some crops harvesting can be performed using rice harvesters; approximately one harvester exists per 50 ha of cropping production land in the MRD (Nguyen et al., 2020a). Minor modifications to the header front, sieves, fan and rotor speeds to suit each crop can be made to optimise harvest yields. Processing equipment is common on farm including mechanical corn shelling machines (Dang et al., 2004) or dryers for moist grain (Nguyen et al., 2020a).

Some identified alternative crops including maize (Rashid et al., 2013) and soybean (Ho Manh et al., 2016) are already grown in the MRD with farmers aware of the production cycle and labour required. However, the production of other alternative crops in the MRD dry season will be influenced by the successful adaption and use of available mechanisation (Nguyen et al., 2020a).

3.6. Profitability and availability of a market chain

The production of an alternative dry season crop must be financially viable for farmers. The shift from double- to triple-rice production initially improved the profitability of rice monoculture systems in the MRD, but required significant increases in inputs, particularly fertilisers and pesticides. Over time, as the cost of these inputs has increased, the profit margin of triple-rice production has gradually decreased (WorldBank, 2016). The cost of pesticides and fertilisers was recently estimated at 50–60% of total production costs in the MRD, while the profitability of triple-rice systems relative to double-rice systems had declined significantly, with total yields in some cases less than in double-rice systems (Tran et al., 2018b).

Viability includes having an available market to trade produce. Farmers in the MRD are familiar with identifying new market chains when adapting to alternative farming practices, as evidenced by the implementation of rice and shrimp farming (Dang, 2020). In addition, MRD farmers have already established market chains for some alternative crops including maize and soybean. In a 2004 survey, farmers reported that large quantities of maize could be sold via traders and collectors from the farm gate which saved on transportation labour and costs (Dang et al., 2004). Further opportunities for selling produce at village markets provides additional income to famers. An absence of market chain exists for crops like quinoa in the MRD, however the global quinoa market is rapidly expanding (Alandia et al., 2020) with over 120 countries now growing it (Bazile et al., 2016). The identified alternative crops are all directly consumable products for human or livestock and do not require large amounts of processing like a fibre crop. This provides MRD farmers with the opportunity to sell directly to traders or consumers to maximise economic return. Export opportunities also exists, but may require further development of relevant value chains (Otsuka and Fan, 2001).

3.7. Overall suitability

The combination of factors discussed above contribute to an overall suitability scale (Fig. 7). This relative scale includes rice as a comparison crop and can be used to examine the suitability of a range of different crops not mentioned above or adapted for a different scenario or location. For the purpose of this review, greater emphasis is placed on a crop's physiological suitability to the MRD dry season, as without the ability to tolerate salinity or grow with minimal water, the adaption required to existing machinery or development of a market cannot occur. Using a 'traffic light' framework such as that presented in Fig. 7, a

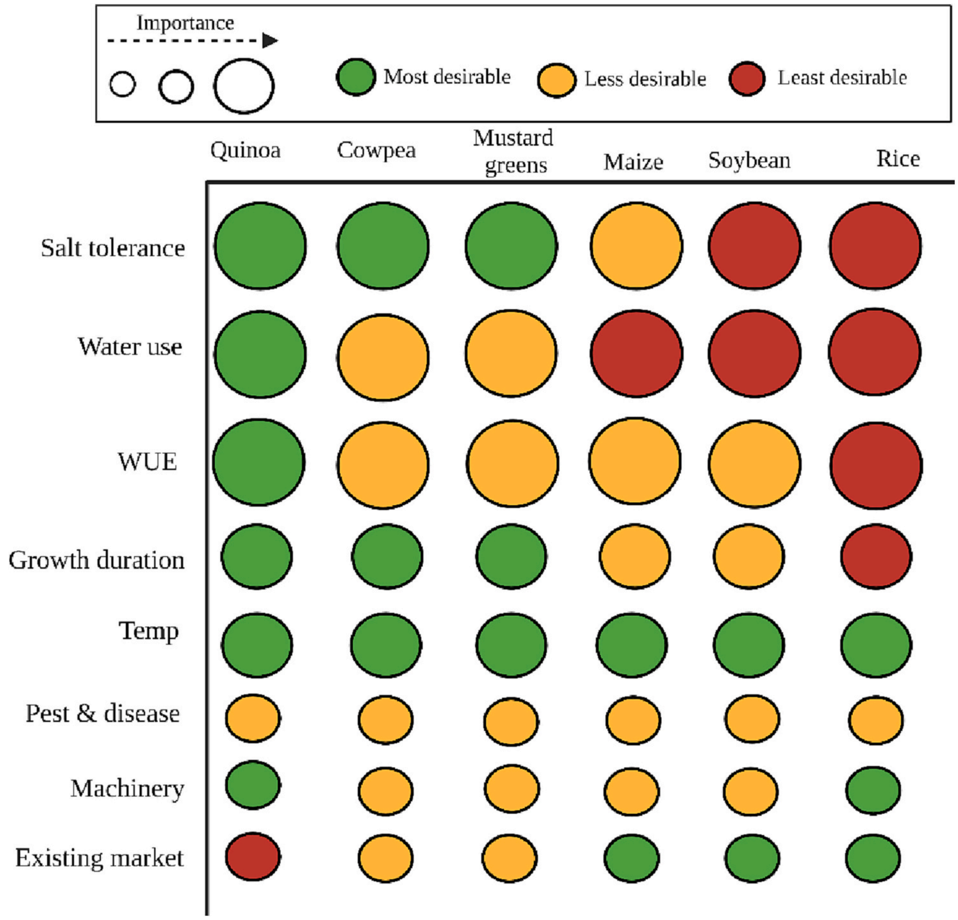

Fig. 7. A relative suitability scale for assessing a crops suitability as an alternative crop for growth in the MRD dry season using several physiological (salt tolerance, water use (mm), water use efficiency (WUE), growth duration, temperature tolerance (Temp), pest and disease tolerance and socioeconomic factors (use of existing machinery (Machinery) and existing market). Greater emphasis is placed on factors with larger circles.

suitable alternative crop would have more green, less orange and minimal to no red. This assessment framework highlights several potentially suitable alternative crops including quinoa, cowpea and mustard greens, despite the lack of a current market. A crop like soybean that has relatively poor salt tolerance and high-water use is less suitable despite an existing market. It is important to note that various crops may suit different regions of the MRD where water scarcity or saline intrusion may vary (Tran et al., 2018a).

4. Alternative management practices

Implementing various management techniques can provide a cost-effective way to reduce the effects of salinity and maximise production of dry season alternative crops. Conserving soil moisture, monitoring irrigation, and establishing effective drainage are well proven management options that can be used in conjunction with a suitable replacement crop.

4.1. Soil moisture conservation

Implementing management techniques that retain soil moisture can decrease the need for frequent irrigation and, where the irrigation water is saline, reduce a crop's consequent exposure to salinity. This can be done via the use of soil surface mulches or soil moisture monitoring devices.

4.1.1. Mulching

Mulching with organic materials is an effective way to maintain soil moisture (Abd El-Mageed et al., 2016), reduce evaporation (Fu et al., 2018), slow capillary rise and reduce the concentration of surface salt (Song et al., 2020). Straw mulch is a cheap, biodegradable soil covering method that has been used by many producers throughout Asia to limit the effects of salinity. The benefits of mulch in relation to soil salinity, soil moisture and yield are summarised in Table 3.

Plastic coverings can decrease evaporation, increase yields, decrease pesticide runoff (Steinmetz et al., 2016) and assist with the adverse effects of transient salinity (Barrett-Lennard et al., 2021). Plastic mulches are beneficial for increasing soil temperatures in cool climates (Lin et al., 2016; Dong et al., 2008), however this is not an issue in the MRD. The majority of plastic mulches are polyethylene based and non-biodegradable, thus the environmental implications of using plastic mulch must be carefully considered (Kasirajan and Ngouajio, 2012). Research into biodegradable plastic mulches and microorganisms that decompose plastic is still developing (Shah and Wu, 2020).

4.1.2. Soil moisture monitoring

Flooded rice production has dominated the MRD and thus there is a lack of knowledge regarding irrigation schedules for upland crops. Monitoring soil moisture throughout the dry season can help producers develop an irrigation schedule that will improve WUE and minimise the amount of saline water applied. Tensiometers can be an effective tool to monitor soil moisture and apply irrigation at the required time to maintain adequate soil moisture, although they are not readily available to producers in the MRD. Successful monitoring of soil moisture in the MRD is dependent on affordable and easy to use devices. The Chameleon soil moisture sensor is a cost-effective device that provides real-time,

Table 3
Summary of the effects of mulch and soil coverings on soil properties and upland crop yield in Asia.

Mulch type	Effect	Location	Reference
Rice straw 5 t ha^{-1}	↓ soil salinity ↑ soil water content ↑ sunflower yield	Ganges Delta	Paul et al. (2020)
Rice straw (5 & 10 t ha^{-1})	↑ soil water content by 3–9% ↓ soil penetration resistance by 28–77%	Bangladesh	Paul et al. (2021)
Wheat straw 4.5–30 t ha^{-1}	↑ vertical distribution of salts ↓ soil salinity ↑ maize yields	China	Pang et al. (2010)
Wheat straw 1.5 t ha^{-1}	↑ cotton yields by 10–17% ↑ WUE	Uzbekistan	Bezborodov et al. (2010)
Buried wheat straw 40 cm deep	↓ soil salinity by 10.5% ↑ soil water by 0.9% ↓ capillary rise	China	Song et al. (2020)
Farmyard manure 3–9 cm deep	↓ soil salinity ↑ Yield of common bean ↓ 80% of irrigation water applied	Egypt	Abd El-Wahed et al. (2017)
White plastic Black plastic Blue plastic	↑ maize yields by 149% compared to no mulch ↑ yields by 109% ↑ yields by 78%	Bangladesh	Haque et al. (2018)

easily gathered information regarding a crops soil moisture status. The sensor measures the water tension in the soil which negates the need to calibrate for soil type (Stirzaker et al., 2017). Three coloured lights indicate soil moisture status with blue as 'wet' (0 to −22 kPa), green as 'moist' (−22 to −50 kPa) and red indicates 'dry' (> −50 kPa) soil. Use of the Chameleon sensor has allowed Tanzanian farmers to implement irrigation schedules based on quantitative data that saves significant amounts of water by reducing the frequency and duration of watering (Mdemu et al., 2020). The adoption of the Chameleon has also created social benefits among farmer groups by generating conversation and awareness of improved irrigation schedules (Moyo et al., 2020). The implementation of the Chameleon soil moisture sensor in the MRD might limit soil salinisation by reducing the frequency of use of saline irrigation water. Used in conjunction with mulching and alternative crops that have a high water use efficiency (WUE) and saline tolerance, the Chameleon might provide a suitable management option for optimising the implementation of alternative crops in the MRD dry season.

4.2. Drainage

Salinity damage to plants can be minimised by removing excess saline water via effective drainage. Increased shoot Na^+ and Cl^- concentrations can occur due to an interaction between waterlogging and salinity (Barrett-Lennard, 2003). Waterlogged rice paddy may also have negative impacts on the subsequent emergence and establishment of alternative crops sown at the end of the rainy He-Thu season. Raised bed systems provide adequate drainage options for waterlogging sensitive plants and can help reduce the effects of salinity. In Bangladesh, a raised bed system combined with mulch produced ~70% more potato tubers than flat ground with no mulch (Islam et al., 2018). The use of drainage pipes can have similar benefits to raised beds (Feng et al., 2017). Subsurface drainage is known to remove excess saline water and helps reduce long-term soil salinisation (Smedema et al., 2000). Whilst the benefits of raised beds and drainage in reducing soil salinity levels are abundant, labour intensiveness must be considered when recommending their use in the MRD. Mechanisation is increasing in popularity in the MRD with a recent farmer survey indicating that one rotary tiller with a walking tractor exists for every 7 ha of rice produced (Nguyen et al., 2020a). As an example of mechanisation, over half a million tractors were used in agricultural production in Vietnam in 2013 (Nguyen et al., 2016).

4.3. Seed preparation

Seed priming is a pre-sowing treatment that can help alleviate the negative effects of salinity where seeds are soaked for up to 12 h in solutions including NaCl, $CaCl_2$ and KCl prior to sowing (Chen et al., 2021; Ashraf and Foolad, 2005). This simple technique has improved germination, plant establishment and plant growth by initiating imbibition and activating metabolic processes (Ashraf and Foolad, 2005). Success across a multitude of crops has been reported with improved germination rates in maize (Ashraf and Rauf, 2001), sorghum (Chen et al., 2021) and quinoa (Yang et al., 2018). However, alternative crops in the MRD are planted at the end of the wet season when soil salinity is low, thus seed priming is of less relevance.

An alternative seed preparation technique that mitigates the negative effects of soil salinity is the use of plant growth-promoting bacterial (PGPB) endophytes (Ali et al., 2014). PGPB act similarly to rhizospheric bacteria where the mutualistic relationship provides benefits to host plants and the bacteria (Souza et al., 2015) and can improve yields in a range of crops including tomato (Ali et al., 2014), maize (Rojas-Tapias et al., 2012) and sunflower (Shilev et al., 2012). One of these benefits is reducing the production of ethylene which is created in response to environmental stresses including waterlogging. The biosynthesis of ethylene can trigger leaf abscission, flower wilting and fruit ripening (Dubois et al., 2018). Whilst PGPB can assist plant growth in saline conditions, the adoption of this technique in the MRD will require development of resources and facilities to ensure the successful inoculation of plants.

5. Conclusion

Dry season salinity intrusion is threatening rice crop production in the MRD. Inland Provinces traditionally not exposed to salt are experiencing rice crop failure and alternative cropping solutions must be developed to supplement the loss of income to farmers. The use of sluice gates and a decrease in groundwater extraction could reduce the extent of saline intrusion on a regional scale, however on a farm level scale, options for dealing with saline intrusion are management based. Growing crops like quinoa and cowpea that have high salt tolerance, low water use and fit the MRD Dong Xuan growing season are opportunities for farmers to decrease production losses incurred from saline intrusion. Market options of these crops are currently limited due to their novelty to the area but have the potential to grow. The growth of alternative crops like maize and soybean are already established in the MRD, primarily as supplementary food and income sources, however their salt tolerance is less, and water use greater than quinoa and cowpea. The use of mulches and plastic coverings significantly increase soil moisture content which help decrease the effects of salinity. Environmental concerns regarding plastic coverings, makes mulch a more desirable option to be used in conjunction with alternative crops. Raised beds can also provide drainage and salinity management strategies required for the successful establishment of waterlogging sensitive crops like quinoa. Combining suitable alternative crops with water saving management techniques like mulches and soil moisture monitoring (e.g., Chameleon sensors) may provide dry season alternative crop options for farmers in saline affected areas of the MRD.

Declaration of Competing Interest

The authors declare that they have no known personal relationships or financial interests that may have influenced the work reported in this paper.

Data availability

No data was used for the research described in the article.

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