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Development of tolerant rice varieties for stress-prone ecosystems in the coastal deltas of Indonesia

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A B S T R A C T

Large areas of lowlands within tidal deltas have been reclaimed for crop production in Indonesia. However, major production constraints such as floods, seawater intrusion from tidal rivers, and adverse soils remain a significant problem, resulting in low rice yields (2–3 t ha^{-1}) and production systems that are prone to risk. This review describes the recent progress in technology development, to address multiple abiotic stresses through the genetic improvement of rice. During the last 15 years, rice breeding programs and germplasm evaluation systems for coastal deltas have been revitalized. Local landraces, modern varieties and elite stress-tolerant genotypes were screened and physiological response to the stress and agronomic performance of promising genotypes were characterized. These efforts resulted in the release of the first series of flood- and salinity-tolerant varieties for lowlands in Indonesia. On-farm trials with these varieties demonstrated yield advantages of up to 125%, over popular varieties currently used by farmers in the marginal lowlands. Some of these varieties made an impact; Ciherang-Sub1, a submergence-tolerant variety near-isogenic of Indonesia's popular variety (Ciherang), occupied over 430,000 ha of rice lowlands within four years of its release in 2012. There are large "exploitable yield gaps" between the attainable farm yield and mean farm yield, and appropriate crop and natural resource management guidelines for the new rice varieties are being developed. These achievements highlight opportunities for sustainable development in unfavorable rice environments of coastal deltas and are relevant to other areas in South and Southeast Asia.

1. Introduction

The Indonesian archipelago comprises some 17,504 islands with a total land area of almost 2 million km^2, 31.5% of which is agricultural land (Statistics Indonesia, 2015). A substantial proportion of this agricultural land is within close proximity to the sea. For example, on the island of Java, about 29% of rice growing areas lie within 10 km of the sea. Although there are no big rivers in the Indonesian archipelago, a number of rivers form lowland deltas exploitable for rice farming due to large annual precipitation (1300–3000 mm). The Kapuas (ca. 1140 km) and Mahakam (ca. 980 km) rivers in Kalimantan form deltas of over 1500 km^2, while the Musi river (ca. 750 km) delta in Sumatra is around 500 km^2. As mixed fluvial-tidal deltas, these comprise alluvial floodplain areas that are influenced by tides and the adjacent non-tidal coastal plains.

Indonesia has 8.1 million ha of rice area, consisting of 4.76 million ha for irrigated lowland, 2.25 million ha for rainfed lowland, and 1.09 million ha for upland, with an annual harvested area of 14.1 million ha to produce 75.4 million tons of rice in 2015 (Center for Agricultural Data and Information System, 2017a). However, the government of Indonesia is striving for national rice self-sufficiency and to meet rising demands; yet, the country imported 0.84 million tons of rice in 2014

Abbreviations: GIS, geographical information system; ICRR, Indonesian Center for Rice Research; IRRI, International Rice Research Institute; QTL, quantitative trait locus

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(Statistics Indonesia, 2015). As a further challenge, some of the most productive agricultural areas are being lost as land is converted to residential, commercial or other purpose. The conversion of agricultural land has led to the loss of approximately 187,000 ha of rice land per year (Irawan, 2002). In addition, Suroso et al. (2013) estimated that by 2050, the area of coastal rice fields could be reduced by a total of 291,992 ha, mainly in Java, Sulawesi, Kalimantan, Sumatra and Lombok islands due to a projected global sea level rise of between 0.18 and 0.59 m by 2100 (IPCC, 2007). Opportunities to further expand agricultural land in Indonesia are limited (Putri, 2013) and have serious short and long term implications for the environment (Tilman et al., 2011; Phalan et al., 2013). It is a major challenge to increase current growth rates of production under these circumstances. One approach to address this is to increase productivity and intensify rice production in less favorable ecosystems where the current mean yields are only 2–3 t ha^{-1}, in contrast to the national mean yield of 5.5 t ha^{-1} for lowland rice (Statistics Indonesia, 2015) and yield in excess of 9 t ha^{-1} in some parts of Java (Stuart et al., 2016).

The major climate change associated impacts on rice-based systems in coastal areas are expected due to changes in rainfall patterns and seawater rise (Nicholls and Cazenave, 2010). Changes in rainfall patterns, for example, may increase the frequency and intensity of floods and droughts, while rising sea levels and consequently higher tides will cause a broader area of rice land to be affected by salinity and submergence (Forster et al., 2011; Wassmann et al., 2009). Indonesia is also vulnerable to the El Niño Southern Oscillation phenomenon (Harger, 1995; Naylor et al., 2007). Rice areas damaged by drought sharply increase during El Niño years, while flood damage increases during La Niña years (Boer, 2011). The El Niño in 2015 caused serious drought for 815,132 ha of total rice fields in the country, mainly in rainfed and coastal lowlands in Java, Sulawesi and Sumatra (Center for Agricultural Data and Information System, 2017b).

Sustainable improvements in rice production in unfavorable rice ecosystems in the coastal deltas are crucial issues for the Indonesian rice sector, the rural communities and smallholder farmers. Particularly, the lack of high-yielding varieties tolerant of abiotic stresses has been one of the main reasons for low rice productivity in the coastal deltas (Ruskandar et al., 2006; Nugraha and Rumanti, 2017). Initial work on the varietal improvement in 1960s in Indonesia aimed to replace long-duration landraces in tidal deltas (Subiyanto et al., 1977), relying on the pure line selection of landraces. In 1980s, some of modern varieties such as IR38 and IR42 (released in 1977) were introduced to tidal deltas (Carew, 1984). Consequently, in 1990s, the majority of farmers in these areas cultivated landraces or varieties suitable for favorable lowlands but not bred for marginal ones (Khairullah et al., 2006; Suhartini and Makarim, 2009). Since 2002, the Indonesian Center for Rice Research (ICRR), the main national rice research center in the country, initiated selection and development of "climate-ready varieties" that have improved tolerance of submergence, salinity, adverse soils and drought, and associated crop management guidelines for the target environments (Manzanilla et al., 2016). Stress-tolerant elite rice genotypes were sourced through the international rice testing programs of the International Rice Research Institute (IRRI) to be used as either donors for the national breeding program or for direct release into the country. In addition to routine yield trials at target sites, ICRR also established new breeding schemes with updated germplasm evaluation systems under the support of IRRI. The impact of this collaboration was not confined to the research findings in rice science. As emphasized by Atlin et al. (2017), the release of new stress-tolerant varieties provides entry points for sustainable development in unfavorable rice environments. In this review, we describe the agro-ecological characteristics of the coastal deltas of Indonesia and document the development of rice varieties and management technologies for abiotic stress tolerance in the coastal deltas of Indonesia during the last 15 years.

2. Agro-ecological characteristics of coastal deltas in Indonesia

Coastal deltas and the adjacent plains in Indonesia are affected by oceanic processes such as sea level rise, tide regime, land and sea breezes. Areas affected by tides represent 8.4–8.9 million ha from a recent national survey (Agus et al., 2015), among which different soil conditions were identified:

- Favorable areas with agricultural potential presenting soil with a pyrite layer deeper than 50 cm.
- Acid sulphate soils, stress-prone areas with adverse soils with a pyrite layer from 0 to 50 cm depth.
- Peatland areas with soils composed of significant peat layers in the upper layer from 0 to 50 cm.
- Saline areas affected by salinity intrusion mainly during the dry season.

There are large areas of tidal lowlands along the coast of east Sumatra, the coastal areas in Kalimantan, Papua and eastern small islands. These have unique characteristics due to the influence of water movement caused by sea tides; for example, controlling the water depth in the tidal lowlands, but also by the interactions with rainfall and river flow. Tidal lowlands can be classified into four groups based on the prevailing water levels in the fields, i.e., types A–D (Fig. 1) (Suprianto et al., 2010):

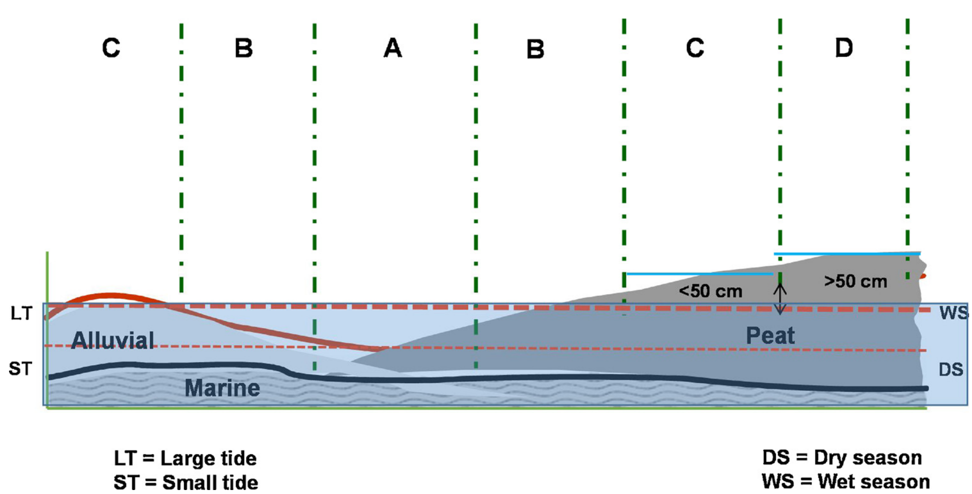

Fig. 1. Classification of tidal lowlands with variation of tide with season and distance from sea.