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Fingerprinting environmental conditions and related stress using stable isotopic composition of rice (*Oryza sativa* L.) grain organic matter

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ABSTRACT

Sea level rise (SLR) is a primary factor responsible for inundation of low-lying coastal regions across the world, which in turn governs the agricultural productivity. In this study, rice (*Oryza sativa* L.) cultivated seasonally in the Kuttanad Wetland, a SLR prone region on the southwest coast of India, were analysed for oxygen, hydrogen and carbon isotopic ratios ($\delta^{18}O$, $\delta^{2}H$ and $\delta^{13}C$) to distinguish the seasonal environmental conditions prevalent during rice cultivation. The region receives high rainfall during the wet season which promotes large supply of fresh water to the local water bodies via the rivers. In contrast, during the dry season reduced river discharge favours sea water incursion which adversely affects the rice cultivation. The water for rice cultivation is derived from regional water bodies that are characterised by seasonal salinity variation which co-varies with the $\delta^{18}O$ and $\delta^{2}H$ values. Rice cultivated during the wet and the dry season bears the isotopic imprints of this water. We explored the utility of a mechanistic model to quantify the contribution of two prominent factors, namely relative humidity and source water composition in governing the seasonal variation in oxygen isotopic composition of rice grain OM. $\delta^{13}C$ values of rice grain OM were used to deduce the stress level by estimating the intrinsic water use efficiency (WUE_i) of the crop during the two seasons. 1.3 times higher WUE_i was exhibited by the same genotype during the dry season. The approach can be extended to other low lying coastal agro-ecosystems to infer the growth conditions of cultivated crops and can further be utilised for retrieving paleo-environmental information from well preserved archaeological plant remains.

1. Introduction

Coastal regions globally are vulnerable to sea level rise (SLR). In this context, the predicted high rate of SLR in the future (Nicholls and Cazenave, 2010) is quite alarming, and the inundation of fertile agricultural lands in these places with saline sea water has the potential to severely affect food grain production. Rice is one of the important cereals cultivated in the tropical and subtropical coastal regions and its productivity depends on factors such as water availability and salinity condition (Maas and Hoffman, 1977; Shannon et al., 1998; Sultana et al., 2002). In a region affected by sea water incursion, intermittent mixing of sea water with available freshwater induces stress in the rice plant (Zeng and Shannon, 2000) and adversely affects the productivity. The list of countries that are at high risk of reduced rice production due to SLR include Bangladesh, Japan, Taiwan, Egypt, Myanmar and Vietnam (Chen et al., 2012). Coastal regions of India are also prone to inundation due to SLR. Kochi (Cochin), an important coastal city in the Indian state of Kerala, recorded the highest SLR of 1.75 mm/yr during the last century amongst other coastline stations along the North Indian Ocean (Unikrishnan and Shankar, 2007). The dependence of this state's economy on agriculture together with the high population density exerts high pressure on cultivable land.

The estuary at Kochi, known as Cochin Estuary, extends inland into a continuous chain of lagoons or backwaters. Located at these backwaters is a large water body, named Vembanad Lake – a Ramsar Site (http://www.ramsar.org/), which together with the adjoining land area (outlined in Fig. 1) forms a wetland ecosystem, referred to as the "Kuttanad Wetland". This wetland has been extensively used for rice cultivation for the past 200 years. The region is known as the rice bowl of Kerala as it contributes nearly 20% of total rice production in the state. During 2013, the United Nation's Food and Agriculture Organisation (FAO) granted heritage status for the below sea level (0.6–2.2 m) farming system in

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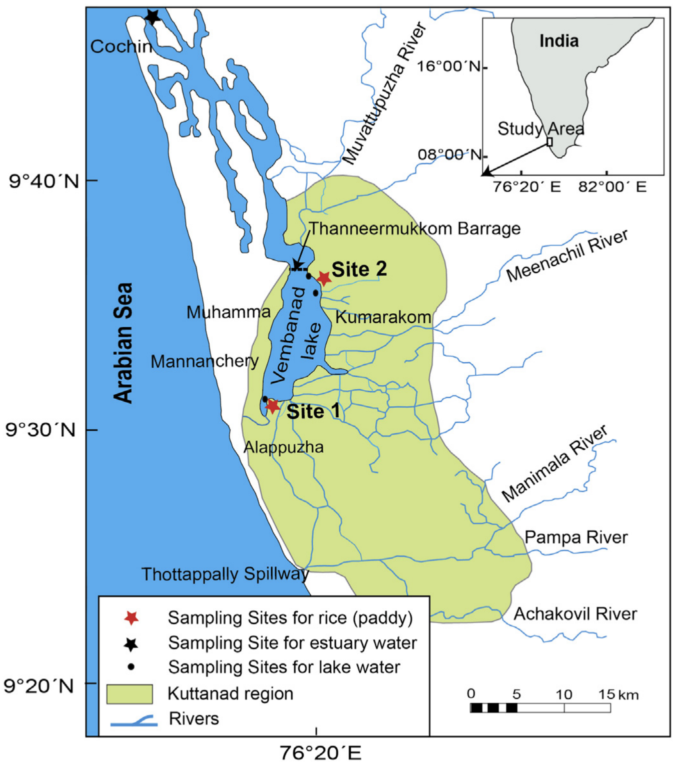

Fig. 1. Map of Kuttanad region showing rice and water sampling locations. Also shown here are river channels, the adjoining sea and the extent of Vembanad Lake.

Kuttanad and assigned it a tag of Globally Important Agricultural Heritage System (GIAHS). Given the significance of this wetland in contributing to the state's food security, it is important to study the environmental factors, such as salinity and rainfall which can directly affect the rice cultivation. Today, rice is cultivated in this region twice a year coinciding with the wet and the dry season (http://www.kuttanadpackage.in/). During the dry months, i.e. from December till March, sea water intrusion is prevalent, while during the wet months which coincides with the southwest monsoon season, i.e. from June till September, riverine input dominates. The Kuttanad region covers an area of 1100 km^2, about 50% of which was reclaimed from the Vembanad Lake. Despite restriction imposed by bunds sea water intrusion into the lake occurs through a few inlets (MSSRF-Report, 2007), thereby affecting the salinity spatially (Nasir and Harikumar, 2012).

Rice is a salt sensitive crop (Maas and Hoffman, 1977), with salinity and drier conditions in the low lying tropical coastal regions inducing stress and in turn affecting its productivity (Sultana et al., 2002; Joseph and Mohanan, 2013). Oxygen, hydrogen and carbon isotope ratio determination in plant OM is a powerful technique in ecological research to decipher the origin of source water used by the plants (Dawson and Ehleringer, 1991; Cerling et al., 1997; Barbour, 2007; Ewe et al., 2007; West et al., 2006) and the stress (Poss et al., 2000; Ouerghi et al., 2000) experienced during their growth. Changes in the δ^{18}O and δ^{2}H values of source water during plant growth is reflected in the isotopic values of plant OM (Yakir and DeNiro, 1990) and can be used as indicator of the prevalent environmental conditions. The transfer of this isotopic signature to OM happens via the process of photosynthesis (refer to Fig. 2 and inset) which entails the reduction of atmospheric CO_2 by plant water, in the presence of photosynthetically active radiation and enzymes. The metabolites thus synthesised comprise of carbon from the atmospheric CO_2 and oxygen and hydrogen from the water. The same approach has been used in studies (Kelly et al., 2002; Korenaga et al., 2010) for discriminating rice OM originating from diverse geographical regions and proved to be a reliable indicator of source water δ^{18}O and δ^{2}H values (Kelly et al., 2002; Suzuki et al., 2008; Korenaga et al., 2010; Suzuki et al., 2013). Similarly, determination of carbon isotope discrimination (Δ^{13}C) in the rice grain OM (Poss et al., 2004) has facilitated distinguishing salinity stress tolerance of different rice varieties.

The objective of our investigation was to show that the δ^{18}O, δ^{2}H and δ^{13}C values of rice grain OM from a coastal agro-ecosystem can serve as fingerprints of environmental condition and the associated stress prevalent during the period of rice growth. Being close to the coast, the regional water bodies of this wetland are adversely affected by sea water intrusion at seasonal time scales (Thampatti and Padmakumar, 1999; Babu et al., 2011; Kannan et al., 2014; MSSRF-Report, 2007), signature of which gets recorded in the δ^{18}O, δ^{2}H and the salinity level values (Nasir and Harikumar, 2012). In majority of the times, irrigation for rice cultivation is supported by the water derived from these water bodies. The translation of water δ^{18}O to rice OM δ^{18}O is simulated here using a model (Barbour et al., 2004; available from http://ecophys.utah.edu/download/Projects/Tree_Ring/) which involves hydrological, biophysical and environmental parameters. The parameters which play a dominant role in governing the δ^{18}O values of plant OM are δ^{18}O of source water and relative humidity (Roden and Ehleringer, 1999; Helliker and Ehleringer, 2002). The simulation allowed estimating the sensitivity of δ^{18}O of rice OM to these two key parameters. The measured δ^{13}C values, on the other hand were used to infer the change in intrinsic water use efficiency (WUE_i).

For clarity, we have organised the paper as follows. Section 2 comprises of sampling details and method of isotopic analyses together with description, parameterisation and sensitivity analysis of the model used. The results of isotopic analyses are given in Section 3 and are explained with the help of models in Section 4. We present our conclusion in Section 5.

2. Materials and methods

2.1. Study area and sample collection

The area selected for this study is the Kuttanad Wetland, which lies between geographical coordinates 09° 08′ – 09° 52′ N and 76° 19′ –76° 44′ E (Fig. 1) and experiences a tropical humid climate. It is fed by five major rivers (Meenachil, Manimala, Pampa, Achenkoil and the Muvattupuzha), which originate from the Western Ghats and flow into the Cochin estuary via the Vembanad Lake. This estuary is the second largest estuarine system in India and receives an influx of nearly 0.291 hm^3 a^{-1} fresh water riverine discharge (Srinivas et al., 2003). These rivers predominantly carry rainwater during southwest monsoon (wet season) from the upland catchment region (illustrated in Fig. 2). Data from the nearest India Meteorological Department (IMD) station at Cochin shows that the rainy season in this region commences in early June and continues till the end of September when ~1100 mm of cumulative rainfall is received. The period from December till March is designated as the dry season when the rainfall and river discharge becomes minimal thereby promoting seawater intrusion into the region, as illustrated in Fig. 2.

Two study sites (Site 1 and Site 2) were chosen where rice (paddy) fields experienced different levels of water salinity during the two seasons of rice cultivation. Site 1 was selected at the southern extreme of the Vembanad Lake in the district of Alappuzha, while Site 2 was selected at the northern boundary of the lake, in the district of Kottayam and immediately south of the Thanneermukkom Barrage – the major barrier which regulates the entry of sea water during the dry season (Fig. 1). Harvested mature rice