Investigating unproductive water losses from irrigated agricultural crops in the humid tropics through analyses of stable isotopes of water

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Abstract. Reliable information on water flow dynamics and water losses via irrigation on irrigated agricultural fields is important to improve water management strategies. We investigated the effect of season (wet season, dry season), irrigation management (flooded, non-flooded), and crop diversification (wet rice, dry rice, and maize) on soil water flow dynamics and water losses via evaporation during plant growth. Soil water was extracted and analysed for the stable isotopes of water (δ^2H and δ^{18}O). The fraction of evaporation losses were determined using the Craig–Gorden equation. For all crops, shallow soil compartments (0 to 0.2 m) were more isotopically enriched than deep soils (below 0.2 m). Soil water losses due to evaporation decreased from 40 % from the beginning to 25 % towards the end of the dry season. The soil in maize fields showed stronger evaporation enrichment than in rice during that time. A greater water loss was encountered during the wet season, with 80 % at the beginning of the season to 60 % at its end. The isotopic enrichment of ponding surface water due to evaporation was reflected in shallow soils of wet rice. It decreased towards the end of both growing seasons during the wet and the dry season. We finally discuss the most relevant soil water flow mechanisms, which we identified in our study to be that of matrix flow, preferential flow through desiccation cracks and evaporation. Isotope data supported the fact that unproductive water losses via evaporation can be reduced by introducing dry seasonal crops to the crop rotation system.

1 Introduction

Soil water studies are essential for a better understanding of the role soils play in the hydrological cycle, in order to estimate the water budget and water availability for plants, groundwater recharge, other organisms as well as solute transport. Stable isotopes of water (δ^2H and δ^{18}O) as ideal natural tracers have become a powerful tool for such studies ((Kendall and Caldwell,

1999) They are particularly helpful in better understanding the evaporation dynamics in soil water (Braud et al., 2009; Kool et al., 2014; Rothfuss et al., 2015) because the composition and distribution of stable isotopes of water in a soil profile provide insight to evaporation fractionation and water flux processes (Wenninger et al., 2010).

The determination of soil evaporation and the fraction of evaporation in relation to total evapotranspiration have been widely studied using several methods for different crops. For example, Liu et al. (2002) studied evapotranspiration from winter wheat and maize, using weighing lysimeters. Zhou et al. (2016) partitioned evaporation and transpiration fluxes for corn, soya bean, grassland and forests using flux tower measurements. Kool et al. (2014) applied different methods such as chamber, micro-lysimeter, and soil heat pulse to estimate the evaporation and used stable isotopes of water to separate evaporation from transpiration. Soil isotopic profiles can be subdivided into two parts (Barnes and Allison, 1984), first, the shallow soil, in which water moves by vapour diffusion and which is affected by evaporation, and second, the deep soil, where direct flows take place and which is barely affected by evaporation. However, the isotopic composition of soil water is not only affected directly by evaporation, mixing of new and old water (Gazis and Feng, 2004) , and altering input signals (Barnes and Turner, 1998), but also indirectly by other processes such as transpiration (Barnes and Allison, 1988), water transport (Kutilek and Nielsen, 1994; Melayah et al., 1996), and hydrodynamic dispersion (Wang et al., 2017). The isotopic enrichment of shallow soil water is generally driven by evaporation during drier periods (Gangi et al., 2015; Liu et al., 2015) and affected by equilibrium and kinetic fractionation (Benettin et al., 2018). Due to this complexity, many experiments on the effects of evaporation on soil water using isotope methods are often restricted to the laboratory-scale or short-term field studies or to one particular location (Beyer et al., 2016; Gaj et al., 2016; Oerter and Bowen, 2017; Rothfuss et al., 2015; Sprenger et al., 2017; Twining et al., 2006; Volkmann et al., 2016).

Studying water fluxes in rice-based cropping systems is important, because rice (Oryza sativa L.) is the dominant staple food for nearly half of the world's population, yet water resources are limited. More than 80 % of the global rice production area is located in Asia (Kudo et al., 2014) Rice is one of the highest water-consuming grain crops (Janssen and Lennartz, 2007; Mekonnen and Hoekstra, 2011), consuming approximately 30 % of all freshwater resources worldwide (Maclean et al., 2002). Since rice is extremely sensitive to water shortages (Bouman and Tuong, 2001), 80 % of rice in Asia is cultivated under conventional flooded conditions (Towprayoon et al., 2005); also called wet rice, anaerobic rice, or lowland rice. Water scarcity is a serious environmental problem, especially in the irrigation of agricultural land (Pfister et al., 2011). Therefore, water saving strategies need to be developed to ensure rice production (Belder et al., 2004). By introducing non-flooded crops during the dry season (e.g., maize or non-flooded rice; also called dry rice, aerobic rice or upland rice) is an interesting alternative and has been increasingly applied in food and fodder production in Southeast Asia (FAO, 2016; Timsina et al., 2010). To establish an efficient water-saving management based on crop rotation and season, a functional understanding of hydrological processes of these new rice-based cropping systems is required (Daly et al., 2004; Heinz et al., 2013; Zwart and Bastiaanssen, 2004).

Understanding water flow dynamics and unproductive water losses from irrigated soils is still incomplete, particularly for rice-based cropping systems. Unproductive water losses are those that do not lead directly to biomass production, such as transpiration, and include for example leaching, evaporation from the soil or from ponding water (Bouman, 2007). Studies on the effects of evaporation, its seasonal variability, as well as the impact of various crop rotations are still missing. None of the studies conducted so far have quantified the fraction of evaporation losses in rice-based cropping systems, taking into account the effect of crop species and various growing stages. The objectives of this study are, therefore (I) to investigate soil water isotopic profiles to study the effect of crop species (wet rice, dry rice, and maize) and growing stages on evaporation during the wet and dry season; (II) to understand flow mechanisms of soil water in the soil matrix; and (III) to quantify the fraction of evaporation losses from agricultural fields based on stable isotopes of water.

2 Material and Methods

2.1 Site description and experimental design

The field trial was established at the experimental station of the International Rice Research Institute (IRRI), in Los Baños, Laguna, Philippines (14°11'N, 121°15'E, 21 m a.s.l.). The average total precipitation was 1,700±50 mm during the wet season (WS, June to November) and 300±25 mm during the dry season (DS, December to May). The mean seasonal temperature and relative humidity were 28.5±0.9°C and 83±6 % during the WS 2015, as well as 27.6±1.8°C and 74±11 % during the DS 2016, respectively. Climate data were obtained from the climate unit at IRRI. The experiment was conducted during WS 2015 and DS 2016. The soil type in the study area is classified as a Hydragric Anthrosol (He et al., 2015) with clay-dominated soil texture (Table 1). The clay fraction mainly consists of vermiculite and smectite as three layer clays, and kaolinite as a two-layer clay. Three-layer vermiculite is mainly responsible for the swelling and shrinking of the soil matrix (Tertre et al., 2018). The experimental design (Fig. 1) consisted of nine fields (3 wet rice–wet rice, 3 wet rice–dry rice, 3 wet rice–maize) with an average field size of about 540 m^2, each split into three plots with different treatments. Of these plots, only those with straw application and the control plots (without straw) were used for our experiment. Straw was not applied as a typical mulch layer to reduce evaporation but was partly worked into the soil to reduce crack formation during dry soil conditions and resulting preferential flow losses. During the WS, all nine fields were cropped with wet rice (cultivar NSIC Rc222). During the DS, three fields were each cultivated with wet rice, dry rice (cultivar NSIC Rc192), and maize (Pioneer P3482YR). Wet rice fields were maintained at water-flooded conditions, except for the first and last two weeks between transplanting and harvest. Dry rice and maize fields were only irrigated when weather conditions suggested a water shortage (i.e., 5–10 times during the growing season for maize fields). Field workers from the IRRI were responsible for watering dry crops in times of soil water shortage. The decision of watering was not set by specific thresholds or indicators, but by expert knowledge. The total irrigation amount for wet rice fields was 470±50 mm during the WS, and 1,270±300 mm, 517±50 mm, and 212±50 mm for wet rice, dry rice, and maize during the DS, respectively. Transplanting and harvesting dates for rice were July 21st and October 30th during the WS. During the DS, the transplanting date was January 8th, and harvesting dates were April 10th for wet rice and April 17th for dry rice, and January 6th and May 11th for maize in 2016, respectively (Fig. 2).

2.2 Soil and root sampling

Samples were collected during the three main growing stages (GS) described by Counce et al. (2000), i.e., at the vegetative stage (GS1, from germination to panicle initiation), the reproductive stage (GS2, from panicle initiation to flowering), and the ripening stage (GS3, from flowering to maturity). The growing stages were used as reference points during the growing season (Fig. 2). Growing stages for rice and maize were assumed to be similar to maintain consistency of sampling conditions. Samples were taken on one day during each growing stage at 26, 55, 85 days after transplanting during the WS, and 40, 60, 90 days after transplanting during the DS, respectively. Soil cores were taken using a manual soil corer (length=0.6 m, diameter=0.05 m). Each core was divided into 9 depth intervals from the surface to 0.6 m (0, 0.05, 0.1, 0.15, 0.2, 0.2–0.3, 0.3–0.4, 0.4–0.5, 0.5–0.6 m). Altogether, 972 samples were taken (9 fields x 2 treatments x 2 seasons x 3 growing stages x 9 soil depths). A plastic ring (diameter=0.5 m) was used to drain the water around the sampler prior to coring in wet rice fields. Samples were stored in sealed aluminium bags (CB400–420BRZ, 80 mm x 110 mm, Weber packaging, Güglingen, Germany) and immediately placed in an ice-filled Styrofoam box for transfer to the laboratory where they were kept frozen.

Soil water was extracted from soil aliquots (10–15 g of the sample) via cryogenic vacuum extraction (Orlowski et al., 2013) at the Institute for Landscape Ecology and Resources Management (Justus Liebig University Giessen, Germany) for four hours at 200°C under a pressure of 0.3 Pa. The gravimetric soil water content along the soil profiles was determined based on the soil weight loss following cryogenic water extraction. Soil water content determined this way deviates from the classical oven drying method and results in slightly lower values. In the case of oven drying, samples are taken via stainless steel cores. These soil cores still have intact pore systems that contain pore water. Pore water is not captured by cryogenic extraction. However, we use the gravimetric soil water content from cryogenic extraction not as an absolute value, but rather as a relative value to identify differences along the soil profile. Groundwater and surface ponded water of flooded rice were collected once a week from each plot at existing sampling stations (Heinz et al., 2013). Rainwater and irrigation water were sampled event-based. For detailed information on the experimental design and sample collection, see Mahindawansha et al. (2018b).

2.3 Isotopic measurements

The oxygen and hydrogen isotopic compositions of the water samples (extracted soil water and liquid samples) were measured via off-axis integrated cavity output spectroscopy (OA–ICOS, DLT–100–Liquid Water Isotope Analyzer, Los Gatos Research Inc., Mountain View, CA, USA) and reported in permil [‰]. The analytical precision for δ^{18}O and δ^{2}H was 0.2 ‰ and 0.6 ‰, respectively. All water sources (isotopic data) were checked for spectral interferences using the Spectral Contamination Identifier (LWIA-SCI) post-processing software (Los Gatos Research Inc.). According to this test, none of the soil water samples were contaminated. The global meteoric water line (GMWL) was determined following Rozanski et al. (1993) ($\delta^2\mathrm{H} = 8.2\delta^{18}\mathrm{O} + 11.3$). The Local Meteoric Water Line (LMWL) was calculated with $\delta^2\mathrm{H} = 7.52\delta^{18}\mathrm{O} + 5.86$, using stable isotope compositions of local precipitation collected from 2000 until 2015 (GNIP–IAEA, 2016). Line conditioned excess (lc-excess) was calculated for soil water samples as suggested by Landwehr and Coplen (2006), with $\mathrm{lc\text{-}excess} = \delta^2\mathrm{H} - \mathrm{a}\delta^{18}\mathrm{O} - \mathrm{b}$, where

a and b refer to the slope and intercept of the LMWL, respectively. We used the lc-excess to infer the seasonal dynamics of evaporation fractionation (Sprenger et al., 2017).

2.4 Calculation fraction of evaporation

The joint effect of equilibrium and kinetic isotopic fractionation during the phase transition from liquid water to vapour can be estimated using the Craig–Gordon model (Craig and Gordon, 1965). Sprenger et al. (2017) have recently used Equation 1 to estimate evaporation from the topsoil (0–0.1 m). We assume that this model controls the development of soil water isotopic composition in the uppermost soil compartment. This isotopic signal is then carried to deeper compartments via leaching. In deeper compartments, mixing of soil water with water transported through cracks may occur. The concept of multi-compartment transport indicates the history of the evaporation process as well as the depth and degree of isotope signal changes by the preferential flow. Equation 1 is based on the Craig–Gordon model and formulations introduced by Gonfiantini (1986) to estimate the fraction of evaporation loss (F_E) for an isotope mass balance as follows:

$$F_E = 1 - \left[\frac{(\delta_S - \delta^*)}{(\delta_P - \delta^*)}\right]^m \tag{1}$$

where δ_S is defined as the isotopic signal of the soil [‰], δ_p is the original isotopic signal of soil water [‰], δ^* is the limiting isotopic enrichment factor [‰], and m is the temporal enrichment slope [–]. In our study, the original isotopic signal δ_p is the signal of the water input via precipitation or irrigation. During the WS, δ_p was estimated as the weighted average of the isotopic signals from the most frequent large precipitation events. For the DS, we used the weighted mean of the irrigation water as the input signal. We assumed steady state conditions, as the samples were taken between 10–12 a.m. and thus at a time when steady state conditions in rice fields can be assumed (Wei et al., 2015). Variables δ^* and m were calculated following Equations 2 and 3, respectively, as described in Benettin et al. (2018)(2018) and Gibson et al. (2016):

$$\delta^* = \frac{(RH\delta_A + \varepsilon_k + \varepsilon^+/\alpha^+)}{(RH - 10^{-3}(\varepsilon_k + \varepsilon^+/\alpha^+))} \tag{2}$$

$$m = \frac{(RH - 10^{-3}(\varepsilon_k + \varepsilon^+/\alpha^+))}{(1 - RH + 10^{-3}\varepsilon_k)} \tag{3}$$

where δ_A is the isotopic composition of atmospheric vapour [‰] (assuming that the isotopic composition of atmospheric vapour is in equilibrium with precipitation), RH is the relative humidity, ε_k is the kinetic fractionation factor [‰], and α^+ [–] and ε^+ [‰] are equilibrium fractionation factors. The temperature-dependent parameter α^+ was calculated for δ^2H and $\delta^{18}O$ separately (Benettin et al., 2018). Furthermore, ε_k was calculated according to Benettin et al. (2018), presuming diffusive transport in soil pore spaces (Barnes and Allison, 1983). The equilibrium isotopic separation between liquid and vapour was computed as $\varepsilon^+ = (\alpha^+ - 1)10^3$ [‰] (Benettin et al., 2018). As part of the calculation of ε_k, the aerodynamic diffusion parameter

n [–] has to be set. It ranges from n=0.5 for open water or saturated soils to n=1 for dry soil (Benettin et al. 2018). We set n=0.5 for wet rice fields, 0.7 for dry rice, and 0.9 for maize.

2.5 Statistical analysis

We tested for significant statistical differences in stable isotopes of water (δ^2H and δ^{18}O) during seasons, growing stages, and treatments between all water sources. Normal distribution was tested by the Shapiro Wilk test and homogeneity of variances by the Fligner Killeen test (Python 2.7.10.0). Because of the non-normal distribution of data, we further carried out a non-parametric rank based test considering no ties. We rejected the null hypothesis that two profiles were significantly different ($p \leq 0.05$) referring to different treatments, seasons, and crops.

The isotopic values of the two treatments straw and no-straw application as a control plot were combined for each crop for further analysis, as there were no significant differences for stable isotopes of water between the treatments ($p > 0.05$).

3 Results

3.1 Soil water isotopic distribution

Both δ^2H and δ^{18}O values of surface water and groundwater were higher at the beginning of each season and decreased towards the end. During both seasons, surface water and groundwater under wet rice showed a relatively similar range of isotopic compositions with no statistically significant differences (Table 2). A distinct difference in the composition of GW was only observed under maize in the DS. Stable isotope compositions of irrigation water were not significantly different in both seasons. Rainwater was isotopically similar to groundwater and surface water during the WS, unlike during the DS, where it was significantly different.

Figure 3 displays the δ^2H and δ^{18}O together with the water content and lc-excess values in soil water as a function of soil depth during GS1, GS2, and GS3 of wet rice during the WS, along with wet rice, dry rice, and maize during the DS with the standard deviation of the replicates. The range of isotopic composition of rainwater and irrigation water defines the water input to the system at each season (average values are presented in Table 2). The isotopic composition of soil water from crops during the DS were statistically different from the WS crops (wet rice). GS2 and GS3 of maize and wet rice were statistically different during the DS, and maize and dry rice were statistically different except for the GS3 of dry rice. The isotopic signals of the soil profiles to a depth of ~0.2 m were highly variable, becoming more stable further below. Therefore, soil water isotopic values can be divided into two categories: shallow soil water from 0 to 0.2 m, and deep soil water from 0.2 to 0.6 m. In the wet rice soil, the isotopic values increased until the depth of 0.05 m and then decreased again to about 0.2 m (Fig. 3a, b, e, f). Interestingly, in wet rice soils, the depth of the highest isotope enrichment, which is just below the soil surface, decreased deeper in the soil during the growing period from GS1 to GS3 in both seasons. In contrast, the shape of the isotopic profiles of dry rice and maize follow a different pattern than for wet rice, with higher δ^2H and δ^{18}O values at the soil surface and an exponential decrease down to around 0.2 m soil depth (Fig. 3i, j, m, n). The isotopic composition of shallow soil in dry rice fields decreased from GS1 towards GS3, where the values were stable in maize fields during all phases of plant growth. The isotopic values in deep soil were nearly stable in all the profiles regardless of the crop during both seasons.

Maize was characterized by dry soil conditions at the surface and at shallow depths compared to both rice varieties (Fig. 3c, g, k, o). The highest water content was found for wet rice at the surface soil (17.7±1.2 %), and it was nearly constant below a depth of 0.2 m (12.0±1.3 %) during both seasons. The water content in dry rice soils were rather evenly distributed along the soil profile except at the soil surface. Soils under maize were getting dryer as plant developed, while such clear patterns could not be observed for the rice crops.

The lc-excess is an indicator for evaporation, with lower values reflecting larger evaporative losses. We found an exponential pattern with lower values in shallow soils, particularly for maize, but also, though less apparent, for dry rice soils (Fig. 3d, h, l, p). This indicates a higher evaporation signal in shallow soils for the DS crops compared to the WS crop. The highest evaporation was found near the surface in maize fields with significantly lower lc-excess values. In addition, lc-excess values decreased from GS1 to GS3. In contrast, lc-excess patterns of shallow soils in wet rice fields generally increased with growth during both seasons.

Soil water mixed with incoming precipitation and irrigation, and therefore had a potentially different isotopic composition than the incoming water itself. The δ^2H and δ^{18}O values of soil water plot on a line below the LMWL due to the evaporation effect (Fig. 4). The slope of the regression line and coefficient of determination (R^2) were higher in the DS (avg. slope=5.1, R^2=0.92) than during the WS (avg. slope=3.5, R^2=0.54). Soil water δ^2H and δ^{18}O compositions were higher (enriched) in shallow soils and deviated stronger from the LMWL than soil water from deep soils.

The original isotopic signal of the incoming water changed depending on the season, especially during the WS. As a result of frequent precipitation events introducing strong variations in the isotopic composition (δ^2H from –55.20 to –10.89 ‰ and δ^{18}O from –7.91 to –2.54 ‰), the isotopic signal of the incoming water varies significantly (Fig. 2). We observed lower slopes and more clustered data points in wet rice soil during the WS, indicating lower soil evaporation compared to the DS. During the WS, several shallow soil isotopic values plotted close to the LMWL, and some deep soil values deviate more from the LMWL (Fig. 4a–c). This indicates the movement of isotopic signals stemming from the previous DS to deeper compartments of the soil profile. During the DS, slopes of the regression lines were lower for wet rice (slope=5.2, R^2=0.88) than for dry rice (slope=6.0, R^2=0.94) and maize (slope=5.5, R^2=0.91) (Fig. 4d–l). Due to less frequent and shorter precipitation events during the DS, the isotopic signal of the incoming water was dominated by irrigation water, with nearly constant isotopic composition during the growing period. Small precipitation events were subjected to higher evaporative loss and resulted in enriched isotopic composition during this time (Table 2).

3.2 Fraction of evaporation loss from soil water

The estimated fraction of evaporation F_E at each soil depth was derived by means of an evaporative enrichment of heavier isotopes in the soil water (Fig. 5). During the DS, soils in dry rice fields showed higher soil F_E at shallow depths (0.54±0.1), which decreased both during plant growth to 0.27±0.1, and along with depth towards deep soils (0.20±0.1) (Fig. 5g, h, i).

Evaporation from soils in maize fields decreased with depth for both isotopes (from 0.31±0.1 to 0.07±0.05) and did not fluctuate significantly during plant growth (Fig.5 j, k, l). The F_E at shallow soils of wet rice ranged from 0.42±0.08 to 0.20±0.08 (similar for both isotopes) and remained nearly stable in deep soils at 0.13±0.1 (Fig. d, e, f). However, the fractionation was higher during the WS, and the F_E for δ^2H and δ^{18}O expressed a significant difference (Fig. 5a, b, c), in clear contrast to data from the DS. During the WS, F_E in shallow soil decreased from 0.72±0.12 (GS1) to 0.47±0.06 (GS3) for δ^2H and from 0.87±0.07 (GS1) to 0.76±0.07 (GS3) for δ^{18}O, while the fractionation was lowest during GS2 for both isotopes. Pore water indicated lower F_E in soils below 0.4 m during the GS1 in dry and wet rice, and this depth decreased to about 0.35 m during GS3. However, there was a clear decrease in the extent of evaporation with growth in rice fields. The soil water in wet rice fields carries a signal of high evaporation losses down to 0.5 m during the WS. The estimated F_E from ponding surface water was found to be larger during the WS than during the DS with no significant difference between δ^2H and δ^{18}O. The F_E of ponded water during the WS did not fluctuate with time, and remained close to 0.92±0.07, while during the DS values decreased from GS1 (0.67±0.03) to GS3 (0.24±0.01). Thus, surface water F_E indicates higher evaporation losses during the WS, and the evaporation signal is carried to deeper layers by subsequent percolation.

4 Discussion

General mechanisms in soil water movement

The soil water isotopic profiles reflect a balance between water infiltration (input) and soil evaporation (output) (Hsieh et al., 1998), the latter being responsible for kinetic separation (Barnes and Allison, 1984). Depending on the evaporation effect on soil water isotopic composition and water transport processes, we found this clear isotopic separation at around 0.2 m below the surface in our study site. This has been developed predominantly due to the existence of the dense, least permeable plough pan, which separates the puddled shallow soil and non-puddled subsoil in paddy fields. It is a result of repeated ploughing over many years due to the cultivation (Chen and Liu, 2002). The isotopic profiles we observed are a response to three major mechanisms that drive soil water movement in our sites, i.e., 1) matrix flow, 2) preferential flow, and 3) evaporation. These three mechanisms will be discussed in the following sections.

4.1 Matrix flow

In the unsaturated zone in dry rice and maize fields, vapour transport process is dominant (Bittelli et al., 2008). This leads to build up of heavy water molecules (formed by ^{2}H and ^{18}O) at the water–air interface, which are transported downwards and then mixed with the soil matrix (Horita et al., 2008). Downward water movement at steady state or slowly changing conditions results in an exponential evaporation profile along the depth during the drying stage that is comparable to those found in dry and maize soils (Fig. 3i, j, m, n) (Zimmermann et al., 1966; Barnes and Allison, 1988; Rothfuss et al., 2015). The downward flow in our study site can be mainly via advection, diffusion and continuous slow infiltration from the liquid phase through the clay matrix in flooded fields (Koeniger et al., 2016).

Under flooded conditions of wet rice, water slowly percolates from the ponding, open water body. The upper soil layer is affected by isotopically enriched water via a gravity-driven, piston-like matrix flow. The isotopic composition of soil water increased with the depth (until the most enriched point) (Fig. 3a, b, e, f). We assume this is a result of the successive displacement of pre-existing mobile soil water by infiltrating water. During ponding, infiltration modifies the soil water isotopic composition in the uppermost part of the profile and re-evaporation of infiltrated water has been interpreted and termed as soil evaporation. Still, soil water in fine pores represents quasi-stationary storage exchanging water and isotopes with the mobile phase (Gazis and Feng, 2004). As a result, the ponding water column together with the soil water at shallow depth down to the infiltration front acted as a single compartment reflecting the evaporation signal from the ponding water in the rice paddies. Isotopic values below this point showed a strong depletion until reaching a stable value below approximately 0.2 m. Baram et al. (2013) have found a similar isotopic pattern in clay soil in Israel, which they explained by gravity driven, piston-like matrix flow under continuous ponded infiltration.

The significant capillary rise can happen depending on the soil texture and depth of the groundwater head. It has been shown that capillary rise of depleted shallow groundwater can also influence soil compartments at greater soil depths (Baram et al., 2013; Clark and Fritz, 1997). This upward matrix flow also occurred in our system given the fine textured soils (Table 1) and the rather shallow groundwater levels between 0.5 to 1.7 m (Mahindawansha et al., 2018a).

The observed smoothing of the isotopic signals in the shallow soils could also indirectly be explained by water redistribution via root uptake through transpiration, because transpiration decreases the soil moisture, but preserves the isotopic composition (Baram et al., 2013). With decreasing soil moisture, incoming water has a relatively stronger imprint on the soil isotopic composition. Further, hydraulic redistribution of water in the vadose zone is an important process of passive transport of soil water along a hydraulic gradient through the rooting system (Richards and Caldwell, 1987). Therefore, hydraulic redistribution can influence the pore water stable isotopic composition and reshape the soil water isotopic profile. Sprenger et al. (2016) discussed the significance of hydraulic redistribution in the soil hydrological cycle. However, the influence of hydraulic redistribution on the isotopic composition is likely very small (Walter, 2010).

4.2 Preferential flow through desiccation cracks

Desiccation cracks in maize fields (below 0.2 m) reached deeper (~0.2 m) and were narrower (~0.02 m) than those developed in the dry rice fields (own observation). Baram et al. (2012) observed that naturally formed desiccation crack systems can create preferential flow paths that reach more than a meter deep. In our maize fields, we observed that the groundwater isotopic compositions are strongly influenced by irrigation water suggesting the existence of fast flow conduits (Mahindawansha et al., 2018a). He et al. (2017) have also observed leaching losses of water and nutrients in a lysimeter experiment, which they attributed to crack flow mechanisms. Preferential flow through desiccation cracks is therefore likely a dominant flow pathway in rice-based cropping systems, also for crops grown in the dry season that are planted to replace water-demanding wet rice. During irrigation, preferential flow transports water with an evaporation imprint, affecting the capillary gradient between the soil matrix and crack walls. We recorded a gradual isotopic depletion towards deep soils of dry rice and maize fields. This indicates subsurface mixing of isotopically enriched soil water and depleted irrigation water that percolated into the deep vadose zone via preferential flow paths (Baram et al., 2012; Nativ et al., 1995).

4.3 Evaporation effect

Evaporation and the lc-excess

Systematic isotopic depletion and increasing negativity of lc-excess profiles indicated declining evaporation from GS1 to GS3 in rice (Fig. 3). In both, dry and wet rice, the isotopic profiles showed a clear shift from enriched to depleted values along the growth, especially in shallow soils and regardless of the season. However, we observed a transfer of the most isotopically enriched water in wet rice down to greater depths in conjunction with plant growth (Fig. 3a, b, e, f). A different pattern of lc-excess was observed in maize fields (Fig. 3p) compared to rice (Fig. 3d, h, l). Here, the evaporation fraction gradually increased towards the end of the season when irrigation ceased (Fig. 2), resulting in dry soil conditions and a soil water deficit. Therefore, we conclude that there is an influence of the crop type and growth stage on evaporation fractionation in the soil water, matching previous reports that the plant cover reduces kinetic fractionation processes in the soils (Burger and Seiler, 1992; Dubbert et al., 2013).

Evaporation and the LMWL

Comparisons of regression lines of soil water samples to the GMWL in the dual isotope space (δ^{18}O, δ^{2}H) helped identifying the environmental conditions during soil evaporation with regard to season and crop (Fig. 4). The slope of the δ^{18}O–δ^{2}H relationship decreases because of kinetic fractionation (Sprenger et al., 2016). This deviation can be used to estimate evaporation losses (Clark and Fritz, 1997). The steeper slopes of the dry soils (maize, dry rice) can be explained by an increase in the effective thickness of the vapour transport layer (Barnes and Allison, 1988) compared to the soils of wet rice. For soils under wet rice, a steeper gradient near the surface was found, similar to observations made by Allisons (1982) for saturated soils. The δ^{18}O–δ^{2}H relation of deep soil water under wet rice fell even further below the LMWL during the WS from GS2 and GS3 (Fig. 4b, c). In contrast, shallow soils plotted closer to the LMWL indicated lower evaporation rates. Furthermore, deep soil water showed isotopic similarity to the irrigation water. Following these observations, we assume that the deep soil isotopic profiles result from mixing of soil water with irrigation water, the latter likely stemming from the previous DS (memory of the old isotopic signal) that moved downward via matrix flow. Due to the low rates of percolation of 1 to 5 mm d^{-1} in clay paddy soils (Bouman and Tuong, 2001), deep soil profiles with multiple compartments may reveal a record of antecedent evaporation conditions or preferential flow shortcuts between compartments.

Apart from this, all soil profiles presented enriched values and distinct evaporation processes during the WS (Fig. 4a–c). Lower slopes of evaporation lines in wet soil compared to dry soil point out to greater kinetic effects (Cooper et al., 1991). Slopes of evaporation lines <3.5 were reported to indicate diffusion processes (Allison et al., 1983). We, therefore, assume that diffusion processes in the subsurface were relevant for shaping soil isotopic profiles in the WS, especially at GS1 and GS3 (Fig. 4a, c).

During GS2, mixing processes between infiltrating water dominated and limited diffusion processes due to continuous intense precipitation events during that time. In line with this, a higher correlation between plant water and rainwater during this time compared to the other growing stages was reported by Mahindawansha et al. (2018b). Overall, an enrichment of soil water isotopic composition during the WS and a depletion during the DS is comparable to observations made by Hsieh et al. (1998) in an arid to humid transect in Hawaii. Similar differences between depleted winter and enriched summer isotopic profiles in combination with mixing processes were also reported by Baram et al. (2013) and DePaolo et al. (2004).

Unproductive water losses via evaporation

Kinetic fractionation and its imprint on soil water isotopic profiles in the shallow soil is relatively small in tropical climates given generally high relative humidity (Gonfiantini, 1986). Nevertheless, our observations point to kinetic fractionation down to a depth of ~0.2 m, shallower than the average depth in temperate regions (~0.3 m) (Gazis and Feng, 2004; Sutanto et al., 2012), the Mediterranean (~0.5 m) (Oshun et al., 2016; Simonin et al., 2014), or in arid climates (~3 m) (Allison and Hughes, 1983; Singleton et al., 2004). Shallow soils exhibit a decreasing trend of F_E during both WS and DS from the beginning of the growing season towards its end (Fig. 5), most likely driven by an increase in the leave area of the aboveground vegetation. Rothfuss et al. (2010) made comparable observations in a lab-based experiment on soil columns and reported changes in F_E over time. They found values starting with 100 % at bare soil conditions, and ending with 5 % at full development of the deep-rooting perennial grass grown in the columns. The fraction of soil evaporation was estimated as percentages 40 % from the beginning of the DS and decreased to 25 % towards the end, while it dropped from 80 to 60 % during the WS. Values of about 30 % evaporation were reported for Asia (Bouman et al., 2005), and 40 % for flooded rice fields in semi-arid region of south-eastern Australia (Simpson et al., 1992). During the WS however, F_E was higher in the shallow soil compared to the DS. This partly contradicting finding might be related to the high temperatures along with high relative humidity values leading to water pressure deficits. The substantially large difference for F_E during the WS between δ^2H- and δ^{18}O- based assessments, can be related to the different hydrogen compounds. The values we obtained refer to the fraction of water loss from the soil matrix and small/intermediate pores. With isotope methods, we only estimated unproductive evaporation losses from the soil, because transpiration does not change the isotopic signal as it is known as non-fractionating process (Zimmermann U. et al., 1967). However, Wei et al. (2018) showed that an isotopic approach can also lead to higher estimates of the fractions compared to model results for rice and maize in Tsukuba, Japan. Overall, we conclude that the isotope method provides comparable results to previous studies.

4.4 Differences in fractionation of δ2H and δ18O

Apart from the highly depleted isotopic signal for δ^2H observed in deep soil under wet rice fields during the WS (Fig. 3b), there was a systematic deviation of about 20 % between δ^2H and δ^{18}O fractionation in shallow soil and 40 % in deep soil. (Fig. 5a–c). This difference may have resulted from the formation of specific hydrogen compounds under continuous inundation conditions. Flooding affects soils chemically, physically, and biologically, resulting in a reduction of redox potential (Fageria et al., 2011; Zhang et al., 2015). Due to the anaerobic conditions that develop in submerged soil, hydrogen compounds such as CH_4, H_2S, H_2, and NH_4^+ can be produced via microbial anaerobic respiration (Fageria et al., 2011; Gerardi, 2003). The formation of these hydrogen compounds leads to isotopic exchange and bias in δ^2H, as observed by Baram et al. (2013) in clay soils below ponded wastewater conditions. CH_4 emissions in wet rice fields on our study site were higher during the WS compared to the DS (Weller et al., 2016), and this may have caused lower slopes in the dual isotope plots as observed (Fig. 4a–c).

Furthermore, the equilibrium constant for isotopic partitioning of liquid water with vapour (1,000 lnα) is a function of the temperature (here we present the values at 27°C) and the sign of the value (positive), e.g., $H_2O_{(l)} \leftrightarrow H_2O_{(g)}$ for δ^{18}O +9.2 (Freidman and O'Neil, 1977; Majoube, 1971) and +74.3 for δ^2H (Majoube, 1971). Water vapour δ^2H further isotopically fractionates with $CH_{4(g)}$ (1,000 lnα=+23.4, see Bottinga, (1969)), $H_2S_{(g)}$ (1,000 lnα=+851.0 as in Galley et al., ((1972); Clark and Fritz, (1997)), as well as liquid water with $CH_{4(g)}$ with 1,000 lnα=+242.1 (Horibe and Craig, 1995), leading to higher δ^2H (enriched) in both phases. Moreover, liquid water and water vapour further manifest an equilibrium with $H_{2(g)}$ with higher equilibrium fractionation (Bottinga, 1969; Rolston et al., 1976). As a result, the assumption of δ^2H enrichment is further reinforced. The difference between δ^2H and δ^{18}O has been found to be more pronounced at a greater depth, stipulating formation of hydrogen compounds in deeper soil (Fig. 5 a–c). Besides, exchange rates and fractionation with kaolinite and smectite (Gilg and Sheppard, 1996) are faster and more pronounced for δ^2H. The assumption for this dissimilarity between δ^2H and δ^{18}O can be quantified by a sensitivity analysis, giving a relative depletion by 5±2 ‰ of δ^2H. Because of the above processes, bias can result in the calculation of F_E during the WS. Due to the high standard deviation of the isotopic composition in extreme precipitation events during the WS, prediction of the original water source at a time was also more uncertain. The F_E values are sensitive to the isotopic composition of atmospheric vapour and original water input. Nevertheless, only seasonal averages were assigned in the calculation. This difference was not prominent in wet rice fields during the DS, where oxidizing conditions occurred in time gaps between irrigation events; it was also not observed in dry rice and maize fields.

In addition, vacuum-extracted soil water also contains bound water plus adsorbed water, making isotopic composition lower (Gaj et al., 2017; Velde, 1992)), separate from additional systematic errors resulting from the extraction method (Orlowski et al., 2016). High water-holding capacity (Brouwer et al., 2001; Hazelton and Murphy, 2016) and the shrinking and swelling behavior (Baram et al., 2013; Dasog et al., 1988) of clayey soil add complexity to the analysis. Determination of α_k can also result in estimations errors of 1 to 29 %, depending on the value of α_k and the day of the partition (Rothfuss et al., 2010).

5 Conclusions

We identified three main processes, which are responsible for variations in the soil water isotopic profile: (I) soil evaporation, (II) soil water movement, and (III) the refilling of deep soil water through preferential flows via desiccation cracks. Apart from this, we were able to quantify unproductive soil water losses and relate these crop rotations and seasons. However, independent tools to confirm the findings of complex soil water isotope studies on evaporation would be highly appreciated. There was a clear isotopic separation between shallow and deep soil, with higher enrichment in shallow soil at around 0.2 m below the surface. Deep soil in wet rice fields often presented inverted evaporated profiles because of lower compartments carrying over the history of the transported evaporation signal from the previous season. Shallow soils in maize fields showed a stronger soil evaporation effect than rice fields. However, compared to the original water input, greater water loss was estimated during the WS compared to the DS when referring to evaporation from the soil matrix. The observation of difference in the fractionation of δ^2H and δ^{18}O deserves further research. Even though we provided a theoretical background of how this fractionation might occur, we were not able measuring the different components. Further research into these processes would help better understanding the evaporation process.

To conclude, water losses via soil evaporation is a major unproductive loss next to leaching losses, especially during the early growing stage. Therefore, our study helps to increase understanding of soil water transport processes and evaporation losses from soil in response to crop rotation systems. Our hypothesis of reducing the unproductive water losses by introducing dry seasonal crops is supported by isotope data. Farmers should apply mitigation methods to reduce soil water evaporation, e.g. by mulching, or growing cover crops in the fallow period and by protecting the plough pan.

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References

Allison, G. B.: The relationship between 18O and deuterium in water in sand columns undergoing evaporation, J. Hydrol., 55(1–4), 163–169, 1982.

Allison, G. B. and Hughes, M. W.: The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region, J. Hydrol., 60(1–4), 157–173, 1983.

Baram, S., Kurtzman, D. and Dahan, O.: Water percolation through a clayey vadose zone, J. Hydrol., 424–425, 165–171, doi:10.1016/j.jhydrol.2011.12.040, 2012.

Baram, S., Ronen, Z., Kurtzman, D., Külls, C. and Dahan, O.: Desiccation-crack-induced salinization in deep clay sediment, Hydrol. Earth Syst. Sci., 17(4), 1533–1545, doi:https://doi.org/10.5194/hess-17-1533-2013, 2013.

Barnes, C. J. and Allison, G. B.: The distribution of deuterium and 18O in dry soils: 3. Theory for non-isothermal water movement, J. Hydrol., 74(1), 119–135, doi:10.1016/0022-1694(84)90144-6, 1984.

Barnes, C. J. and Allison, G. B.: Tracing of water movement in the unsaturated zone using stable isotopes of hydrogen and oxygen, J. Hydrol., 100(1–3), 143–176, doi:10.1016/0022-1694(88)90184-9, 1988.

Barnes, C. J. and Turner, J. V.: Chapter 5 - Isotopic Exchange in Soil Water, in Isotope Tracers in Catchment Hydrology, edited by C. Kendall and J. J. McDONNELL, pp. 137–163, Elsevier, Amsterdam., 1998.

Belder, P., Bouman, B. A. M., Cabangon, R., Guoan, L., Quilang, E. J. P., Yuanhua, L., Spiertz, J. H. J. and Tuong, T. P.: Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia, Agric. Water Manag., 65(3), 193–210, doi:10.1016/j.agwat.2003.09.002, 2004.

Benettin, P., Volkmann, T. H. M., von Freyberg, J., Frentress, J., Penna, D., Dawson, T. and Kirchner, J.: Effects of climatic seasonality on the isotopic composition of evaporating soil waters, Hydrol. Earth Syst. Sci., 22(5), 2881–2890, doi:10.5194/hess-22-2881-2018, 2018.

Beyer, M., Koeniger, P., Gaj, M., Hamutoko, J. T., Wanke, H. and Himmelsbach, T.: A deuterium-based labeling technique for the investigation of rooting depths, water uptake dynamics and unsaturated zone water transport in semiarid environments, J. Hydrol., 533, 627–643, doi:10.1016/j.jhydrol.2015.12.037, 2016.

Bittelli, M., Ventura, F., Campbell, G. S., Snyder, R. L., Gallegati, F. and Pisa, P. R.: Coupling of heat, water vapor, and liquid water fluxes to compute evaporation in bare soils, J. Hydrol., 362(3), 191–205, doi:10.1016/j.jhydrol.2008.08.014, 2008.

Bottinga, Y.: Calculated fractionation factors for carbon and hydrogen isotope exchange in the system calcite-carbon dioxide-graphite-methane-hydrogen-water vapor, Geochim. Cosmochim. Acta, 33(1), 49–64, doi:10.1016/0016-7037(69)90092-1, 1969.

Bouman, B. A. M.: Water Management in Irrigated Rice: Coping with Water Scarcity, Int. Rice Res. Inst., 2007.

Bouman, B. A. M. and Tuong, T. P.: Field water management to save water and increase its productivity in irrigated lowland rice, Agric. Water Manag., 49(1), 11–30, 2001.

Bouman, B. A. M., Peng, S., Castañeda, A. R. and Visperas, R. M.: Yield and water use of irrigated tropical aerobic rice systems, Agric. Water Manag., 74(2), 87–105, doi:10.1016/j.agwat.2004.11.007, 2005.

Braud, I., Biron, P., Bariac, T., Richard, P., Canale, L., Gaudet, J. P. and Vauclin, M.: Isotopic composition of bare soil evaporated water vapor. Part I: RUBIC, J. Hydrol., 369(1–2), 1–16, doi:10.1016/j.jhydrol.2009.01.034, 2009.

Brouwer, C., Prins, K., Kay, M. and Heibloem, M.: Irrigation Water Management: Irrigation Methods, Training manual, FAO - Food and Agriculture Organization of the united nations, Via delle Terme di Caracalla, 00100 Rome, Italy. [online] Available from: http://www.fao.org/docrep/s8684e/s8684e00.htm#Contents, 2001.

Burger, H. M. and Seiler, K. P.: Evaporation from soil water under humid climate conditions and its impact on deuterium and ^{18}O concentrations in groundwater, Isot. Tech. Water Resour. Dev. 1991 [online] Available from: http://inis.iaea.org/Search/search.aspx?orig_q=RN:23034850 (Accessed 8 November 2018), 1992.

Chen, S.-K. and Liu, C. W.: Analysis of water movement in paddy rice fields (I) experimental studies, J. Hydrol., 260(1), 206–215, doi:10.1016/S0022-1694(01)00615-1, 2002.

Clark, I. D. and Fritz, P.: Environmental Isotopes in Hydrogeology, CRC Press., 1997.

Cooper, L. W., DeNiro, M. J. and Keeley, J. E.: The relationship between stable oxygen and hydrogen isotope ratios of water in astomatal plants, , 247–255, 1991.

Counce, P. A., Keisling, T. C. and Mitchell, A. J.: A Uniform, Objective, and Adaptive System for Expressing Rice Development, Crop Sci., 40(2), 436–443, doi:10.2135/cropsci2000.402436x, 2000.

Craig, H. and Gordon, L. I.: Deuterium and oxygen 18 variations in the ocean and the marine atmosphere, , 17, 1965.

Daly, E., Porporato, A. and Rodriguez-Iturbe, I.: Coupled Dynamics of Photosynthesis, Transpiration, and Soil Water Balance. Part I: Upscaling from Hourly to Daily Level, J. Hydrometeorol., 5(3), 546–558, doi:10.1175/1525-7541(2004)005<0546:CDOPTA>2.0.CO;2, 2004.

Dasog, G. S., Acton, D. F., Mermut, A. R. and JONG, E. D.: Shrink-swell potential and cracking in clay soils of Saskatchewan, Can. J. Soil Sci., 68(2), 251–260, 1988.

DePaolo, D. J., Conrad, M. E., Maher, K. and Gee, G. W.: Evaporation Effects on Oxygen and Hydrogen Isotopes in Deep Vadose Zone Pore Fluids at Hanford, Washington, Vadose Zone J., 3(1), 220–232, doi:10.2136/vzj2004.2200, 2004.

Dubbert, M., Cuntz, M., Piayda, A., Maguás, C. and Werner, C.: Partitioning evapotranspiration – Testing the Craig and Gordon model with field measurements of oxygen isotope ratios of evaporative fluxes, J. Hydrol., 496, 142–153, doi:10.1016/j.jhydrol.2013.05.033, 2013.

Fageria, N. K., Carvalho, G. D., Santos, A. B., Ferreira, E. P. B. and Knupp, A. M.: Chemistry of Lowland Rice Soils and Nutrient Availability, Commun. Soil Sci. Plant Anal., 42(16), 1913–1933, doi:10.1080/00103624.2011.591467, 2011.

FAO: Save and Grow in Practice: Maize, Rice, Wheat–a Guide to Sustainable Cereal Production, in Save and Grow in practice: maize, rice, wheat : a guide to sustainable cereal production, p. 124., 2016.

Freidman, T. and O'Neil, J. R.: Compilation of stable isotope fractionation factors of geochemical interest: US Geol, Surv. Prof Pap., 440, 1977.

Gaj, M., Beyer, M., Koeniger, P., Wanke, H., Hamutoko, J. and Himmelsbach, T.: In situ unsaturated zone water stable isotope (^{2}H and ^{18}O) measurements in semi-arid environments: a soil water balance, Hydrol. Earth Syst. Sci., 20(2), 715–731, doi:10.5194/hess-20-715-2016, 2016.

Gaj, M., Kaufhold, S., Koeniger, P., Beyer, M., Weiler, M. and Himmelsbach, T.: Mineral mediated isotope fractionation of soil water: Mineral mediated isotope fractionation of soil water, Rapid Commun. Mass Spectrom., 31(3), 269–280, doi:10.1002/rcm.7787, 2017.

Galley, M. R., Miller, A. I., Atherley, J. F. and Mohn, M.: GS process physical properties, Atomic Energy of Canada Ltd., 1972.

Gangi, L., Rothfuss, Y., Ogée, J., Wingate, L., Vereecken, H. and Brüggemann, N.: A New Method for In Situ Measurements of Oxygen Isotopologues of Soil Water and Carbon Dioxide with High Time Resolution, Vadose Zone J., 14(8), doi:10.2136/vzj2014.11.0169, 2015.

Gazis, C. and Feng, X.: A stable isotope study of soil water: evidence for mixing and preferential flow paths, Geoderma, 119(1–2), 97–111, doi:10.1016/S0016-7061(03)00243-X, 2004.

Gerardi, M. H.: The Microbiology of Anaerobic Digesters, John Wiley & Sons, Hoboken, New Jersey., 2003.

Gibson, J. J., Birks, S. J. and Yi, Y.: Stable isotope mass balance of lakes: a contemporary perspective, Quat. Sci. Rev., 131, 316–328, doi:10.1016/j.quascirev.2015.04.013, 2016.

Gilg, H. A. and Sheppard, S. M.: Hydrogen isotope fractionation between kaolinite and water revisited, Geochim. Cosmochim. Acta, 60(3), 529–533, 1996.

Gonfiantini, R.: Environmental isotopes in lake studies, Handb. Environ. Isot. Geochem. Terr. Environ., 2, 113–168, 1986.

Hazelton, P. and Murphy, B.: Interpreting Soil Test Results: What Do All the Numbers Mean?, Csiro Publishing., 2016.

He, Y., Siemens, J., Amelung, W., Goldbach, H., Wassmann, R., Alberto, Ma. C. R., Lücke, A. and Lehndorff, E.: Carbon release from rice roots under paddy rice and maize–paddy rice cropping, Agric. Ecosyst. Environ., 210, 15–24, doi:10.1016/j.agee.2015.04.029, 2015.

He, Y., Lehndorff, E., Amelung, W., Wassmann, R., Alberto, Ma. C., von Unold, G. and Siemens, J.: Drainage and leaching losses of nitrogen and dissolved organic carbon after introducing maize into a continuous paddy-rice crop rotation, Agric. Ecosyst. Environ., 249, 91–100, doi:10.1016/j.agee.2017.08.021, 2017.

Heinz, E., Kraft, P., Buchen, C., Frede, H.-G., Aquino, E. and Breuer, L.: Set Up of an Automatic Water Quality Sampling System in Irrigation Agriculture, Sensors, 14(1), 212–228, doi:10.3390/s140100212, 2013.

Horibe, Y. and Craig, H.: DH fractionation in the system methane-hydrogen-water, Geochim. Cosmochim. Acta, 59(24), 5209–5217, doi:10.1016/0016-7037(95)00391-6, 1995.

Horita, J., Rozanski, K. and Cohen, S.: Isotope effects in the evaporation of water: a status report of the Craig–Gordon model, Isotopes Environ. Health Stud., 44(1), 23–49, doi:10.1080/10256010801887174, 2008.

Hsieh, J. C. C., Chadwick, O. A., Kelly, E. F. and Savin, S. M.: Oxygen isotopic composition of soil water: Quantifying evaporation and transpiration, Geoderma, 82(1), 269–293, doi:10.1016/S0016-7061(97)00105-5, 1998.

Janssen, M. and Lennartz, B.: Horizontal and vertical water and solute fluxes in paddy rice fields, Soil Tillage Res., 94(1), 133–141, doi:10.1016/j.still.2006.07.010, 2007.

Kendall, C. and Caldwell, E.: Fundamentals of isotope geochemistry, in Isotope Tracers in Catchment Hydrology, pp. 51–86, Elsevier., 1999.

Koeniger, P., Gaj, M., Beyer, M. and Himmelsbach, T.: Review on soil water isotope-based groundwater recharge estimations, Hydrol. Process., 30(16), 2817–2834, doi:10.1002/hyp.10775, 2016.

Kool, D., Agam, N., Lazarovitch, N., Heitman, J. L., Sauer, T. J. and Ben-Gal, A.: A review of approaches for evapotranspiration partitioning, Agric. For. Meteorol., 184, 56–70, doi:10.1016/j.agrformet.2013.09.003, 2014.

Kudo, Y., Noborio, K., Shimoozono, N. and Kurihara, R.: The effective water management practice for mitigating greenhouse gas emissions and maintaining rice yield in central Japan, Agric. Ecosyst. Environ., 186, 77–85, doi:10.1016/j.agee.2014.01.015, 2014.

Kutilek, M. and Nielsen, D. R.: Soil hydrology: texbook for students of soil science, agriculture, forestry, geoecology, hydrology, geomorphology and other related disciplines., Soil Hydrol. Texbook Stud. Soil Sci. Agric. For. Geoecology Hydrol. Geomorphol. Relat. Discip., pp.370 pp. ref.30 pp., 1994.

Landwehr, J. M. and Coplen, T. B.: Line-conditioned excess: a new method for characterizing stable hydrogen and oxygen isotope ratios in hydrologic systems, in International Conference on Isotopes in Environmental Studies, pp. 132–135, Int. At. Energy Agency Vienna., 2006.

Liu, C., Zhang, X. and Zhang, Y.: Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter, Agric. For. Meteorol., 111(2), 109–120, doi:10.1016/S0168-1923(02)00015-1, 2002.

Liu, Y., Liu, F., Xu, Z., Zhang, J., Wang, L. and An, S.: Variations of soil water isotopes and effective contribution times of precipitation and throughfall to alpine soil water, in Wolong Nature Reserve, China, CATENA, 126, 201–208, doi:10.1016/j.catena.2014.11.008, 2015.

Maclean, J. L., Dawe, D. C. and Hettel, G. P., Eds.: Rice almanac: source book for the most important economic activity on earth, 3rd ed., CABI Pub, Oxon, U.K., 2002.

Mahindawansha, A., Breuer, L., Chamorro, A. and Kraft, P.: High-Frequency Water Isotopic Analysis Using an Automatic Water Sampling System in Rice-Based Cropping Systems, Water, 10(10), 1327, doi:10.3390/w10101327, 2018a.

Mahindawansha, A., Orlowski, N., Kraft, P., Rothfuss, Y., Racela, H. and Breuer, L.: Quantification of plant water uptake by water stable isotopes in rice paddy systems, Plant Soil, doi:10.1007/s11104-018-3693-7, 2018b.

Majoube, M.: Fractionnement en oxygène 18 et en deutérium entre l'eau et sa vapeur, J. Chim. Phys., 68, 1423–1436, doi:10.1051/jcp/1971681423, 1971.

Mekonnen, M. M. and Hoekstra, A. Y.: The green, blue and grey water footprint of crops and derived crop products, Hydrol Earth Syst Sci, 15(5), 1577–1600, doi:10.5194/hess-15-1577-2011, 2011.

Melayah, A., Bruckler, L. and Bariac, T.: Modeling the Transport of Water Stable Isotopes in Unsaturated Soils Under Natural Conditions: 2. Comparison With Field Experiments, Water Resour. Res., 32(7), 2055–2065, doi:10.1029/96WR00673, 1996.

Nativ, R., Adar, E., Dahan, O. and Geyh, M.: Water Recharge and Solute Transport Through the Vadose Zone of Fractured Chalk Under Desert Conditions, Water Resour. Res., 31(2), 253–261, doi:10.1029/94WR02536, 1995.

Oerter, E. J. and Bowen, G.: In situ monitoring of H and O stable isotopes in soil water reveals ecohydrologic dynamics in managed soil systems, Ecohydrology, 10(4), e1841, doi:10.1002/eco.1841, 2017.

Orlowski, N., Frede, H.-G., Brüggemann, N. and Breuer, L.: Validation and application of a cryogenic vacuum extraction system for soil and plant water extraction for isotope analysis, J. Sens. Sens. Syst., 2(2), 179–193, doi:10.5194/jsss-2-179-2013, 2013.

Orlowski, N., Breuer, L. and McDonnell, J. J.: Critical issues with cryogenic extraction of soil water for stable isotope analysis, Ecohydrology, 9(1), 1–5, doi:10.1002/eco.1722, 2016.

Oshun, J., Dietrich, W. E., Dawson, T. E. and Fung, I.: Dynamic, structured heterogeneity of water isotopes inside hillslopes, Water Resour. Res., 52(1), 164–189, doi:10.1002/2015WR017485, 2016.

Pfister, S., Bayer, P., Koehler, A. and Hellweg, S.: Projected water consumption in future global agriculture: Scenarios and related impacts, Sci. Total Environ., 409(20), 4206–4216, doi:10.1016/j.scitotenv.2011.07.019, 2011.

Richards, J. H. and Caldwell, M. M.: Hydraulic lift: substantial nocturnal water transport between soil layers by Artemisia tridentata roots, Oecologia, 73(4), 486–489, 1987.

Rolston, J. H., Den Hartog, J. and Butler, J. P.: The deuterium isotope separation factor between hydrogen and liquid water, J. Phys. Chem., 80(10), 1064–1067, doi:10.1021/j100551a008, 1976.

Rothfuss, Y., Biron, P., Braud, I., Canale, L., Durand, J.-L., Gaudet, J.-P., Richard, P., Vauclin, M. and Bariac, T.: Partitioning evapotranspiration fluxes into soil evaporation and plant transpiration using water stable isotopes under controlled conditions, Hydrol. Process., 24(22), 3177–3194, doi:10.1002/hyp.7743, 2010.

Rothfuss, Y., Merz, S., Vanderborght, J., Hermes, N., Weuthen, A., Pohlmeier, A., Vereecken, H. and Brüggemann, N.: Long-term and high-frequency non-destructive monitoring of water stable isotope profiles in an evaporating soil column, Hydrol Earth Syst Sci, 19(10), 4067–4080, doi:10.5194/hess-19-4067-2015, 2015.

Rozanski, K., Araguás-Araguás, L. and Gonfiantini, R.: Isotopic Patterns in Modern Global Precipitation, in Climate Change in Continental Isotopic Records, edited by P. K. Swart, K. C. Lohmann, J. Mckenzie, and S. Savin, pp. 1–36, American Geophysical Union., 1993.

Simonin, K. A., Link, P., Rempe, D., Miller, S., Oshun, J., Bode, C., Dietrich, W. E., Fung, I. and Dawson, T. E.: Vegetation induced changes in the stable isotope composition of near surface humidity, Ecohydrology, 7(3), 936–949, doi:10.1002/eco.1420, 2014.

Simpson, H. J., Herczeg, A. L. and Meyer, W. S.: Stable isotope ratios in irrigation water can estimate rice crop evaporation, Geophys. Res. Lett., 19(4), 377–380, doi:10.1029/91GL02952, 1992.

Singleton, M. J., Sonnenthal, E. L., Conrad, M. E., DePaolo, D. J. and Gee, G. W.: Multiphase Reactive Transport Modeling of Seasonal Infiltration Events and Stable Isotope Fractionation in Unsaturated Zone Pore Water and Vapor at the Hanford Site, Vadose Zone J., 3(3), 775–785, doi:10.2136/vzj2004.0775, 2004.

Sprenger, M., Leistert, H, Gimbel, K and Weiler, M: Illuminating hydrological processes at the soil-vegetation-atmosphere interface with water stable isotopes, Rev. Geophys., 54(3), 674–704, doi:10.1002/2015RG000515, 2016.

Sprenger, M., Tetzlaff, D. and Soulsby, C.: Soil water stable isotopes reveal evaporation dynamics at the soil-plant-atmosphere interface of the critical zone, Hydrol. Earth Syst. Sci., 21(7), 3839–3858, doi:10.5194/hess-21-3839-2017, 2017.

Sutanto, S. J., Wenninger, J., Coenders-Gerrits, A. M. J. and Uhlenbrook, S.: Partitioning of evaporation into transpiration, soil evaporation and interception: a comparison between isotope measurements and a HYDRUS-1D model, Hydrol. Earth Syst. Sci., 16(8), 2605–2616, doi:10.5194/hess-16-2605-2012, 2012.

Tertre, E., Savoye, S., Hubert, F., Prêt, D., Dabat, T. and Ferrage, E.: Diffusion of Water through the Dual-Porosity Swelling Clay Mineral Vermiculite, Environ. Sci. Technol., 52(4), 1899–1907, doi:10.1021/acs.est.7b05343, 2018.

Timsina, J., Jat, M. L. and Majumdar, K.: Rice-maize systems of South Asia: current status, future prospects and research priorities for nutrient management, Plant Soil, 335(1), 65–82, doi:10.1007/s11104-010-0418-y, 2010.

Towprayoon, S., Smakgahn, K. and Poonkaew, S.: Mitigation of methane and nitrous oxide emissions from drained irrigated rice fields, Chemosphere, 59(11), 1547–1556, doi:10.1016/j.chemosphere.2005.02.009, 2005.

Twining, J., Stone, D., Tadros, C., Henderson-Sellers, A. and Williams, A.: Moisture Isotopes in the Biosphere and Atmosphere (MIBA) in Australia: A priori estimates and preliminary observations of stable water isotopes in soil, plant and vapour for the Tumbarumba Field Campaign, Glob. Planet. Change, 51(1), 59–72, doi:10.1016/j.gloplacha.2005.12.005, 2006.

Velde, B.: Introduction to clay minerals: chemistry, origins, uses and environmental significance., Introd. Clay Miner. Chem. Orig. Uses Environ. Significance [online] Available from: https://www.cabdirect.org/cabdirect/abstract/19931982767 (Accessed 21 January 2020), 1992.

Volkmann, T. H. M., Haberer, K., Gessler, A. and Weiler, M.: High-resolution isotope measurements resolve rapid ecohydrological dynamics at the soil–plant interface, New Phytol., 210(3), 839–849, doi:10.1111/nph.13868, 2016.

Walter, K.: Einfluss der Pflanzen auf die Isotopenzusammensetzung des Abflusses in Einzugsgebieten, PhD Thesis, Diplomarbeit, Institut für Hydrologie, Albert-Ludwigs-Universität Freiburg i …., 2010.

Wang, Z., Ankeny, M. and Horton, R.: The impact of water vapor diodes on soil water redistribution, J. Hydrol., 552, 600–608, doi:10.1016/j.jhydrol.2017.07.009, 2017.

Wei, Z., Yoshimura, K., Okazaki, A., Kim, W., Liu, Z. and Yokoi, M.: Partitioning of evapotranspiration using high-frequency water vapor isotopic measurement over a rice paddy field: Partitioning of evapotranspiration, Water Resour. Res., 51(5), 3716–3729, doi:10.1002/2014WR016737, 2015.

Wei, Z., Lee, X., Wen, X. and Xiao, W.: Evapotranspiration partitioning for three agro-ecosystems with contrasting moisture conditions: a comparison of an isotope method and a two-source model calculation, Agric. For. Meteorol., 252, 296–310, doi:10.1016/j.agrformet.2018.01.019, 2018.

Weller, S., Janz, B., Jörg, L., Kraus, D., Racela, H. S. U., Wassmann, R., Butterbach-Bahl, K. and Kiese, R.: Greenhouse gas emissions and global warming potential of traditional and diversified tropical rice rotation systems, Glob. Change Biol., 22(1), 432–448, doi:10.1111/gcb.13099, 2016.

Wenninger, J., Beza, D. T. and Uhlenbrook, S.: Experimental investigations of water fluxes within the soil–vegetation–atmosphere system: Stable isotope mass-balance approach to partition evaporation and transpiration, Phys. Chem. Earth Parts ABC, 35(13), 565–570, doi:10.1016/j.pce.2010.07.016, 2010.

Zhang, G., Yu, H., Fan, X., Liu, G., Ma, J. and Xu, H.: Effect of rice straw application on stable carbon isotopes, methanogenic pathway, and fraction of CH4 oxidized in a continuously flooded rice field in winter season, Soil Biol. Biochem., 84, 75–82, doi:10.1016/j.soilbio.2015.02.008, 2015.

Zhou, S., Yu, B., Zhang, Y., Huang, Y. and Wang, G.: Partitioning evapotranspiration based on the concept of underlying water use efficiency, Water Resour. Res., 52(2), 1160–1175, doi:10.1002/2015WR017766, 2016.

Zimmermann, U., Münnich, K. O., Roether, W., Kreutz, W., Schubach, K. and Siegel, O.: Tracers Determine Movement of Soil Moisture and Evapotranspiration, Science, 152(3720), 346–347, doi:10.1126/science.152.3720.346, 1966.

Zimmermann U., MüNnich K. O. and Roether W.: Downward Movement of Soil Moisture Traced by Means of Hydrogen Isotopes, Isot. Tech. Hydrol. Cycle, doi:10.1029/GM011p0028, 1967.

Zwart, S. J. and Bastiaanssen, W. G. M.: Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize, Agric. Water Manag., 69(2), 115–133, doi:10.1016/j.agwat.2004.04.007, 2004.

Tables and Figures

Table 1. Soil texture and average bulk densities of different depths along the soil profile

Soil depth (m)	Texture			Bulk density (g cm^{-3})	
	Clay (%)	Silt (%)	Sand (%)	Rice fields	Maize fields
0.0–0.1	58.3	33.4	8.4	0.92±0.03	1.17±0.02
0.1–0.2	59.5	30.9	9.7	1.02±0.03	1.13±0.04
0.2–0.4	58.9	29.6	11.5	n.a	n.a
0.4–0.6	50.0	26.7	23.4	n.a	n.a

Table 2. Mean±standard deviation (SD) of all water samples (rainwater weighted mean (RW), irrigation water (IW), groundwater (GW), and surface water (SW)) from different crops (wet rice, dry rice, and maize) during the wet season (WS) and dry season (DS).

Season	Crop	Water type	δ^2H±SD ‰	δ^{18}O±SD ‰
WS		RW	-26.82±2.30	-4.42±0.34
		IW	-32.00±3.25	-4.34±0.65
	Wet rice	GW	-23.76±5.24	-3.03±1.21
	Wet rice	SW	-24.06±7.36	-3.22±1.69
DS		RW	8.73±0.62	0.05±0.08
		IW	-34.60±3.56	-4.89±0.56
	Wet rice	GW	-14.66±7.46	-1.75±1.27
	Wet rice	SW	-14.15±9.41	-1.80±1.41
	Dry rice	GW	-12.56±8.75	-1.37±1.52
	Maize	GW	-22.57±7.60	-3.10±1.19

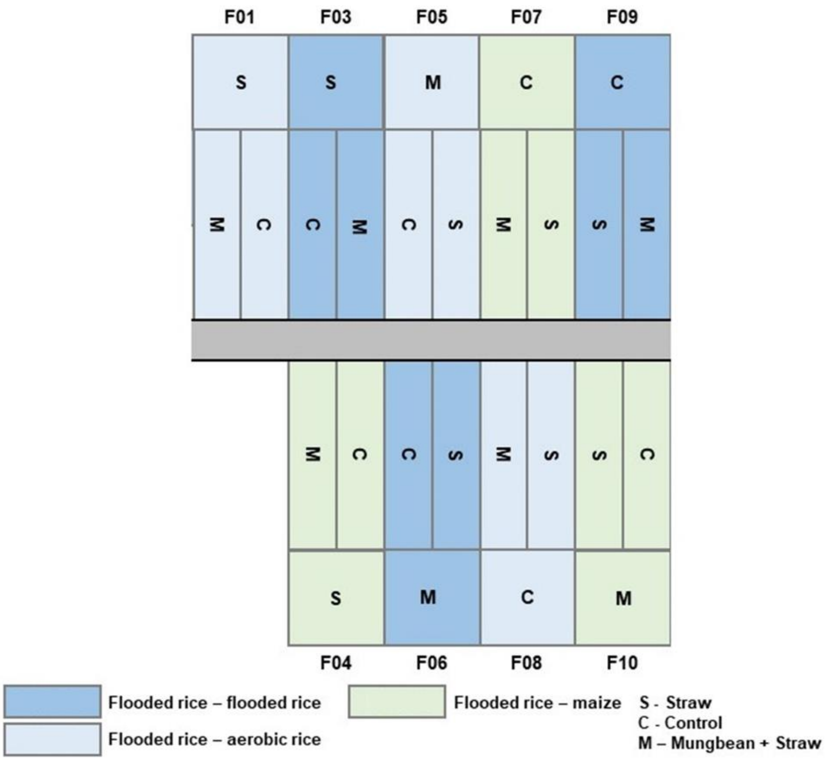

Figure 1. Experimental field design. The experiment consisted of nine fields (F) with three different crop rotations and water management practices. During the wet season, all fields were cultivated with wet rice, while during the dry season, three fields each were cultivated with wet rice, dry rice, and maize. Each field is divided into three different treatments (S=straw incorporated in the soil, C=control, M=straw plus mung bean as an inter-crop in the dry to wet transition period). Note that the mung bean plots are not part of this study but are depicted for completeness of the field trial.

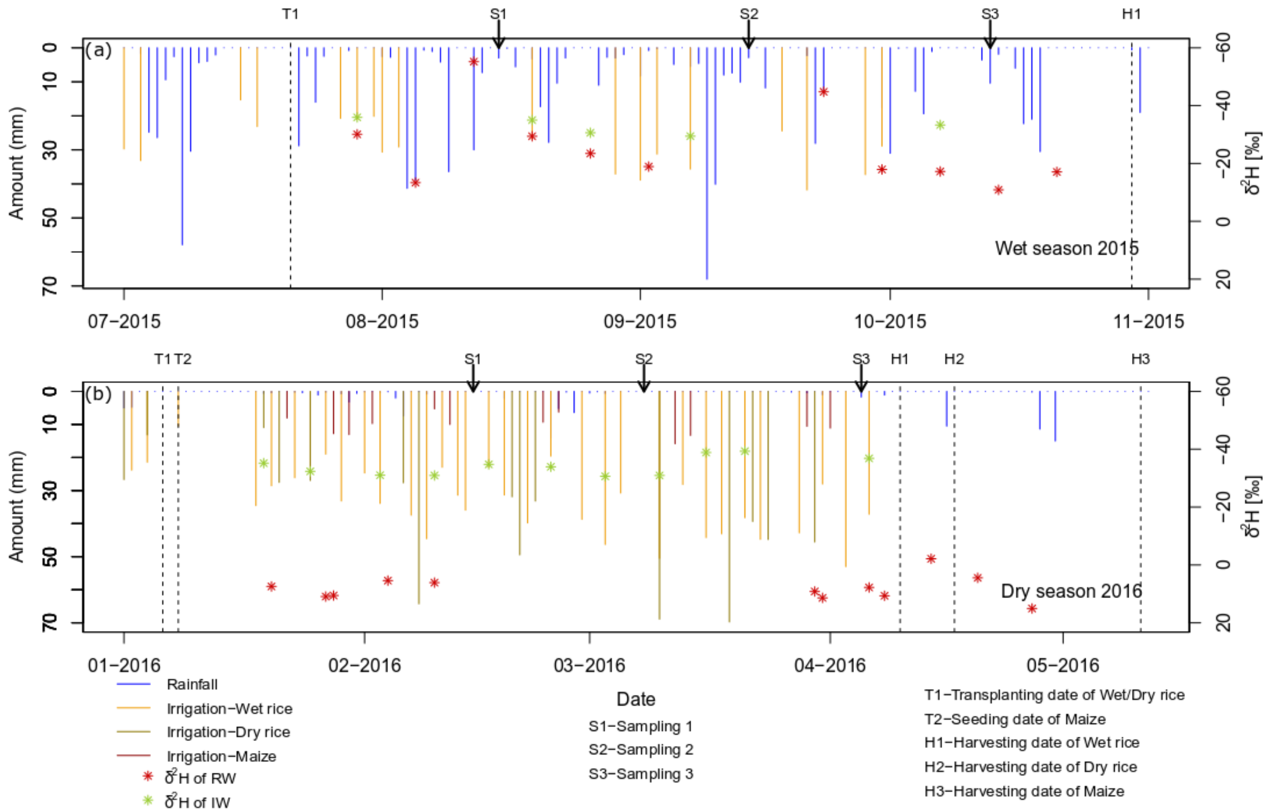

Figure 2. Temporal variation of water inputs (rainfall and irrigation water) of wet rice, dry rice and maize fields for the wet season 2015 (top) and dry season 2016 (bottom). Three main sampling dates during each season together with transplanting and harvesting dates are marked. Values of δ^2H are presented for rainwater (RW) and irrigation water (IW) during both seasons.

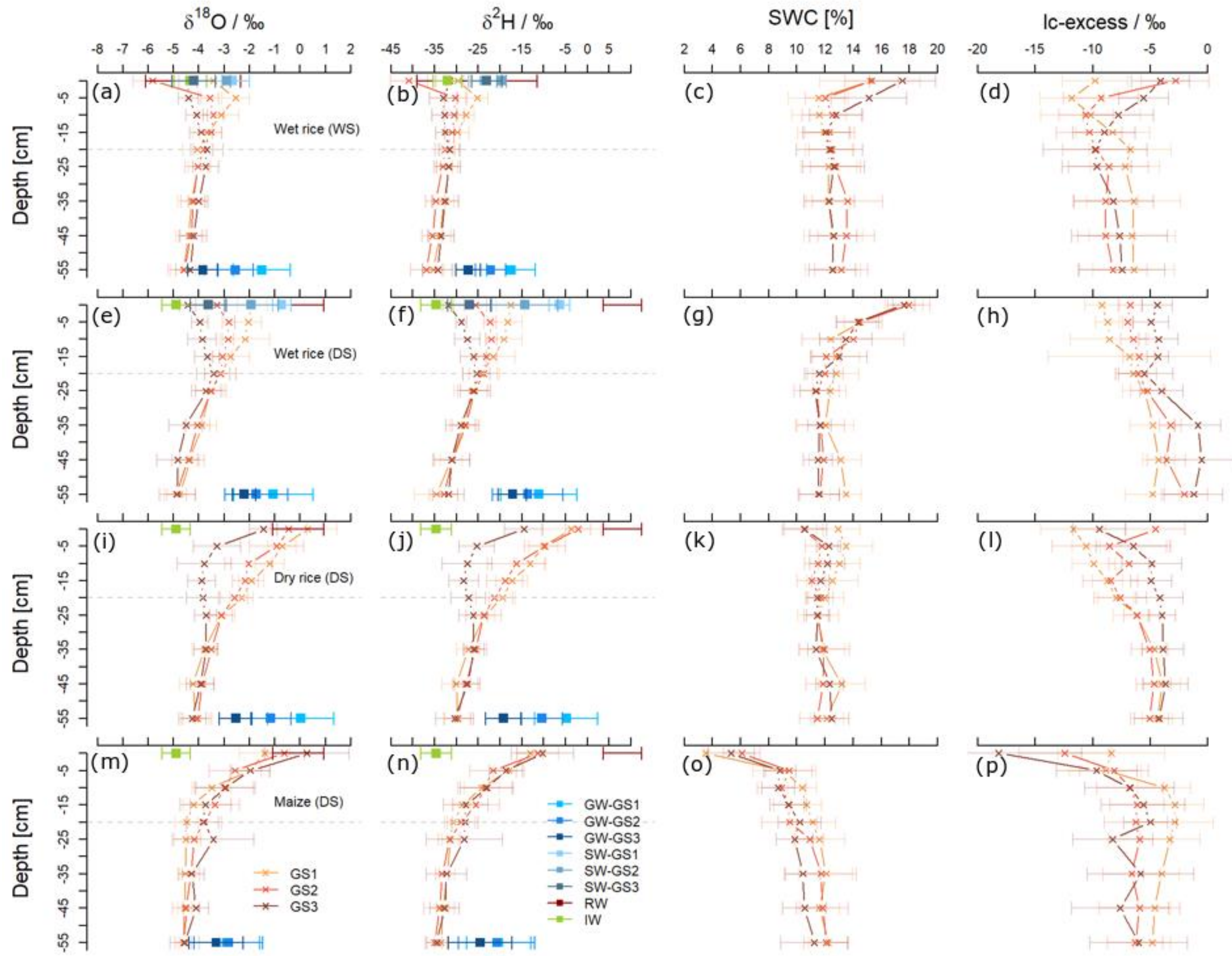

Figure 3. Depth profiles of means +/- standard deviation for $\delta^{18}O$ /‰, $\delta^{2}H$ /‰, soil water content (SWC) [%], and lc-excess /‰ from three main growing stages (GS1 to GS3) of wet rice (a–d) during the wet season (WS), and wet rice (e–h), dry rice (i–l), maize (m–p) during the dry season (DS). Seasonal averages +/- standard deviation of all water sources: rainwater (RW), irrigation water (IW), groundwater (GW) and surface water (SW). Isotopic values are displayed at the top and bottom of the soil profiles.

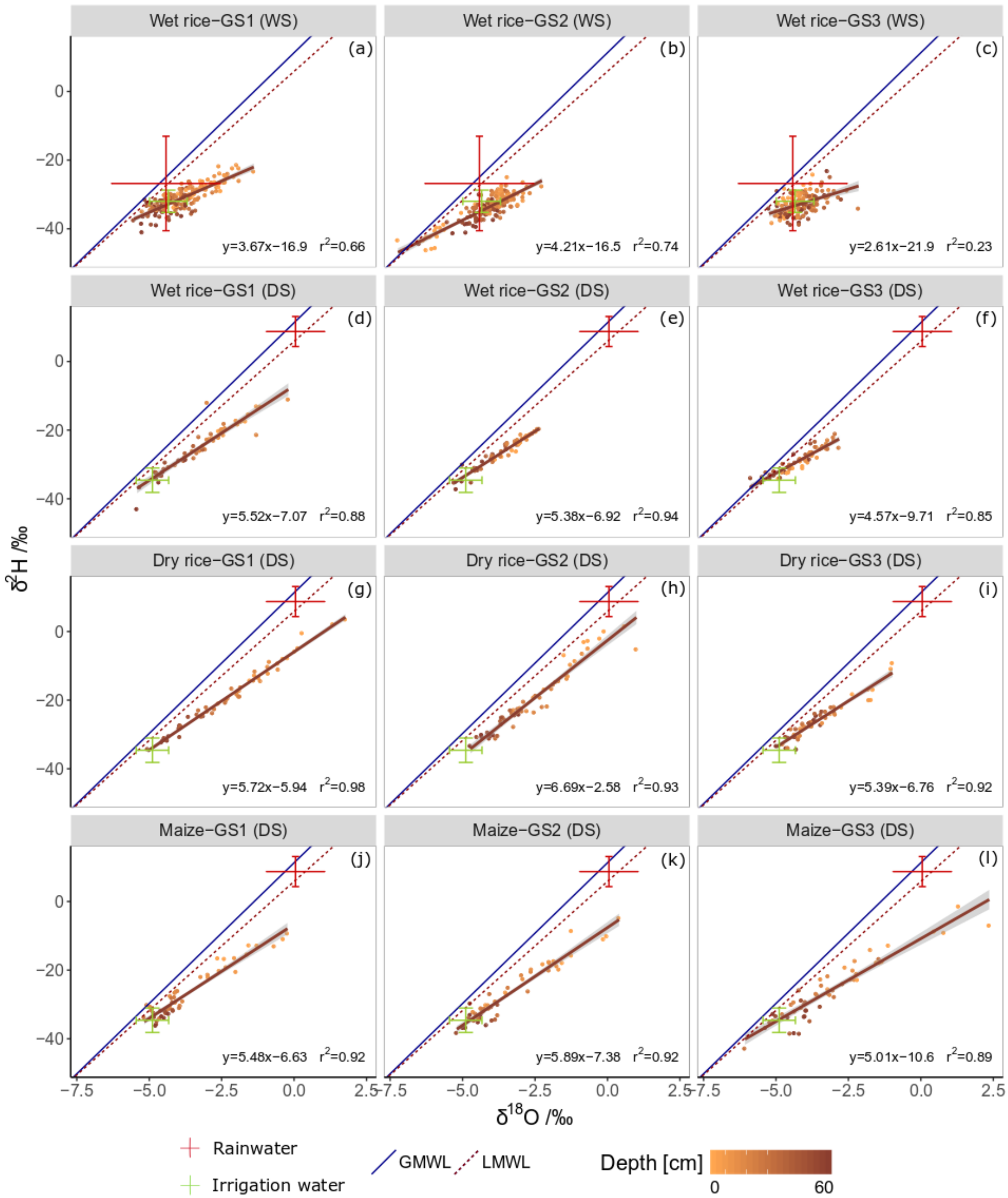

Figure 4. Dual (δ^{18}O, δ^{2}H) isotope plots of soil water at 0–0.6 m depth, and ranges of other water sources (rainwater, irrigation water) from growing stage GS1 (a, d, g, j), GS2 (b, e, h, k), and GS3 (c, f, i, l), from wet rice (a–c) during the wet season (WS), and wet rice (d–f), dry rice (g–i) as well as maize (j–l) during the dry season (DS) in comparison to the local meteoric water line (LMWL) and the global meteoric water line (GMWL). The gray shaded areas represent the 95 % confidence interval of the linear regression lines.

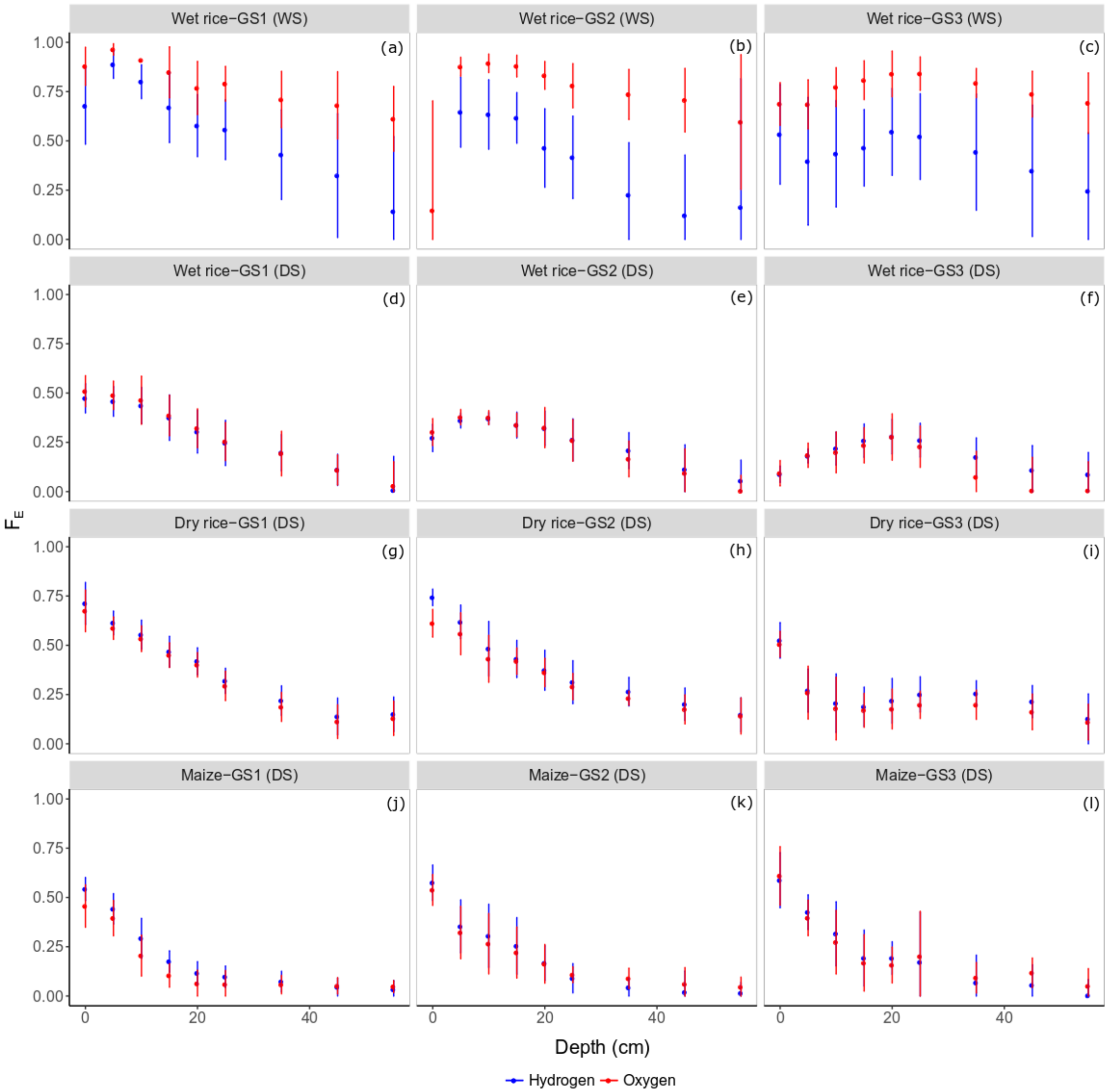

Figure 5. The fraction of evaporation loss (F_E) (Eq.1) estimated from $\delta^{18}O$ and $\delta^{2}H$ for the three main growing stages GS1 (a, d, g, j), GS2 (b, e, h, k) and GS3 (c, f, i, l) of wet rice (a–c) during the wet season (WS), and wet rice (d–f), dry rice (g–i), and maize (j–l) during the dry season (DS). Mean values at each depth (0–0.6 m) are displayed with +/- standard deviations.