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FACULTY 09

Agricultural Sciences,
Nutritional Sciences,
and Environmental Management

✉ ILR ▪ Heinrich-Buff-Ring 26 ▪ 35392 Gießen ▪ Germany

Institute for Landscape Ecology and Resources Management

Chair for Landscape, Water and
Biogeochemical Cycles

Amani Mahindawansha
Heinrich-Buff-Ring 26
35392 Gießen
Germany

Tel.: 0641 / 99 - 37394
Fax.: 0641 / 99 - 37389
Email: Amani.Mahindawansha@umwelt.uni-giessen.de

21.01.2020

Dear Editor,

Please find attached the revised response letters and the manuscript. You might wonder why it took so long to resubmit. First, we had communication problems among our co-authors. After we solved this, the Justus Liebig University Giessen had a severe cyber attack (no lame excuse, see https://www.uni-giessen.de/jluoffline). Since Dec 8th, we had no email system, no access to servers or the shared file systems, where our paper was stuck for weeks. We are now recovering slowly (today, January 21st, is the first day we have internet connection!). All this lead to a significant delay in the revision process of the paper. However, it also had advantages. We had sufficient time to carefully think about our initial response letters to the reviewers. Reading the response letters again, we found that there are even more things we need to change in the manuscript. Hence, we revised not only the manuscript, but also the response letters. We assume it is uncommon, but we ask that you update the response letters as well, if possible.

We are looking forward to your response. Given the limited time we had to work on the paper due to the cyber attack, we were not able to ask a professional language editing service to check the final version of the paper. But we are convinced that the revised version already improved substantially. In case necessary and in case we are allowed, we are happy to ask for a professional language check after the next round of revisions.

We sincerely hope that you will find our manuscript suitable for publication and look forward to hearing back from you.

Kind regards,
On behalf of the authors,

Amani Mahindawansha

Dear Editor,

We would like to thank you for the valuable feedback provided for our manuscript entitled, “Estimating water flux and evaporation losses using stable isotopes of soil water from irrigated agricultural crops in tropical humid regions”.
Herewith we provide the answers to your comments.

Best regards,

On behalf of the authors,

Amani Mahindawansha

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Why would the gravimetric water content be lower when using cryogenic extraction? I would expect that more water is extracted cryogenically than by oven drying.

We understand your assumption that one would expect higher values of soil water content by cryogenic extraction, particularly in our setting with 200°C extraction temperature and a high vacuum of 0.3 Pa. This is for sure the case if we take the same sample type and compare the amount of water measured via cryogenic extraction and oven drying. However, the characteristics of soil samples measured in both methods are different. The small aliquots of disturbed soil that are taken for extraction (in our case 10-15 g of mineral soil) do not have an intact pore system anymore that contains pore water. In cryogenic extraction, we therefore extract water that is immobile and attached around soil aggregates. In the case of oven drying, samples are taken via stainless steel cores (100 cm^3 or 250 cm^3). These small, but intact soil cores still have a pore system that contains pore water.

In the revised version of the paper, we will stress that 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.

It is still unclear where and when the ponding took place. It needs to be very clear when did you calculate evaporation from an unsaturated soil pore spaces and when the evaporation took place from open waters ponding on the fields. This would need to be accounted for when calculating evaporation fractionation as given by Gonfiantini (1986). "

All the wet rice fields are subjected to ponding. We will revise the entire paper and get rid of the misleading information on evaporation, transpiration and evapotranspiration. The revised version will focus on what we have investigated experimentally and that was evaporation. 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. We will make the distinction between open water infiltration during ponding and soil evaporation clear.

Dear Matthias Beyer,

We would like to thank you for the valuable feedback provided for our manuscript entitled, “Estimating water flux and evaporation losses using stable isotopes of soil water from irrigated agricultural crops in tropical humid regions”. Your comments were very helpful to improve the manuscript.

Please find our point-by-point responses (in blue) to the comments (in black) below.

We believe that the modifications based on the referees’ comments have resulted in an improved manuscript and hope that it is now suitable for consideration for publication as research paper in Hydrology and Earth System Sciences.

We look forward to hearing from you.

Best regards,

On behalf of the authors,

Amani Mahindawansha

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Interactive comment on “Estimating water flux and evaporation losses using stable isotopes of soil water from irrigated agricultural crops in tropical humid regions” by Amani Mahindawansha et al. Matthias Beyer (Referee) matthias.beyer@bgr.de Received and published: 20 July 2019

In their manuscript ‘Estimating water flux and evaporation losses using stable isotopes of soil water from irrigated agricultural crops in tropical humid regions’ (hess-2019-213), Mahindawansha et al. investigate the effect of different crop rotations (wet rice/dry rice/maize) in seasonally flooded/ irrigated rice fields. The authors quantified the fraction of soil water evaporation in irrigated agricultural fields while also taking into account the effect of crop species and various growing stages using the Craig-Gordon model. The topic of the study is interesting and timely but, in brief, I have mixed feelings on the manuscript. While it is clearly visible that the collected dataset can be valuable for addressing the objectives of the study, there are several points that need to be addressed in order to make this contribution really valuable for the reader.

First, I have the feeling that the manuscript is lacking some internal review before publishing. The grammar is partially very poor, and I feel that several aspects (e.g. clear statement of the objectives and focus on those in the results/discussion section) should have clarified before submission. I started correcting/improving the grammar, but gave up fast on it because it became clear that major efforts are needed which I as reviewer cannot provide.

As proposed, we will carry out an internal review again and work on the English language. A native proofreader had already checked the initial manuscript, and we were slightly puzzled when reading that the version submitted was still flawed.

Second, the combined effect of Transpiration and Evaporation should be much better addressed throughout the manuscript. Recent studies proved that transpiration is generally a much greater flux compared to Evaporation, and in a study like the presented those two need to be looked at conjunctively. In that regard, also the title is confusing, because when reading ‘estimation of water fluxes’, one would actually expect a water balance for the different systems, but effectively the only flux quantified is evaporation. In addition, I was confused multiple times because I was not sure if the authors speak about evaporation or evapotranspiration? (see later comments).

We agree that transpiration is larger than evaporation. In our work we look at evaporation as an unproductive loss term of the water cycle. We will revise the title accordingly (revised title: 'Investigating unproductive water losses from irrigated agricultural crops in the humid tropics through analyses of stable isotopes of water'). We will further correct the wording carefully to make the distinction of evaporation and transpiration always very clear for the reader.

Also, I was wondering multiple times if the authors really refer to soil evaporation when speaking of wet rice? If the field is flooded, it would be more open water evaporation?

Yes, of course. 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. We will make the distinction between open water evaporation, infiltration of this ponding water and soil evaporation clear.

Having that said, I cannot recommend publishing this manuscript as is. Though the topic and study are interesting and have great potential, this is often not fully explored. With more precisely stated objectives and a subsequent focus on addressing those, I encourage the authors to improve the manuscript and increase the quality and impact of the publication. I wish the authors good luck with the revision of the manuscript.

Down below, further detailed comments can be found.

The authors state: 'None of the studies conducted so far have quantified the fraction of soil water evaporation in irrigated agricultural fields while also taking into account the effect of crop species and various growing stages. Does it make sense to calculate the evaporation from soils for wet rice, which is cultivated in a flooded system (as the authors state) → evaporation would be from open water surface anyways

Suggested objective: study the effect of crop species and various growing stages on evaporation in rotation systems

As stated above, we will fully revise the text and make sure that the terminology correct. We will also follow the suggestion and specify our objectives.

1) Title: why first singular (flux) and then plural (losses)?

We will revise the title to 'Investigating unproductive water losses from irrigated agricultural crops in the humid tropics through analyses of stable isotopes of water'

2) The abstract needs to be improved. There are many sloppy formulations and bad grammar. The results section of the abstract should be underpinned with numbers.

We will revise the abstract and add numbers to the results section.

3) What are the implications of this study and how does it help to improve management or our understanding of such systems? How to compare an irrigated/flooded rice field with a field under natural conditions in terms of water isotope interpretations?

We will add a section in the conclusion about this. It reads “

“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.“

With regard to the second question: We compare flooded and non-flooded fields. In this sense, the dry rice and maize fields are representing the natural conditions with regard to incoming precipitation.

4) While reading the introduction, I wonder if the authors solely mean soil evaporation when they use the wording “evaporation” or if they actually mean “Evapotranspiration” (sometimes, evaporation is used for ET). The authors state that they are interested in studying soil evaporation, but can you look at one (E) without the other (T) in a combined system?

Our work is focusing on unproductive water losses as explained above. Hence, transpiration is not part of this study. To avoid further confusions, we deleted references to evapotranspiration and focus on evaporation only.

5) Methods - Extraction at 200 degrees Celsius. . .good, because very clay-rich. . .but. . .was organic contamination checked? (upper soil layers and plants)

Isotopic composition data of all water source types were checked for spectral interferences using the Spectral Contamination Identifier (LWIA-SCI) post-processing software (Los Gatos Research Inc.). None of the soil water samples were contaminated. This will be explained in the revised version of the paper.

6) Craig and Gordon modeling part should be written more concise.

We will revise section 2.4 and present the Craig-Gordon model in a more concise way.

7) What is the difference between the isotopic signal of the soil and the original isotopic signal of soil water? (do the authors mean the ‘initial signal after rain/irrigation?). How justified are the assumptions made (and those are many)?

This description in the respective section was unclear. We will revise this section in the following way: “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.”

8) For the results, it would be interesting to see if the fraction calculation fits with the modelled results

We revised the entire section and deleted the results of the modeling approach as they were not directly comparable to the experimental results we obtained. The reason is, that the CROPWAT model does not provide information on evaporation, but only on evapotranspiration.

9) P1.l. 13 advance better: improve

Will be corrected.

10) P1.l.18: progressed through the growth – bad grammar

Will be corrected.

11) P1.l.23 compared to over

Will be corrected.

12) P2 l.6-11: not only in recent years, this has been studied since Allison et al. in the 80’s. . .has not been studied as much compared to what?

We will revise this section.

13) p.2.l.13 it p.2.l.20-32: this is well-written!

Thank you!!!

14) p.3.l.5: Our objectives during this study are the objectives of this study are

Will be corrected.

15) p.3. l. 5-8: Objectives should be formulated clear and concise

We will revise the objectives.

16) p.3. l. 21: constancy consistency

Will be corrected.

17) p.3. l. 20-23: if the mung bean plot was not used it is not necessary to mention it here

This sentence has been deleted. We will include a note in the figure caption of Fig. 1 why mung bean plots are depicted in the figure.

18) p.4. l. 6: the model controls?...grammar

Will be corrected.

19) p.4. l. 8: mixing from macropore flow from cracks?...grammar

Will be corrected.

20) p.6. l. 25/26: the shape of the isotopic profiles in the shallow soil water changed depending on the crop and growth stage. → only because of that or also other factors – irrigation water isotope values, precipitation, radiation?

We agree that this statement was incomplete and hence, we will delete it. In the revised version of the manuscript, we will streamline the paper according to the main objectives.

21) What are the conclusions of the authors regarding the magnitudes of evaporation? (Are these numbers given as fraction of total evapotranspiration?)

Yes, the fractions of evaporation are given as percentages of total evapotranspiration. The magnitude of evaporation is higher at the beginning of the growing period and decreases towards the end of the season.

We revised the section accordingly and explain this in more detail and discuss our results in relation to other published values.

22) Fig. 3: bad resolution

We submitted high-resolution graphs separately in the first submission, but obviously, they have not been included in the PDF. We hope it will work out this time.

23) Section 4.3.: the statements here are very interesting and it is appreciable that the authors introduce this discussion. unfortunately they question parts of the isotopic data presented in the study

We think that potential limitations of our method should be discussed. It also directs for future researches. Nevertheless, the effect discussed does not question the study in general as it affects only a limited set of samples. We will make this clear in the revised manuscript.

24) Conclusion: - throughout the manuscript, the phrase ‘redistribution via plants/roots/etc. appears frequently’, but it is not discussed anywhere. I suggest leaving this out or providing further evidence. - ‘the conclusion that isotopic profiles develop via diffusion processes in the shallow soil and are then transported by advection in the matrix or in macropores or cracks’ → please rephrase, poor grammar

We agree with the reviwer and we will include a new section on this process in the discussion. It will read: 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).

Apart from that, we will revise the grammar in the conclusions.

25) p.13., l. 13: Do the authors really mean Evapotranspiration or rather Transpiration?

We meant transpiration fraction of the evapotranspiration and we will correct it in the revised version.

Dear reviewer,

We would like to thank you for the valuable feedback provided for our manuscript entitled, “Estimating water flux and evaporation losses using stable isotopes of soil water from irrigated agricultural crops in tropical humid regions”. Your comments were very helpful to improve the manuscript.

Please find our point-by-point responses (in blue) to the comments (in black) below.

We believe that the modifications based on the referees’ comments have resulted in an improved manuscript and hope that it is now suitable for consideration for publication as a research paper in Hydrology and Earth System Sciences.

We look forward to hearing from you.

Best regards,

On behalf of the authors,

Amani Mahindawansha

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Interactive comment on “Estimating water flux and evaporation losses using stable isotopes of soil water from irrigated agricultural crops in tropical humid regions” by Amani Mahindawansha et al.

Anonymous Referee #2

Received and published: 30 July 2019

Review of Hydrology and Earth System Sciences Manuscript: hess-2019-213 Title: Estimating water flux and evaporation losses using stable isotopes of soil water from irrigated agricultural crops in tropical humid regions Authors: Amani Mahindawansha et al.

This manuscript presents seasonal variations in the soil water isotopic profiles and the fraction of evaporation (FE) for different crops (wet rice, dry rice and maize) under flooded and non-flooded irrigation management practices. This topic is interesting for understanding water cycle and water conservation in agricultural fields. However, there are some issues within the manuscript that requires substantial interpretation and improvement. The following is my detailed comments.

(1) Abstract:

Since only FE values were calculated and no water flux of evaporation were determined in this study, the second sentence (P.1,Lines 13-15) should be changed.

We agree and will revise not only the abstract, but also the title.

Other evidences should be given to prove the occurrence of piston type matrix flow or preferential flow besides the isotopic data in the text (P.1, Lines 22-24).

We will revise the abstract. The discussion of the different flow mechanisms will be more general.

It is helpful to supplement important data in the abstract section to clarify the new findings of this study.

We agree with the reviewer and added the main results to the abstract.

(2) Introduction:

Determination of the soil evaporation flux (E) and the fraction of E in ET (FE) have been widely studied using several methods and techniques for different irrigated crops (Liu et al., 2002; Kool et al., 2014; Sprenger et al., 2016; Zhou et al., 2016). The new scientific merits in this study are not very clearly clarified.

The merit of this study is quantifying the fraction of soil water evaporation in irrigated agricultural fields and taking into account the effect of different crop species and different irrigation and management practice at various growing stages. The references listed will be considered in the revised version of the introduction. To better account for previous work, we will include the following sentences: "
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.."

We do not agree that the research gaps of current studies were not clearly stated. We would like to draw the attention to the end of the introduction where we stated: "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."

(3) Material and Methods:

There are straw and non straw applications conducted for different treatments in the experiments (P.3,Lines 20-21). How does the straw application affect the seasonal variations in the FE for different irrigated crops?

We did not find significant differences between the isotopic compositions of soil water with or without straw application. Therefore, we pooled the results for each crop. See section 2.4 "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 ($p>0.05$)."

One would have expected a stronger effect of straw application on evaporation. However, the straw was not applied as a typical mulch layer to reduce evaporation, but was partly worked into the soil to reduce crack formation. This information is now included in section 2.2.

Please describe in detail how to determine the time when a water shortage occurred in dry rice and maize fields (P.3,Lines 26-27).

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. This information will be added to the text.

The gravimetric soil water content is determined traditionally by oven-drying method. Smaller values might be resulted by using the soil water loss in cryogenic water extraction process to determine the soil water content (P.4,Lines 19-20).

We agree that the results of both methods are not directly comparable. We added a sentence to section 2.2 to address this: “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 an intact pore system that contains 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.”Root length density was analyzed as described in the P.4, Lines 21-22 in the “Material and Methods” section, but non detailed results were shown in the “3 Results” section.

The description of the method to measure root length density was a remnant from a previous draft of the manuscript which we forgot to delete. We will remove it in the revised manuscript.

(4) Results:

The lc-excess was developed/introduced by Landwehr and Coplen (2006) in respect to River Water Line. They used the lc-excess to determine how the isotopic values of river waters differed from their sources (i.e., precipitation). However, the authors use lc-excess to estimate the deviation in the isotopic values of the soil samples from regional precipitation. I do not find any good argument why the authors use lc-excess since there is no river water sampled during their experiments. The lc-excess is not necessarily needed in this study (P.7, Lines 9-16). Instead, the deviation of soil isotopic values from LMWL/GMWL is already indicating the evaporation process and it is more commonly used method. Lower indicates condensation process and higher indicates evaporation process.

Sprenger et al. (2017) stated “…that lc-excess was advantageous over the deuterium-excess (or single isotope approaches with δ2H or δ18O) for inferring evaporation fractionation, because the lc-excess of the precipitation input is about 0‰ and with relatively little seasonal dynamics, while δ2H, δ18O, and d-excess can have an intense seasonal variability.”. As we analyzed soil profiles from different seasons, seasonality effects might be a problem. To avoid this, we used the Ic-excess for comparison. Furthermore lc-excess has been successfully applied it for soil water studies, previously by Sprenger et al. (Sprenger et al., 2016, 2017, 2018), McCutcheon et al. (2017) .

(5) Discussion:

The authors estimate the annual average reference evapotranspiration rates in dry season and wet season, respectively. Does the “evaporation of ~50-80%” in P.11, Line 28 mean evapotranspiration? What is the difference between evapotranspiration and evaporation in this study?

We deleted the section about the CROPWAT model as the model and our field experimental work are not direct comparable. This section was misleading. Furthermore, we only address the evaporation process.

(6) Conclusion:

Seasonal distribution of soil water content and isotopic profiles was analyzed in this study, but no fluxes of unproductive soil water losses were found. Therefore, the sentence in P.13, Lines 24-25 is required to be reorganized.

Evaporation is an unproductive water loss because apart from transpiration the rest of the water outputs from the agricultural system are considered as unproductive water losses, and this is what we have estimated in this work. That will be added to the introduction as follows:

“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).”

(7) The English writing of this manuscript should be polished further. There were some grammar errors in this paper and some sentences were confusing.

As proposed, we will carry out an internal review again and work on the English language. A native proofreader had already checked the initial manuscript, and we were slightly puzzled when reading that the version submitted was still flawed. Nevertheless, we will send the paper again for proofreading.

References: [1] Liu, C.M., Zhang, X.Y., Zhang, Y.Q., 2002. Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. Agr. For. Meteorol. 111, 109-120. [2] Kool, D., Agam, N., Lazarovitch, N., Heitman, J. L., Sauer, T. J., Ben-Gal, A., 2014. A review of approaches for evapotranspiration partitioning. Agric. For. Meteor. 184, 56-70. [3] Zhou, S., Yu, B.F., Zhang, Y., Huang, Y.F., Wang, G.Q., 2016. Partitioning evapotranspiration based on the concept of underlying water use efficiency. Water Resour. Res. 52, 1160-1175. [4] Sprenger, M., Leistert, H., Gimbel, K., Weiler, M., 2016. Illuminating hydrological processes at the soil-vegetation-atmosphere

~~Estimating **water** flux and evaporation **losses** using stable isotopes of soil water **from irrigated agricultural crops in** tropical **humid** regions~~

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

Amani Mahindawansha[1,2], Christoph Külls[4], Philipp Kraft[1], and Lutz Breuer[1,3]

[1]Institute for Landscape Ecology and Resources Management (ILR), Research Centre for BioSystems, Land Use and Nutrition (iFZ), Justus Liebig University Giessen, Giessen 35392, Germany
[2]International Rice Research Institute (IRRI), Los Baños 4030, Philippines
[3]Centre for International Development and Environmental Research (ZEU), Justus Liebig University Giessen, Senckenbergstrasse 3, Giessen 35390, Germany
[4]Faculty of Civil Engineering, Technische Hochschule Lübeck, Mönkhofer Weg 239, Lübeck 23562

Correspondence to: Amani Mahindawansha (Amani.Mahindawansha@umwelt.uni-giessen.de)

Abstract. Reliable information on water flow dynamics and water losses via irrigation on irrigated agricultural fields is important to ~~advance~~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 ~~analyzed~~analysed for the stable isotopes of water (δ^2H and δ^{18}O~~), and the~~). The fraction of evaporation ~~loss was~~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 ~~rice, which increased as the crops progressed through the growth; however, it decreased in both rice varieties~~in rice during ~~both seasons. Greater~~that time. A greater water loss was encountered during the wet season~~ even though evaporation signals were stronger during~~, with 80 % at the ~~dry~~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~~, and it~~. It decreased towards the end of ~~growth~~both growing seasons during the wet and the dry ~~seasons. Isotope data indicated that~~ season. We finally discuss the most relevant soil water flow mechanisms~~ varied depending on field conditions. In flooded conditions, surface soil was consistently affected by piston type~~, which we identified in our study to be that of matrix flow~~. During non-flooded conditions, matrix flow via diffusion dominated compared to upwards evaporative~~

~~flux. Occasionally~~, preferential ~~flows occurred~~flow through desiccation cracks~~, especially in maize fields. In wet rice fields, soil water was largely influenced by short-term variability of precipitation events during the wet season and subsequent formation of hydrogen compounds as a result of continued wetness and anaerobic physiochemical conditions that depleted δ^2H with respect to δ^{18}O.~~ 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 (Sprenger et al., 2015; Vereecken et al., 2016). Stable isotopes of water (δ^2H and δ^{18}O) have become a powerful tool for such studies as ideal natural tracers (Kendall and Caldwell, 1999). Stable isotopes of water have been used to identify and understand environmental processes, including soil water movement and solute transport (Groh et al., 2018), flow pathways and mixing (Mueller et al., 2014; Stumpp and Maloszewski, 2010; Windhorst et al., 2014), groundwater recharge (Beyer et al., 2015; Houben et al., 2014), hydraulic redistribution (Priyadarshini et al., 2016), plant water uptake (Mahindawansha et al., 2018b), soil water exchange in the deep vadose zone (Gehrels et al., 1998), extreme events such as droughts (Chiogna et al., 2018), and isotopic sub-daily patterns in groundwater and ponding water (Mahindawansha et al., 2018a). In recent years, the interest has shifted towards 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). However, the quantification of soil evaporation processes is also empirically more demanding (Bittelli et al., 2008), and therefore, the quantification process has not been studied as much (Evaristo et al., 2015; Sprenger et al., 2017).~~

~~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 it 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). Many experiments on the effects of evaporation on soil water using isotope methods are restricted to laboratory-scale or short-term field studies or to one particular location (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 rice-based crops is important, because rice (Oryza sativa L.) is the dominant staple food for nearly half of the world's population. More than 80 % of global rice production area is located in Asia (Kudo et al., 2014). It 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, 2002). Because rice is extremely sensitive to water deficit (Bouman and Tuong,~~

~~2001), 80 % of rice production is cultivated under conventional flooded conditions in Asia (Towprayoon et al., 2005) also called wet rice, anaerobic rice, or lowland rice. Water scarcity is a serious environmental problem, especially concerning irrigation in agricultural lands (Navarro-Ortega et al., 2015; Pfister et al., 2011). Therefore, water saving strategies need to be developed to ensure safe rice production for future generations (Belder et al., 2004). By introducing non-flooded crops during the dry season (e.g., rotating maize/dry rice with wet 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 system based on crop rotation and seasonal changes, and to adapt to the effect of climatic changes, a detailed and functional understanding of hydrological processes and water fluxes in irrigated agricultural systems is necessary (Daly et al., 2004; Heinz et al., 2013; Zwart and Bastiaanssen, 2004).~~

~~Understanding water flow dynamics and estimations of evaporation fluxes from irrigated soils in the subsurface is a general fundamental challenge and is poorly understood in hydrological and ecohydrological studies in rice-based cropping systems. Moreover, studies on the effects of evaporation on the dynamics of stable isotopes of soil water, its temporal (i.e., 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 soil water evaporation in irrigated agricultural fields while also taking into account the effect of crop species and various growing stages.~~

~~Our objectives during this study are: (I) to investigate natural soil water isotopic profiles as a function of soil depth depending on season (wet and dry), type and growth of vegetation (wet rice, dry rice, and maize), and differences in irrigation patterns; (II) to understand flow mechanisms and redistribution patterns of soil water in the soil matrix; and (III) to quantify the fraction of soil evaporation losses at different soil depths based on information about both~~ ~~δ^2H and δ^{18}O.~~

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 ~~trail~~trial was established at the experimental station of the International Rice Research Institute (IRRI), in Los Baños, Laguna, Philippines (14°~~ 11' N~~11'N, 121°~~ 15' E~~15'E, 21 m a.s.l~~.) and used during both the wet (WS) and dry (DS) season.~~.). 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 ~~WS 2015, respectively, as well as 27.6±1.8°C and 74±11 % during DS 2016, respectively. Climate data were obtained from the climate unit at IRRI. The soil type in the study area is classified as a Hydragric Anthrosol (He et al., 2015)~~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 experiment was conducted during WS 2015 and DS 2016. ~~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~~ (i.e., ~~. Of these plots, only those with straw application ~~(S), no straw as a ~~and the control ~~plot (C), and straw application with mung bean as an intercrop (M)). To maintain constancy~~plots (without straw) were used for our experiment~~, plots with mung bean treatment (M) were excluded from sampling, because that treatment was only ~~. Straw was not applied ~~during the transition period between DS and WS. ~~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 ~~a ~~reference ~~time scale along with the plant growth (Fig. 2). Therefore,~~points during the growing season (Fig. 2). Growing stages for rice and maize were assumed to be similar to maintain consistency of sampling conditions. ~~The sampling campaigns~~Samples were ~~conducted~~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. ~~For this experiment, during each sampling campaign (3 in a season) 18 soil~~Soil cores were taken using a manual soil corer (length=0.6 m, diameter=0.05 m~~) were taken. This is a collection of 2 cores from each plot (only from S and C plots) from 2 seasons (during the WS: wet rice n=18, during the DS: six samples each for wet rice, dry rice, and maize, in total n=18).~~). Each core was ~~further~~ divided ~~to~~into 9 depth intervals ~~(9 samples from each core)~~ 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 ~~108 soil cores~~, 972 samples were taken ~~during each of the three~~(9 fields x 2 treatments x 2 seasons x 3 growing stages ~~and throughout both WS and DS, which gave a grand total of 972 samples.~~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. Groundwater and surface ponded water were collected once a week from each plot at existing sampling stations (Heinz et al., 2013). Rainwater and irrigation water were sampled according to their availability. Root length density (cm cm^{-3}) was analyzed using the winRHIZO software (WinRHIZO 1991) in the plant physiology lab at IRRI. For detailed information about the experimental design, sample collection, and root density analysis, 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 $\delta^{18}O$ and $\delta^{2}H$ was 0.2 ‰ and 0.6 ‰, respectively.~~

~~The global meteoric water line (GMWL) was determined following Rozanski et al. (1993) ($\delta^{2}H = 8.2\delta^{18}O + 11.3$). The Local Meteoric Water Line (LMWL) was calculated with $\delta^{2}H = 7.52\delta^{18}O + 5.86$, 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 lc-excess $= \delta^{2}H - a\delta^{18}O - b$, where a and b refer to the slope and intercept of the LMWL, respectively. We used the lc-excess to infer seasonal dynamics of evaporation fractionation (Sprenger et al., 2017).~~

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 $\text{lc-excess} = \delta^{2}\mathrm{H} - \mathrm{a}\delta^{18}\mathrm{O} - \mathrm{b}$, 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 ~~with macropore flow from~~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 ($\mathrm{F_E}$) for an isotope mass balance as follows:

~~$F_E = 1 - \left[\frac{(\delta_S - \delta^*)}{(\delta_P - \delta^*)}\right]^m$ (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 [–]. The original isotopic signal, δ_p, in water during the WS was estimated as the mean isotopic signal from the most frequent large precipitation events, and as the mean of the irrigation water during the DS. We assumed steady state conditions, because the samples were collected between 10–12 a.m., where steady state conditions can be expected in rice fields (Wei et al., 2015). Variables δ^* and m were calculated following Equations 2 and 3 (as described in Benettin et al. (2018) and Gibson (2016)):~~

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

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):

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

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

where δ_A is the isotopic composition of atmospheric ~~vapor [‰] (calculated according to Benettin et al. (2018),~~ vapour [‰] (assuming that the isotopic composition of atmospheric ~~vapor~~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 δ^{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 ~~vapor~~vapour was computed as $\varepsilon^+ = (\alpha^+ - 1)10^3$ [‰] ~~(Gat, 1996; Horita et al., 2008.~~ (Benettin et al., 2018). ~~The~~As part of the calculation of ε_k, the aerodynamic diffusion parameter~~,~~ *n* ~~[–], reaches~~ [–] has to be set. It ranges from *n*=0.5 for open water or saturated soils to *n*=1 ~~when the~~for dry soil ~~is dried to residual moisture levels (Mathieu and Bariac, 1996), presenting turbulent conditions. Therefore, we anticipated that n is~~ (Benettin et al. 2018). We set *n*=0.5 for wet rice fields~~ with saturated soils (Good et al., 2014),~~, 0.7 for dry rice, and 0.9 for maize.

2.5~~4~~ 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 ~~(Kruskal and Wallis, 1952)~~ 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 ~~(S~~straw and ~~C)~~no-straw application as a control plot were combined for each crop for further analysis, ~~because~~as there were no significant differences for stable isotopes of water between the ~~fields with the same crop~~treatments ($p>0.05$).

3 Results

3.1 Soil ~~and~~ 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 ~~at each growing stage~~ with no statistically significant differences (Table 2~~); however, that is not~~). A distinct difference in the ~~case from WS to~~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~~. Although rainwater and irrigation water were statistically similar during the WS, we found~~, where it was significantly different~~ values during the DS~~.

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. ~~The shape of isotopic profiles in the shallow soil water changed depending on the crop and growth stage.~~ 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. ~~However, the~~The isotopic values in deep soil were nearly stable in all the profiles regardless of the crop during both seasons.

~~The wetness of the soil can be identified by water content profiles.~~ Maize was characterized by dry soil conditions at the surface and at shallow depths compared to both rice varieties~~. However, the~~ (Fig. 3c, g, k, o). The highest water content was found for wet rice ~~was~~ at the surface soil (17.7±1.2 %), and it was nearly constant below ~~the~~a depth of 0.2 m (12.0±1.3 %) during both seasons. The water content ~~values~~ in dry rice soils were rather evenly distributed along the soil profile except at the soil surface. Soils under maize were getting dryer as ~~maize~~ plant ~~growth progressed~~developed, while such clear patterns could not be observed for ~~any other~~the rice crops. ~~Below 0.2 m, water content profiles for wet and dry rice illustrated a nearly constant value of about 12 %, while water content gradually decreased in maize fields.~~

The lc-excess is ~~a sign of~~ an indicator for evaporation, with lower values ~~indicating~~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 ~~these~~the DS crops compared to the WS crop. The ~~most~~highest evaporation was found near the surface in maize fields with significantly lower lc-excess values~~;~~ ~~in~~. In addition, lc-excess values ~~further~~ decreased from GS1 to GS3. In contrast, lc-excess patterns ~~at~~of shallow soils ~~for~~in wet rice fields generally increased with growth during both seasons~~, similar to dry rice fields during the DS (except for GS2). For WS wet rice, we even observed decreasing lc-excess along with the profile at shallow depths. In contrast to other crops, this trend then reverted to a gradual increase in deep soils. The lc-excess values in deep soils increased with the growth of rice but decreased with the growth of maize.~~.

~~Existing soil~~Soil water ~~was~~ mixed with ~~the isotopic input signal (i.e.,~~incoming precipitation and irrigation~~),~~, and therefore had a potentially different isotopic composition than the ~~input~~incoming water itself. The δ^{2}H and δ^{18}O values of soil water ~~and source water~~ plot on a line below the LMWL ~~in the dual isotopic coordinate system (δ^{2}H, δ^{18}O)~~ due to the evaporation effect (Fig. 4). The slope of the regression line and coefficient of determination (R^2) were higher ~~during~~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^{2}H and δ^{18}O compositions were higher (enriched) in shallow soils and ~~more~~ deviated stronger from the LMWL than soil water ~~in~~from deep soils.

~~Original~~The original isotopic signal of the incoming water ~~inputs to the system had~~ changed depending on the season, especially during the WS. As a result of frequent precipitation events introducing strong variations in the isotopic composition (δ^{2}H from –55.20 to –10.89 ‰ ~~–~~and δ^{18}O from –7.91 to –2.54 ‰), the isotopic signal of the ~~input~~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, ~~there are some~~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 ~~short~~shorter precipitation events during the DS, the ~~original~~isotopic signal of the incoming water~~ input to~~

~~the system~~ was dominated by irrigation water, with nearly constant isotopic composition during the growing period. Small precipitation events were ~~subject~~subjected to higher evaporative loss and resulted in enriched isotopic composition during this time (Table 2).

3.2 Fraction of evaporation ~~estimation~~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). ~~Soils~~During the DS, soils in dry rice fields showed higher soil F_E at shallow depths (~~from~~ 0.54±0.1), which decreased both during plant growth ~~(~~to 0.27±0.1~~)~~, and along with depth towards ~~the~~ deep ~~soil (to~~ 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 ~~soil~~soils at 0.13±0.1 (Fig. d, e, f). However, the fractionation was higher during the WS, and the F_E for δ^{2}H 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^{2}H 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 ~~at~~in rice fields. ~~During the WS, the~~ 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 ~~higher~~larger during the WS than during the DS with no significant difference between δ^{2}H 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

~~4.1~~ General mechanisms in soil water movement

~~The soil of the wet rice fields was mostly saturated by flooding, while the water saturation at the dry rice fields varies greatly with irrigation and precipitation events (Fig. 2). Soil moisture at the infrequently irrigated maize fields was the lowest throughout the cropping season. Depending on the evaporation effect on soil water isotopic composition and water transport, the soil profile can be subdivided into two parts (Barnes and Allison, 1984): (I) shallow soil in which water moves by vapor diffusion and is affected by evaporation, (II) deep soil, in which liquid transport dominates and is barely affected by evaporation. This isotopic separation 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). Three general mechanisms can explain water movement phenomena~~

~~in irrigated fields: (I) matrix flow via diffusion, (II) fast percolation of water through desiccation cracks/deep roots, and (III) continuous slow infiltration from the liquid phase through the clay matrix in flooded fields.~~

~~Precipitation and irrigation events partially penetrate down to the unsaturated zone and are then consumed gradually by evapotranspiration (Barnes and Allison, 1988). Therefore, 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). Soil water isotopes are affected by an evaporation process in which vapor transport is dominant (Bittelli et al., 2008), especially in dry rice and maize fields. 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 can be via advection, hydrodynamic dispersion (Leibundgut et al., 2009), diffusion (Barnes and Allison, 1983), or preferential flows, which affect the isotopic distribution within the profile in the unsaturated zone (Koeniger et al., 2016). The observed smoothing of isotopic signals in shallow soils can be explained by water redistribution via shallow roots/transpiration or from preferential flow transferring and mixing the evaporated surface water into deeper soil compartments (Baram et al., 2013).~~

~~In maize fields (below 0.2 m), there were deeper (~0.2 m) and narrower (~0.02 m) desiccation cracks than those found in dry rice fields (own observation). However, desiccation cracks in dry rice fields were not as hydraulically active as in maize fields due to differences in irrigation practice (Fig. 2). Therefore, the dominant flow mechanism in maize fields is controlled by preferential flow through desiccation cracks. During irrigation, water flowing through preferential flow conduits transports and redistributes evaporated water, affecting the capillary gradient between the soil matrix and crack walls. However, water loss from the crack surface is limited by water movement through the soil matrix and higher relative humidity during the night (Kamai et al., 2009; Weisbrod and Dragila, 2006). There was a gradual isotopic depletion towards the deep soils of dry rice and maize fields. This indicates subsurface mixing between 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). Baram et al. (2012) have observed that naturally formed desiccation crack systems can create preferential flow paths that reach more than a meter deep. In maize fields at our study site, we observed that the groundwater isotopic compositions are strongly influenced by irrigation water suggesting the existence of fast flow conduits (Mahindawansha et al., 2018a). In addition, He et al. (2017) have observed leaching losses of water and nutrients in a lysimeter experiment. Significant capillary rise is expected in fine textured soils, and therefore the capillary rise of depleted shallow groundwater can also influence compartments at greater depth (Baram et al., 2013; Clark and Fritz, 1997), even though the groundwater level was below sampling depth (below 0.6 m).~~

~~For the constantly flooded condition of wet rice, continuous slow water percolation is observed as expected. The upper soil layer is affected by isotopically enriched liquid phase via a gravity-driven, piston-like matrix flow. The isotopic composition of soil water increased with depth (until the most enriched point) (Fig. 3a, b, e, f). It is assumed that this observation is a result of the successive displacement of pre-existing mobile soil water by infiltrating water. 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 and the soil water at shallow depth down to the infiltration front, act as a single compartment reflecting evaporation from the ponded water. Isotopic values below this point show a strong depletion until reaching a stable value below approximately 0.2 m. A similar pattern has been found by Baram et al. (2013) in clay soil under continuous ponded infiltration in Israel.~~

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 ~~indicate less~~indicated declining evaporation~~ effect~~ from GS1 to GS3 in rice (Fig. 3). In both, dry and wet rice~~ varieties~~, the isotopic ~~profile~~profiles showed a clear shift from enriched to depleted values along the growth, especially in shallow soils and regardless of the season. ~~We~~However, we observed a transfer of the most isotopically enriched ~~depth~~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. ~~Therefore, we can assume~~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~~. It was previously shown~~, matching previous reports that the plant cover ~~generally~~ reduces kinetic fractionation processes in ~~soil water (Burger and Seiler, 1992; Dubbert et al., 2013).~~ the soils (Burger and Seiler, 1992; Dubbert et al., 2013).~~A different pattern of lc-excess was observed in maize fields (Fig. 3p) compared to rice (Fig. 3d, h, l), in which the evaporation fraction gradually increased towards the end of the season, resulting in dryness and water deficit as irrigation diminishes (Fig. 2). Finally, kinetic fractionation was diminished by soil dryness resulting from infrequent irrigation.~~

~~Comparison~~

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) ~~helps to identify~~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 ~~as a result of kinetic fractionation (Sprenger et al., 2016).~~because of kinetic fractionation (Sprenger et al., 2016). This deviation can ~~then be used to estimate evaporation losses (Clark and Fritz, 1997). The higher slopes of the dry soils (in maize and~~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 ~~vapor transport layer (Barnes and Allison, 1988) compared to wet soils (as in wet rice).~~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. Deep soil water under wet rice exhibits isotope data falling~~(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~~), indicating higher soil evaporation.~~). In contrast, shallow soils plotted closer to the LMWL ~~indicate~~indicated lower evaporation rates. Furthermore, deep soil water ~~shows~~showed isotopic similarity to the irrigation water. Following these observations, we ~~can~~ assume that the deep soil isotopic ~~profile results~~profiles result from mixing ~~between~~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 ~~matrix seepage and~~ percolation of 1 to 5 mm d^{-1} in clay ~~soils, (Bouman and Tuong, 2001), deep soil profiles with multiple compartments contain and~~ 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. ~~However~~

Apart from this, all soil profiles ~~present~~presented enriched values and ~~significant~~distinct evaporation processes during the WS (Fig. 4a–c~~) as seen by Baram et al. (2013).~~). Lower slopes of evaporation lines in wet soil compared to dry soil point ~~to greater kinetic effects (Cooper et al., 1991).~~out to greater kinetic effects (Cooper et al., 1991). Slopes of evaporation lines <3.5 were ~~observed under~~reported to indicate diffusion processes (Allison et al., 1983). We, therefore, assume that diffusion ~~conditions (Allison et al., 1983). Therefore, profiles during the WS indicate that diffusion~~ processes in the subsurface ~~are~~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 ~~dominate~~dominated and ~~limit~~limited diffusion processes due to continuous intense precipitation events during that time~~ (Fig. 2). We further observed~~. 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). ~~An enriched~~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.~~(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 ~~previously ~~reported ~~(~~by Baram et al~~., ~~. (2013~~;~~) and DePaolo et al~~., 2004)~~. (2004).

~~In tropical regions, the isotopic composition of precipitation is often correlated with precipitation amount (Araguás-Araguás et al., 2000), and this temporal variation is critical for pore water stable isotope studies, especially during the WS. Taking the variation of vapor source (from precipitation) into account and by comparing the isotopic composition of soil water with the original water input, we can estimate the fraction of evaporation loss for an isotope mass balance.~~

~~4.2 Fraction of evaporation estimation~~

~~Kinetic fractionation in the shallow soil is relatively small in tropical climates. 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 from the beginning of plant growth towards the end from fields in DS (Fig. 5). Pore water in rice fields has low F_E in deep soils, and especially below 0.4 m when reaching the end of the DS, while in maize fields, it was small below ~0.2 m. Under a controlled laboratory experiment on evaporating soil columns, Rothfuss et al. (2010) observed higher pore evaporation fractionation in the top 0.2 m of soil, which diminished below 0.4 m in loamy soil for deep-rooted perennial grass. During the WS, F_E was higher in the shallow soil (due to more pronounced kinetic fractionation processes compared to the DS) and decreased towards the end of the growth period. In a laboratory experiment by Rothfuss et al. (2010), comparable observations were found where F_E changed over time, with 100 % from bare soil that decreased from 94 % to 5 % with respect to the time (from 16 to 43 days after the seeding) of perennial grass. However, the F_E during the WS can be biased due to (I) high variability of isotopic composition during intense precipitation events, (II) effects related to the formation of hydrogen compounds (described in section 4.3), and (III) higher crop evapotranspiration than the reference evapotranspiration.~~

~~The values we obtained refer to the fraction of water loss from the matrix and small/intermediate pores. We must take into account that macropore components cannot be determined with this method. Using the CROPWAT model (FAO 2009) forced with meteorological data for Los Baños, Philippines, we estimated an annual average reference evapotranspiration rate of 3.65 mm d^{-1}, with a DS average of 3.96 mm d^{-1} and a WS average of 3.33 mm d^{-1}. From transplanting to harvest, crop evapotranspiration increased from around 2.4 to 5.0 mm d^{-1} during the DS, and of 3.4 to 4.1 mm d^{-1} during the WS, respectively. This is in the range with other published evapotranspiration rates. For example, daily evapotranspiration rates of 3.74–3.90 mm d^{-1} from maize and 4.13–4.36 mm d^{-1} from rice are given by Alberto et al. (2014) for the same study site during the DS. Furthermore, in the tropics, evapotranspiration rates of 6–7 mm d^{-1} during the DS and 4–5 mm d^{-1} during the WS were~~

~~reported (Datta, 1981). By a simple calculation, we derived approximate evaporation of ~50–80 % from effective precipitation plus irrigation for the entire year. Values of about 30 % evaporation were reported for Asia (Bouman et al., 2005), and 40 % for floodwater in temperate Australia (Simpson et al., 1992). 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.~~

~~4.3 Fractionation differences between δ^{2}H and δ^{18}O and uncertainties~~

~~Apart from the highly depleted isotopic signal for δ^{2}H observed in deep soil under wet rice fields during the WS (Fig. 3b), there was a systematic deviation of about 20 % between δ^{2}H and δ^{18}O fractionation at shallow soil and 40 % at deep soil. (Fig. 5a–c). This may have resulted from the formation of different 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 developed in the 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). Formation of these hydrogen compounds leads to isotopic exchange and bias in δ^{2}H, 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 vapor (1000lnα) 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^{2}H (Majoube, 1971). Water vapor δ^{2}H further isotopically fractionates with $CH_{4(g)}$ (1000lnα=+23.4, see Bottinga, 1969), $H_2S_{(g)}$ (1000lnα=+851.0 as in Galley et al., 1972; Clark and Fritz, 1997), as well as liquid water with $CH_{4(g)}$ with 1000lnα=+242.1 (Horibe and Craig, 1995), leading to higher δ^{2}H (enriched) in both phases. Moreover, liquid water and water vapor 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^{2}H enrichment is further reinforced. The difference between δ^{2}H 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^{2}H. The assumption for this dissimilarity between δ^{2}H and δ^{18}O can be quantified by a sensitivity analysis, giving a relative depletion by 5±2 ‰ of δ^{2}H. 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 vapor 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, 2012), 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~~

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 δ^2H and δ^{18}O

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 ~~water flow dynamics in the field, controlled by three main processes: (I) in non-flooded conditions, the isotopic enrichment produced at the soil surface moves downwards while there is an upwards evaporative flux resulting in an exponential profile; (II) in flooded conditions, the isotopic enrichment of surface water caused by evaporation is reflected in the surface soil, based on a piston-flow-type movement from the surface ponded water, therefore, the explanation of wet rice~~

~~isotopic profiles is more complex; and (III) in dry soils, especially in maize, there is a preferential flow through cracks in addition to matrix flow.~~

~~We identified four~~three main processes, which ~~may be~~are responsible for variations in the ~~natural~~soil water isotopic profile: ~~physical~~(I) soil evaporation, (II) soil water movement, ~~redistribution by roots~~ and ~~transpiration, and~~(III) the refilling of deep soil water through preferential flows via desiccation cracks. ~~This leads to the conclusion that isotopic profiles develop via diffusion processes in the shallow soil and are then transported by advection in the matrix or in macropores or cracks. During flooding, the signal at the surface is reset by infiltration, redistributed in the soil profile, and subsequently smoothened by the root system and transpiration. Evapotranspiration decreases the soil moisture but preserves the profile.~~

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 ~~(supported also by higher lc-excess values). Soil evaporation in wet rice during the WS was largely obscured by short-term variability of high precipitation events. Reduction processes under anaerobic conditions may have affected δ^2H and caused relatively depleted δ^2H values compared to δ^{18}O. Therefore, a higher difference between δ^2H and δ^{18}O in liquid and vapor phases was found in wet rice fields during the WS due to the equilibration of δ^2H with hydrogen compounds. This study suggests that this is a common effect in flooded rice fields affecting stable isotope studies by causing a bias due to the compounds formed in reducing environments.~~ .

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.

~~With~~To conclude, water losses via soil evaporation is a major unproductive loss next to leaching losses, especially during the early growing stage. Therefore, our ~~method, we can determine flow~~study helps to increase understanding of soil water transport processes~~, unproductive soil water losses~~ and ~~relate redistribution patterns~~evaporation losses from soil in response to crop ~~diversification and seasonal differences. However, another independent tool is needed to calculate total evapotranspiration for validation such as eddy covariance, CROPWAT model. In conclusion, our~~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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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

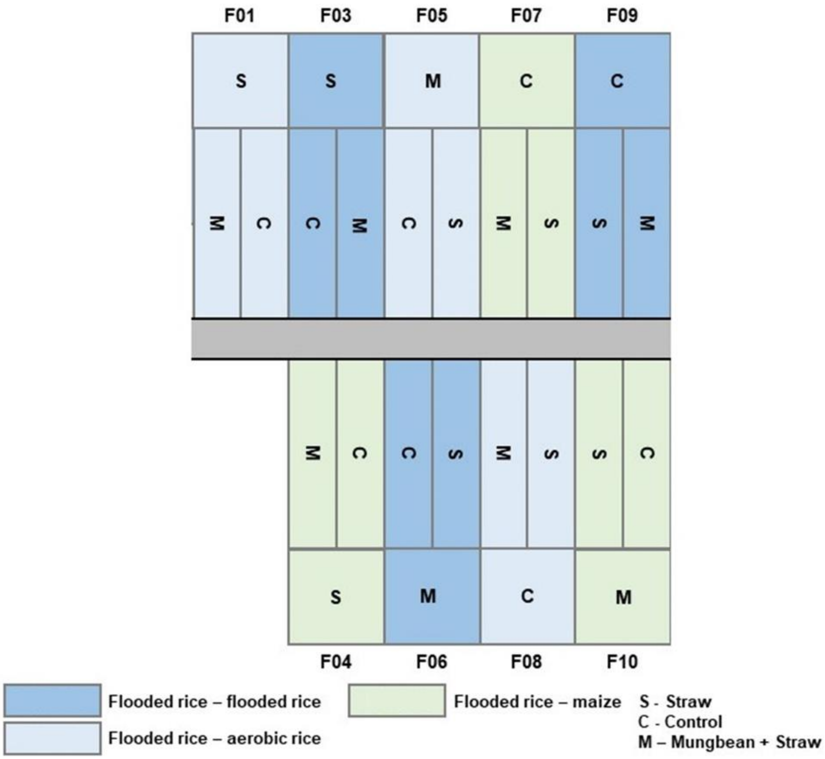

Figure 1. Experimental field design. The experiment consisted of nine fields (F) with three different crop rotations and water management practices. During the wet season, all fields were cultivated with wet rice, while during the dry season, three fields each were cultivated with wet rice, dry rice, 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.

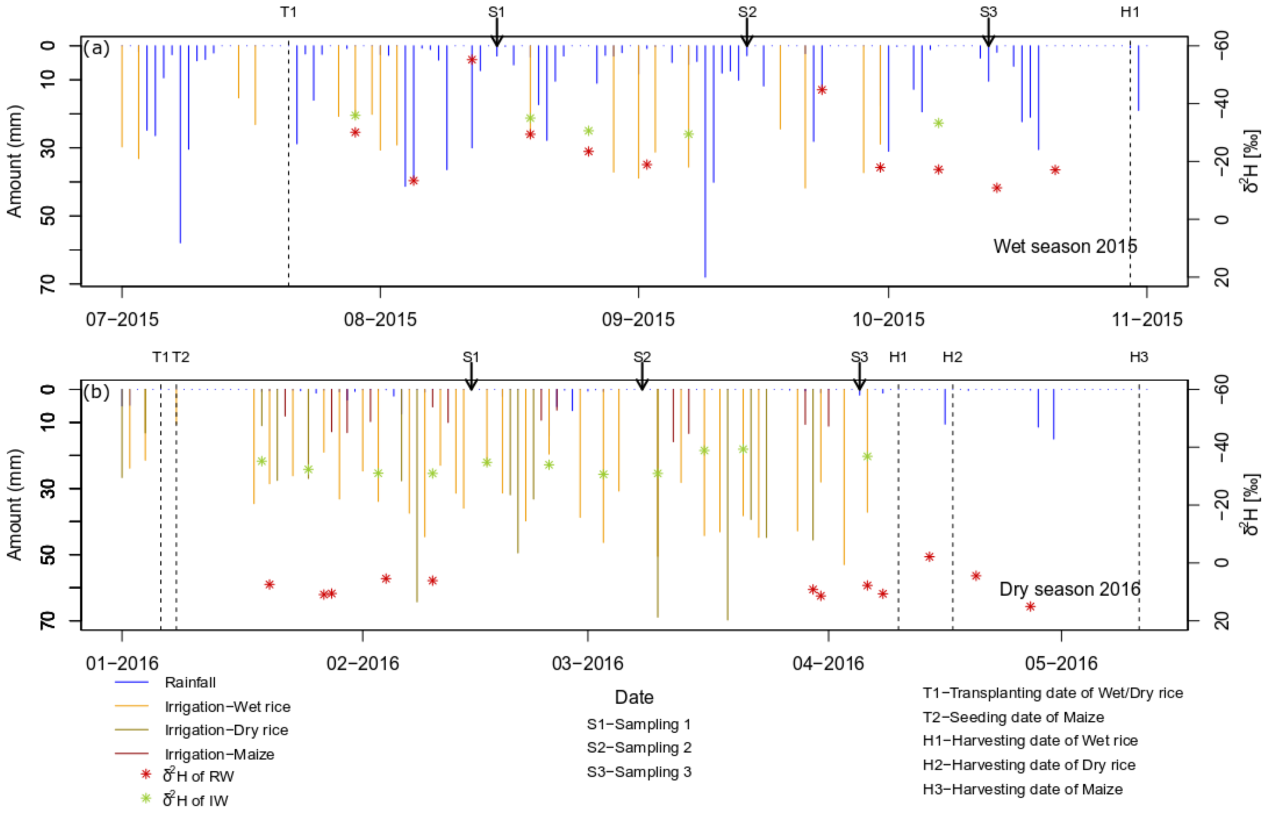

Figure 2. Temporal variation of water inputs (rainfall and irrigation water) of wet rice, dry rice and maize fields for the wet season 2015 (top) and dry season 2016 (bottom). Three main sampling dates during each season together with transplanting and harvesting dates are marked. Values of δ^2H are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

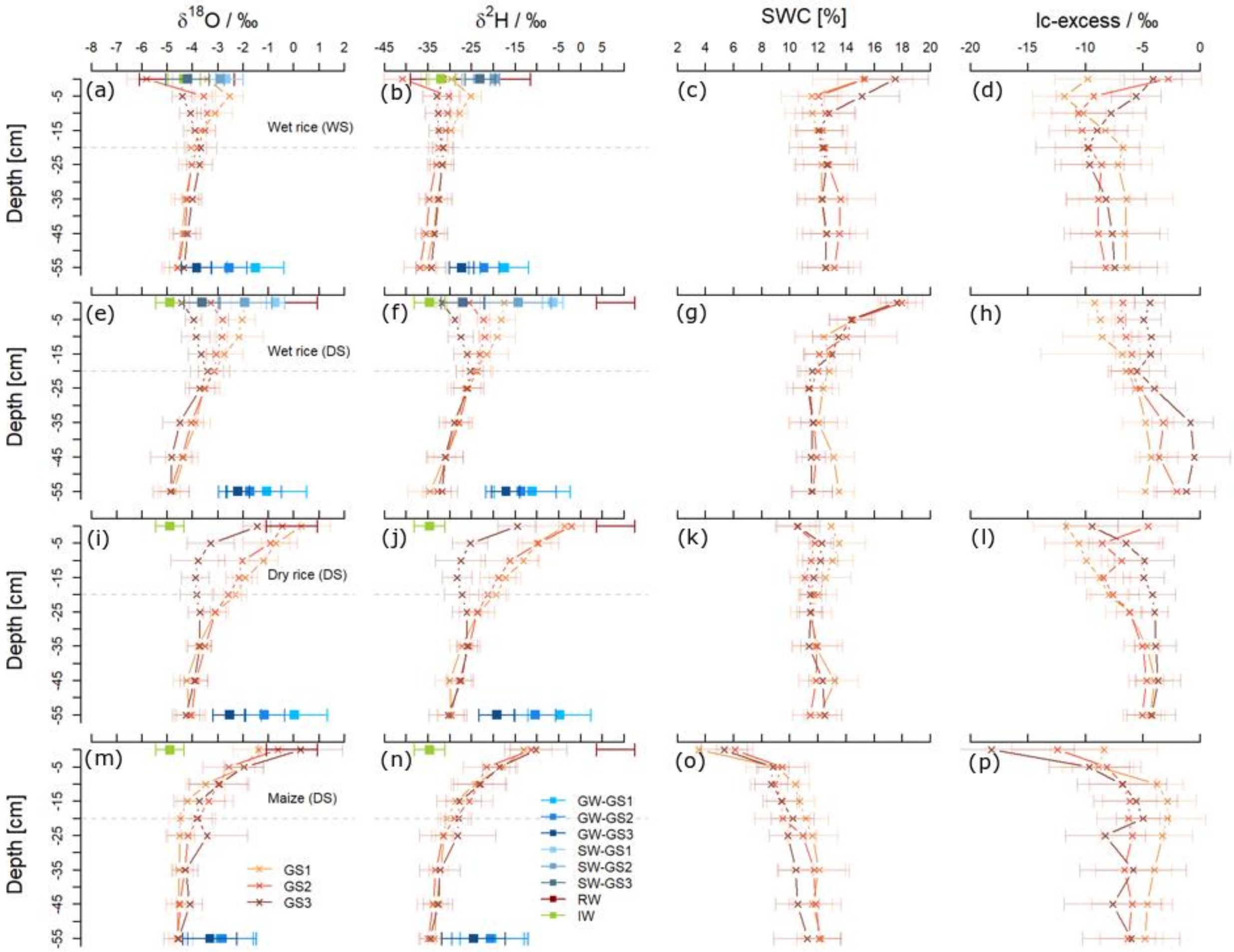

Figure 3. Depth profiles of means +/- standard deviation for δ^{18}O /‰, δ^{2}H /‰, soil water content (SWC) [%], and lc-excess /‰ from three main growing stages (GS1 to GS3) of wet rice (a–d) during the wet season (WS), and wet rice (e–h), dry rice (i–l), maize (m–p) during ~~-~~the dry season (DS).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

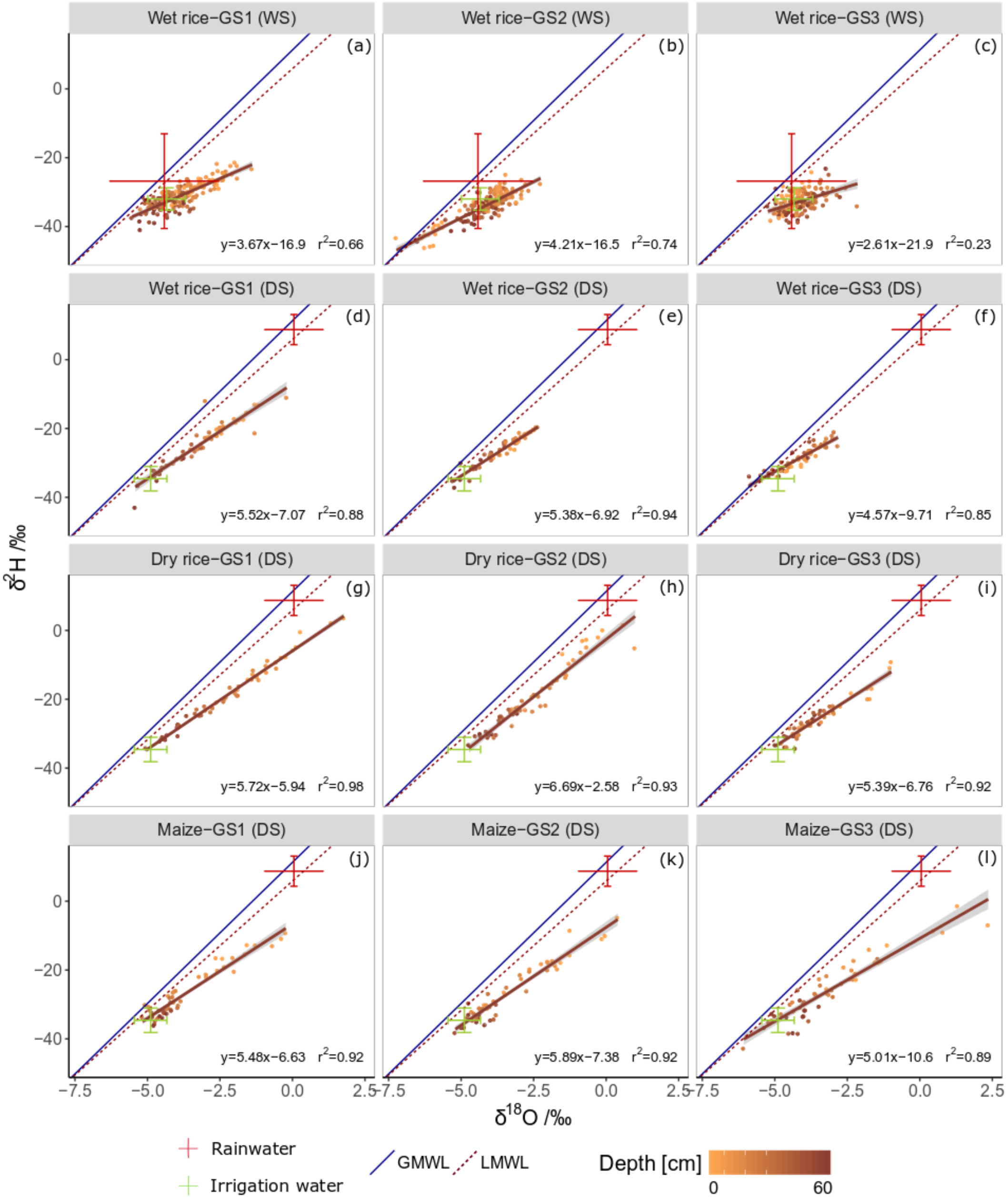

Figure 4. Dual (δ^{18}O, δ^{2}H) isotope plots of soil water at 0–0.6 m depth, and ranges of other water sources (rainwater, irrigation water) from growing stage GS1 (a, d, g, j), GS2 (b, e, h, k), and GS3 (c, f, i, l), from wet rice (a–c) during the wet season (WS), 5 and wet rice (d–f), dry rice (g–i) 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.

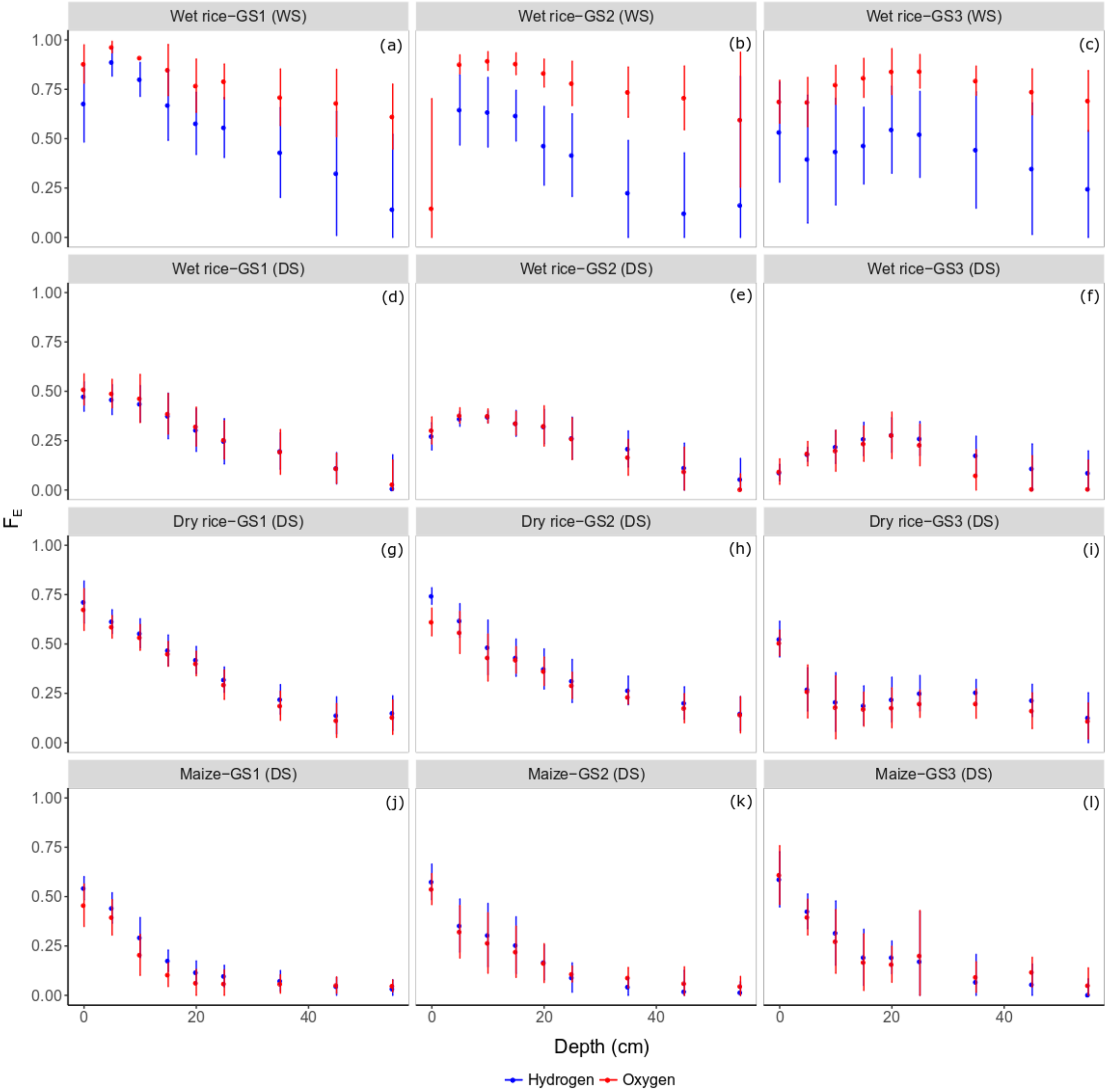

Figure 5. The fraction of evaporation loss (F_E) (Eq.1) ~~following~~ estimated from δ^{18}O~~,~~ and δ^{2}H ~~from~~for the three main growing stages~~: growing stage~~ GS1 (a, d, g, j), GS2 (b, e, h, k) and GS3 (c, f, i, l) of wet rice (a–c) during the wet season (WS), and wet rice (d–f), dry rice (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.