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Sediment-associated organic carbon and nitrogen inputs from erosion and irrigation to rice fields in a mountainous watershed in Northwest Vietnam

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Abstract Maintaining indigenous nutrient supply and positive nutrient balances are key factors in sustaining rice yields. Irrigation systems act as conveyers for water, sediments and nutrients throughout landscapes, especially in mountainous, cultivated tropical areas where erosivity is usually high. Contributions of erosion and irrigation to the nutrient balance of paddy fields, however, are rarely assessed. In this study, a turbidity-based method was used to quantify sediment-associated organic carbon and nitrogen as well as dissolved nitrogen inputs from erosion and irrigation to a 13 ha rice area in Northwest Vietnam. The irrigation source is a surface reservoir, and both reservoir and irrigation channel are surrounded by permanent upland maize cultivation on the steep slopes. Additionally, organic carbon and nitrogen loads in paddy outflow were determined to obtain nutrient budgets. Irrigation

contributed 90 % of sediment-associated organic carbon inputs and virtually all nitrogen inputs. Analysis of ammonium and nitrate in total nitrogen loads showed that 24 % of the total N inputs from irrigation to the rice area, or 0.28 Mg ha^{-1} a^{-1}, were plant-available. Loads measured at the outlet of rice fields showed that paddies were a trap for sediment-associated nutrients: balancing inputs and outflow, a net load of 1.09 Mg ha^{-1} a^{-1} of sediment-associated organic carbon and 0.68 Mg ha^{-1} a^{-1} of sediment-associated nitrogen remained in the rice fields. Sediment-associated organic carbon and nitrogen inputs thus form an important contribution to the indigenous nutrient supply of rice in these maize-paddy systems, while the rice fields simultaneously capture nutrients, protecting downstream areas from the effects of land use intensification on surrounding slopes. These results underscore the importance of upland-lowland linkages in tropical, mountainous, erosion-prone areas.

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Introduction

Irrigation systems convey sediment and nutrients in landscapes (Schmitter et al. 2012). At the field scale, King et al. (2009) found that irrigation increased the field nutrient status: furrow irrigation created a net input of organic carbon (OC) and nitrogen (N) by leaving behind nutrient-rich sediments. They estimated that irrigation water contributed 31.2 kg ha^{-1} sediment-associated OC to the irrigated fields. Beyond the field scale, man-made irrigation channels cross catchment boundaries, exporting surface water from the watershed into a neighboring one. Thus irrigation structures also cause nutrient transfers between catchments, the nature of which depends on the source of the irrigation water and its quality. Schmitter et al. (2012), for example, measured total carbon and N in irrigation water, combining sediment-associated and dissolved nutrients, and reported that an irrigation channel exported 5.7 Mg of OC and 4.7 Mg of N from a small mountainous watershed in one rainy season (May to September).

The main irrigated crop in Southeast Asia is rice, and in Vietnam, where this study was conducted, 97 % of paddy rice is irrigated—mainly with water from surface reservoirs (FAO Aquastat 2014). Reservoirs intercept and store sediments and nutrients in the global hydrological cycle (Beusen et al. 2016; Vörösmarty et al. 2003) and reservoir flushing or release can thus result in peaks of organic carbon and nitrogen export from catchments (Chung et al. 2008). The contribution of sediment-associated nutrients from irrigation to the nutrient balance of paddy systems, however, is not well known. The impact of these nutrient transfers depends on other inputs and losses, which in turn depend on the nature of the rice cropping system. In traditional irrigated rice systems before the Green Revolution, nutrient uptake and removal rates were low. Additions from sediment and rainfall were an important component of the nutrient balance in this setting, enabling even poor soils to sustain yields of 1–2 Mg ha^{-1} and allowing rice to be cultivated in paddy fields in monoculture for decades or even centuries (Reichardt et al. 1998).

In current, intensive rice production, inputs through irrigation water are rarely quantified. Cassman et al. (1998) reported that in most irrigated rice systems, N inputs from rainfall and irrigation are negligible. Schmitter et al. (2010), however, found that rice yields in paddy fields increase with distance to the irrigation channel, showing a distinct spatial trend in soil fertility induced by sediments from irrigation water. In the same watershed, Schmitter et al. (2012) measured nutrient contents of irrigation water combining sediment-associated and dissolved fractions, and reported an amount of 0.8 Mg ha^{-1} of OC and 0.7 Mg ha^{-1} N entering the paddies through irrigation water in one rice cropping season, an amount that could influence the endogenous nutrient supply of the fields. Dung et al. (2009) monitored a small catchment in Northern Vietnam with a composite swiddening system in the uplands, where between 50 and 227 kg of total N entered the paddies from upland slopes and even larger outflows were recorded, resulting in a slightly negative N balance. In the latter study, the negative balances indicated that the nutrients brought in by overland flow were lost again, going downstream.

Irrigation water not only provides nutrient inputs, irrigation management additionally affects nutrient losses from paddies and watersheds. Yan et al. (2010) found paddies to trap N and purify the N in rainwater, with riverine N output amounting to less than 1.5 % of all combined N inputs. Kim et al. (2006) quantified N concentrations in paddy outflows during different rainfall events and reported that N export from paddy fields during storms depended on irrigation status of the fields (ponded or not) and fertilizer application. Maruyama et al. (2008) calculated a paddy mass balance for N and reported that 8.5 % of N inputs were lost via percolation and runoff combined, indicating a filtering effect important in protecting a downstream lake.

These differing results indicate the importance of understanding upland-lowland linkages as well as the cropping systems surrounding the paddies and the irrigation system in place. The nutrient status of paddies cannot be seen separately from the erosivity of the uplands surrounding the rice fields and surface reservoirs. In Northern Vietnam, 60 % of paddies are enclosed in hilly areas (Rutten et al. 2014). However, the subsistence-based shifting cultivation systems with long fallow periods, which used to dominate these hills, have dwindled in the last decades. Under

the influence of political decision making, market mechanisms, and population pressure, they have given way to intensified production systems such as permanent maize cultivation (Fox et al. 2009).

These changing farming systems have brought about an extensively documented deterioration of soil fertility on the slopes. Based on a review of studies in Southeast Asia, Bruun et al. (2009) report losses of soil organic carbon from 13 to 40 % after converting a shifting cultivations system to continuous annual cropping. Specifically in Northern Vietnam, yearly N balances for a cropping cycle of 2 years of upland rice, followed by 1 year of cassava were found to be negative in the upland fields by Dung et al. (2008), with 247 kg of N per hectare lost cumulatively over five years.

Continuous maize cultivation, in particular, is often a culprit for declining soil quality on steep slopes (Valentin et al. 2008). Maize is known to cause especially high amounts of erosion during the onset of the rainy season, before establishment of the crop, when soil cover is very poor (Tuan et al. 2014). According to Pansak et al. (2008), under maize mono-cropping on moderate slopes in Northeast Thailand, between 12 and 15 kg of N ha^{-1} a^{-1} were lost via runoff, soil loss and leaching—amounting to almost one quarter of the amount of N applied through fertilizer. In Yen Chau district, the same district were this study was conducted, Häring et al. (2014) found SOC losses on steep slopes between 0.6 and 1.3 Mg ha^{-1} a^{-1} for fields converted from forest into maize 5–20 years ago resulting in an approximate average loss of 40 t ha^{-1} of SOC for the entire 20 year period. Tuan et al. (2015), also on steep slopes in Yen Chau district, reported losses of 21–23 kg N ha^{-1} a^{-1} under maize mono-cropping.

A loss at the plot scale is not necessarily associated with a loss at the watershed or even basin scale—as nutrients that disappear through erosion are not automatically lost to the whole watershed (van Noordwijk et al. 1997; Valentin et al. 2008). The eroded nutrients could either be redeposited in lower parts of the catchment, or be exported from the catchment altogether, in which case other catchments or water bodies downstream will be affected. As such, rice fields can benefit from the nutrient re-allocation processes in the landscape by trapping, or become additional sources of nutrient loss, depending on the topography. Sink-source relationships at the landscape

level are therefore highly variable, and this variability occurs not only in space but also in time. Rice fields can be net sinks during specific periods of the cropping season but become a source due to ploughing and leveling practices at the onset of the season (Kundarto et al. 2002; cited in Maglinao et al. 2003). Furthermore, depending on the water level of paddies, the irrigation and/or rainfall pattern, additional runoff can be created, turning paddies from nutrient sinks into sources during the rainy season. Therefore, a high temporal resolution of nutrient re-allocation in the catchment is needed to understand upland–lowland sink–source relationships and in particular the role of rice fields in intensively cultivated upland areas. This type of nutrient budget studies requires new techniques that continuously quantify sediment and nutrient loads, both within and exported from paddies, in combination with assessments of nutrient flows into and out of the watershed.

In this study, a turbidity-based method developed by Slaets et al. (2014) was applied to quantify the re-allocation of sediment-associated OC, sediment-associated and dissolved N transport in an intensely cultivated, irrigated watershed containing continuous maize cultivation on the uplands and paddy rice in the valley. Our specific aims were (i) to determine the effect of irrigation derived from an upstream surface reservoir on sediment-associated OC and N as well as dissolved N inputs for paddy fields, (ii) to quantify the effect of overland flow from surrounding upland areas on sediment-associated OC and N inputs for paddy rice, (iii) to estimate the load of sediment-associated OC and N exported from the paddy area and lost from the watershed, and (iv) to assess the proportion of plant-available N in the total N inputs from irrigation water and overland flow, and thus the potential impacts of these upland-lowland linkages on rice production.

Materials and methods

Study site

The study was conducted in Chieng Khoi commune (Fig. 1, 350 m a.s.l., 21°7′60″N, 105°40′0″E), Yen Chau district, Northwest Vietnam within the framework of the collaborative research center "The Uplands Program", an international research project funded by the German Research Foundation (DFG) on

Fig. 1 Situation of the study site in Chieng Khoi commune, Yen Chau district, Vietnam, showing the surface reservoir, the irrigated paddies, and the measurement locations in the irrigation channel (locations 1, 2 and 3) and in the river (locations A and B)
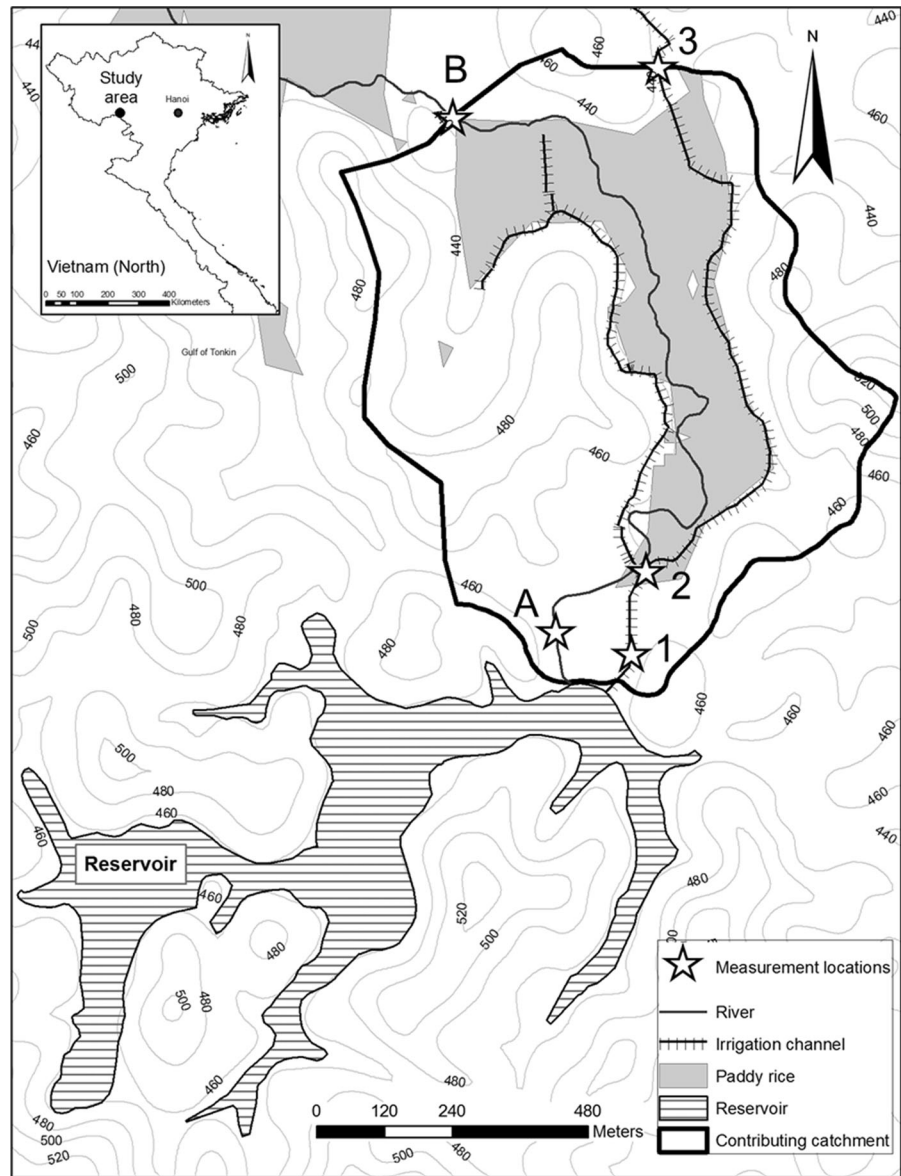
the conservation of natural resources and the improvement of livelihoods of the rural population in mountainous areas of Southeast Asia. The rainfall pattern follows a typical monsoon pattern with a rainy season from April till October, and an average annual rainfall of 1200 mm. Alisols and Luvisols are the most important soil types in the area (Clemens et al. 2010). The main crops on the hills are maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz), whereas paddy rice (*Oryza sativa* L.) dominates in the valleys.

Farmers irrigate the paddy fields with water from a surface reservoir that feeds a concrete irrigation channel. A contributing area of 490 ha, containing maize and cassava upland fields and forest, drains to the reservoir, which has a buffering capacity of 10^6 m^3 and covers a total surface of 26.3 ha if the maximum water depth of 13.67 m is reached. The reservoir supplies water the whole year around to the 13 ha of paddy fields in the studied watershed, ensuring two rice crops per year: a fully irrigated spring crop from February till June, and a summer (rainy season) crop from July till October that receives supplementary irrigation. The main channel splits into two: one providing water for the paddy fields on the left bank of

a river that transects the watershed, and one for the paddy fields on the right bank (Fig. 1). The water from the left bank of the channel is used up fully within the watershed, while the right bank still contains water as it leaves the catchment and enters a neighboring one. The irrigated paddy fields subsequently drain into the river which in its turn exports the excess water from the watershed.

Measuring sediment-associated OC and N fluxes at the watershed scale

Monitoring locations

Two sources contribute sediment-associated OC and N to the paddy fields: irrigation water from the surface reservoir during both the dry and rainy season, and direct overland flow generated on the surrounding steep upland fields draining into the irrigation channel during the rainy season (Fig. 1). As a part of the irrigation water in the right channel is not used within the studied watershed, a portion of the particulate OC and N released by the reservoir will be transported to the neighboring catchment. To separate these sources and to quantify the amount of water allocated to the left and right channel, three different monitoring locations were installed in the irrigation channel. The station in the channel directly below the reservoir (location 1 in Fig. 1) monitored the quantity of and sediment-associated OC and N concentrations in the irrigation water. The site directly below the split of the channel (location 2 in Fig. 1) quantified the amount of water going into each branch of the channel and therefore irrigated to each bank of paddy fields. A measurement station at the end of the right concrete channel (location 3 in Fig. 1), just before it leaves the catchment, determined the amount of water, N and sediment-associated OC released to the neighbouring catchment and allowed for the quantification of total irrigated OC and N loads to the paddies (i.e., between locations 2 and 3). Simultaneously monitoring these two sites allowed us to determine the contribution of overland flow from surrounding upland fields to the OC and N loads. In the river, a similar setup characterized the nutrient loads exported from the full 13 ha paddy area: location A (Fig. 1) measured nutrient loads before the paddy

fields, and location B (Fig. 1) quantified the loads after translocation trough the monitored paddy area.

Hydrological data

During the monitoring years of 2010 and 2011, water levels were recorded using pressure sensors at 2-min-intervals (Ecotech, Germany). Discharge predictions were obtained using the area-velocity method for the river and the salt dilution method for the channel (Herschy 1995). Satisfactory accuracy was achieved for all stations (R^2 from 0.97 to 0.99; Slaets et al. 2015). Rainfall was registered by a tipping-bucket rain gauge (accuracy 0.1 mm) which was part of a weather station (Campbell Scientific, USA) that was installed in the upper part of the catchment (Lamers et al. 2011).

Turbidity was measured with NEP395 nephalometric turbidity sensors (McVan, Australia) and recorded at 2 min intervals using CR200 data loggers (Campbell Scientific, USA). The sensors were suspended with the optical eye down in a perforated pipe, installed at the center point of flow but allowing the pipe to be pushed upwards in the water column with rising water levels (Slaets et al. 2014). Automatic wipers were programmed to clean the optical eye every hour to prevent fouling of the sensors.

Nutrient concentrations

Water samples were collected in order to establish a relationship between nutrient content and predictor variables such as turbidity and discharge. The sampling was done manually rather than with automatic samplers, as flow-proportional automatic sampling can be challenging in irrigation channels where discharge is affected by management (Schmitter et al. 2012) and composite sampling is not appropriate for calibration of the sensors. A storm-based approach was chosen to catch the full range of OC and N concentrations. Typically ten to twenty samples were collected per event. A 0.5 L sample was taken at each sampling, horizontally and opposite to the flow direction, in order to minimize particle disturbance. The samples were refrigerated on site and transported to the lab after the event, where they were frozen until analysis.

Samples were analyzed for sediment-associated OC, total and dissolved N by a combustion method with a LiquiTOC II (Elementar, Germany) on the full

sample containing sediment, and on the supernatants after letting the sediment settle down, as is recommended for water samples with very high sediment concentrations (ASTM 2013). More details can be found in Slaets et al. (2014). Additionally, ammonium and nitrate concentrations were determined for 595 samples (42 samples during base-flow, the remainder during rainfall events). Ammonium was determined using the modified indophenol method (0.1 M KCl extraction; Sparks et al. 1996) and nitrate was analyzed with the Cataldo method (0.01 M KCl extraction; Cataldo et al. 1975). The ammonium and nitrate concentrations were determined on the water samples containing sediments.

Predicting sediment-associated OC and N loads

Data quality control

Discharge and turbidity data were checked before use for concentration predictions by comparing upstream and downstream locations in the same stream against rainfall over the different years. Where discharge data were missing due to malfunctioning of the sensors for short periods of time (defined as less than 1 day, and during periods of no rainfall only), discharge was linearly interpolated. The 2 year period encompassed 420 rainfall events (192 events in 2010 and 228 events in 2011). In the dry season of 2011 at the river inlet, there was a more extended period of time with missing turbidity data due to technical problems. In that case, the monthly averaged base-flow values of the previous year were used.

Flow component separation

In order to separate the contribution of irrigation water and direct Hortonian overland flow to the OC and N inputs of the paddy fields, the discharge in the irrigation channel was separated into water volume from irrigation and water volume from runoff. The irrigation channel is lined with concrete, so there was no interflow or base-flow present. Therefore the base-flow hydrological balance during periods without rainfall can be described by

$$Q_{in} = Q_{irr} + Q_{out}, \qquad (1)$$

where Q_{in} is the discharge at location 2, Q_{out} is the discharge at location 3, and Q_{irr} is the discharge

irrigated to the paddy fields, all in m^3 s^{-1}. As Q_{in} and Q_{out} were measured directly, the irrigated discharge can be calculated as the difference between the two. During rainfall, however, when both direct rainfall and Hortonian overland flow enter the irrigation channel, the hydrological balance in the channel changes to

$$Q_{pp} + Q_{in} + Q_{of} = Q_{irr} + Q_{out}, \qquad (2)$$

where Q_{pp} is the direct precipitation into the channel and Q_{of} is the overland flow entering the channel from surrounding uplands during rainfall. Q_{pp} can be quantified directly, as the direct precipitation into the channel can be calculated from the rainfall intensity, which is measured by the rain gauge, and the channel dimensions. Q_{irr} was assumed to be equal to the product of pre-event irrigation rates (calculated from Eq. 1 and the measured Q_{in} and Q_{out} prior to event onset), and the relative change in reservoir release (Q_{in}) due to irrigation management since the onset of the event. We can then determine Q_{of} from the upland area as the only remaining unknown from Eq. 2. The flow component separation is described in more detail by Schmitter et al. (2012).

Concentration prediction models

Continuous sediment-associated OC and N concentrations were estimated using a linear mixed model with turbidity, discharge and depth of the surface reservoir as predictor variables (Slaets et al. 2014). As a larger dataset was available in this study compared to Slaets et al. (2014), a separate model was fitted for each location, rather than one model with location-specific regression coefficients in the previous analysis. Model validation was performed using fivefold cross validation with a SAS macro described in Slaets et al. (2014). Sample size and Pearson's correlation coefficient between observed and predicted values for the different monitoring locations are shown in Table 1. Input variables were chosen based on forward selection with Pearson's correlation coefficient after cross-validation as selection criterion.

To account for serial correlation in the data, the error was modeled by fitting a first-order autoregressive variance–covariance structure to the data where the events were considered as independent subjects. All statistical analyses were done using the MIXED procedure of SAS 9.4.

Table 1 Model fit for the nutrient concentration predictions from the linear mixed model with turbidity and discharge as predictor variables

Position	OC		N		TN	
	n	r^2	n	r^2	n	r^2
Channel	535	0.60	377	0.62	600	0.61
River (A)	102	0.59	108	0.71	112	0.77
River (B)	70	0.71	73	0.62	72	0.62

Shown are number of observations (n) and squared Pearson's correlation coefficient (r^2) of observed versus predicted values after fivefold cross-validation for sediment-associated organic carbon (OC), sediment-associated nitrogen (N) and Total nitrogen (TN) concentration predictions for the different measurement locations in Fig. 1

When applying these models to the whole time series, the predictions showed a small overprediction for base-flow, which is typical (Nearing 1998) but would have a large effect on annual load estimates. Therefore a qualitative variable for flow regime was included in the model, so that regression coefficients could vary according to the flow regime. To stabilize the variance, the response variable was Box-Cox transformed using a macro developed by Piepho (2009).

Estimated OC and N concentrations during base-flow sometimes yielded negative values, when the total or dissolved concentrations were below the detection limit of the CN analyzer (0.05 mg L^{-1}). Leaving out these values may introduce bias into the model as these low values are not missing completely at random. Because there was a strong correlation between total and sediment-associated nutrient concentrations, however, the missing concentration values were imputed using Multiple Imputation as implemented in the MI procedure of SAS 9.4. Specifically, we employed the fully conditional specification method (FCS), which assumes a joint distribution of these variables (van Buuren 2007). All imputations were done on the log-transformed scale.

Load estimates

Instantaneous loads can be calculated by multiplying OC or N concentrations, as predicted from the models, with the discharge at that time point. To obtain load estimates over a time interval, for example an annual load, the instantaneous loads are summed up:

$$\hat{L}_{1\,\text{to}\,t} = \sum_{i=1}^{t}(\hat{L}_i * D), \tag{3}$$

where $\hat{L}_{1\,\text{to}\,t}$ (Mg) is the total load over a time interval 1 to t, $\hat{L}_i$ is the instantaneous load at a time i (Mg s^{-1}) and D the duration of the prediction interval (s), which corresponds to 120 s for our 2-min turbidity and discharge recordings.

In order to calculate confidence intervals on the load, a bootstrap method was adopted where both uncertainties of the discharge and concentration predictions were taken into account (Slaets et al. in revision; "Appendix"). The imputation of the missing low sediment-associated concentrations was repeated for each bootstrap replicate in order to take this source of uncertainty into account. As the bootstrap also removes bias (Efron and Tibshirani 1993), load estimates are reported here as the medians of the bootstrap estimates, rather than the direct estimates resulting from Eq. 3.

Results

Sediment-associated paddy OC and N inputs from irrigation

Irrigation water from the surface reservoir transported a total of 13.84 Mg of OC in 2010 and 14.74 Mg in 2011 into the 13 ha rice area (Table 2). Sediment-associated N loads brought into the paddies amounted to 9.16 Mg in 2010 (Table 3) and 9.37 Mg in 2011 (Table 4). Percentages of OC and N in the sediments were determined by dividing these sediment-associated OC and N loads by corresponding sediment loads for the same area reported in Slaets et al. (2015). The OC and N percentages in the sediment in irrigation water changed throughout the year, being highest at the start of the spring season and at the end of the summer crop (Fig. 2). They were lowest when surface reservoir water level was very low, e.g. at the end of the spring cropping season (May), as at this time, highly erosive rains fell into a small volume of water, bringing in unfertile sediments, low in nutrients. The OC to N ratio of the sediments in the irrigation water was around 1.6 and changed little throughout the year (Fig. 3).

Table 2 Sediment-associated organic carbon budget for rice fields in Chieng Khoi catchment in 2010 and 2011

| Sediment source | Sediment-associated organic carbon (Mg a^{-1}) | | | | | |
| | 2010 | | | 2011 | | |
	LL	Med	UL	LL	Med	UL
Reservoir water						
Irrigated to paddy area	12.75	13.84 (90 %)	15.85	13.19	14.74 (92 %)	19.08
Exported via channel	3.11	3.39	3.99	3.11	3.43	4.35
Spillover to river	nd	nd	nd	5.76	6.72	10.45
Overland flow						
Irrigated to paddy area	1.04	1.55 (10 %)	2.47	0.79	1.35 (8 %)	2.55
Exported via channel	0.32	0.50	0.83	0.26	0.40	0.74
Total paddy input		15.39 (100 %)			16.09 (100 %)	
Paddy outflow	nd	nd	nd	0.03	1.94 (12 %)	6.13
Net paddy balance	nd	nd	nd		14.15 (88 %)	
Paddy balance per ha		nd			+1.09 Mg ha^{-1} a^{-1}	
Watershed losses		nd			12.4	

Contributions are shown for inputs through irrigation water from the surface reservoir and direct overland flow from the 37 ha upland area surrounding the rice fields, as well as export from the 13 ha paddy area in Mg a^{-1} out of the watershed (see Fig. 1). Percentages indicate contributions compared to total combined inputs from irrigation and overland flow

Med median of bootstrap sample; *LL, UL* lower, upper 95 % confidence limits; *nd* not determined

Table 3 Nitrogen inputs to rice fields in Chieng Khoi catchment in 2010

| Source | Nitrogen (Mg a^{-1}) | | | | | | | | |
| | Sediment-associated | | | Dissolved | | | Total | | |
	LL	Med	UL	LL	Med	UL	LL	Med	UL
Reservoir water									
Irrigated to paddy area	8.72	9.16 (97 %)	9.92	2.46	5.55 (99 %)	11.14	11.79	14.71 (98 %)	20.33
Exported via channel	2.12	2.22	2.40	0.60	1.34	2.69	2.87	3.57	4.93
Overland flow									
Irrigated to paddy area	0.17	0.28 (3 %)	0.45	0.00	0.01 (1 %)	0.15	0.22	0.29 (2 %)	0.38
Exported via channel	0.06	0.11	0.14	0.00	0.00	0.05	0.07	0.09	0.12
Total paddy input		9.44 (100 %)			5.56 (100 %)			15.00 (100 %)	
Inputs per hectare		0.73 Mg ha^{-1}			0.43 Mg ha^{-1}			1.15 Mg ha^{-1}	

Shown are sediment-associated and dissolved nitrogen contributions from overland flow from the 37 ha upland area surrounding the paddies and from irrigation water from the surface reservoir

Med median of bootstrap sample; *LL, UL* lower, upper 95 % confidence limits; *nd* not determined

The sediment-associated OC and N loads from irrigation water into the paddies showed substantial monthly differences (Fig. 4). While the percentage of OC and N in the sediments varied throughout the year, differences in monthly loads were mainly driven by alterations in water volume irrigated to the paddies over the year (Fig. 4a). For both years and both nutrients, the summer rice season received larger OC and N loads than the spring season.
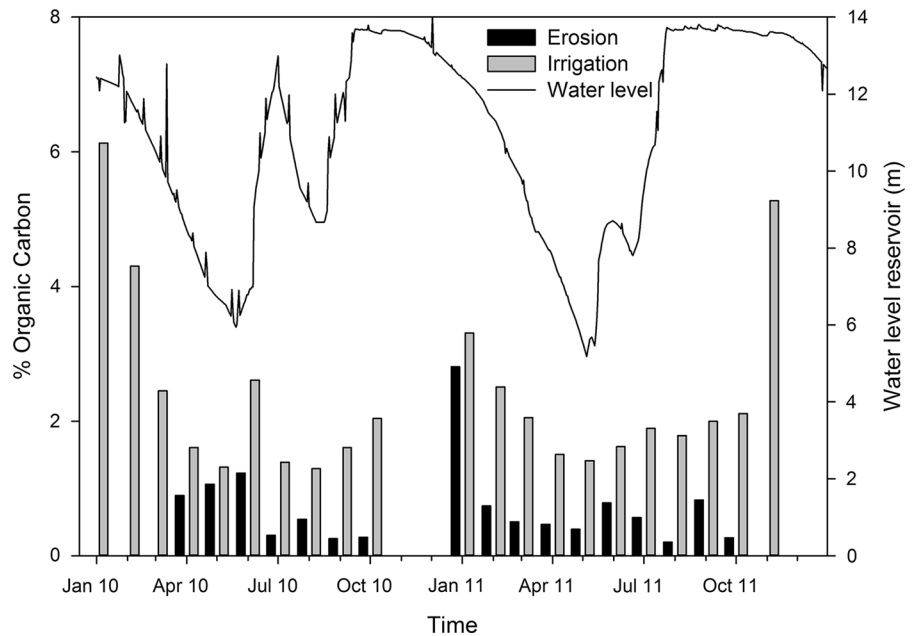
Table 4 Nitrogen budget for rice fields in Chieng Khoi catchment in 2011

Source	Nitrogen (Mg a^{-1})								
	Sediment-associated			Dissolved			Total		
	LL	Med	UL	LL	Med	UL	LL	Med	UL
Reservoir water									
Irrigated to paddy area	8.83	9.37 (98 %)	10.43	2.49	5.62 (100 %)	10.99	12.06	14.93 (99 %)	20.20
Exported via channel	2.08	2.19	2.48	0.53	1.31	2.58	2.84	3.50	4.74
Spillover to river	0.60	0.86	1.23	6.87	7.98	14.47	7.84	8.84	15.36
Overland flow									
Irrigated to paddy area	0.00	0.20 (2 %)	0.35	0.00	0.00 (0 %)	0.17	0.09	0.22 (1 %)	0.29
Exported via channel	0.04	0.07	0.11	0.00	0.00	0.03	0.05	0.07	0.08
Total paddy input		9.57 (100 %)			5.62 (100 %)			15.15 (100 %)	
Paddy outflow	0.20	0.68	1.58	−0.62	3.72	10.33	0.18	4.44	10.67
Net paddy balance		8.89 (93 %)			na			na	
Paddy balance per ha		+0.68 Mg ha^{-1} a^{-1}			na			na	
Watershed losses		3.80			13.01			16.85	

Shown are sediment-associated and dissolved nitrogen contributions through overland flow from the 37 ha upland area surrounding the paddies, inputs through irrigation water from the surface reservoir, export from the 13 ha paddy area, and the net balance for the paddies

Med median of bootstrap sample; *LL, UL* lower, upper 95 % confidence limits; *na* not applicable

Fig. 2 Average monthly organic carbon (**a**) and nitrogen content (**b**) of the sediments (%) in irrigation water and overland flow (Erosion). Additionally shown are water level in the surface reservoir (**a**) and monthly rainfall (**b**) in the study years 2010 and 2011
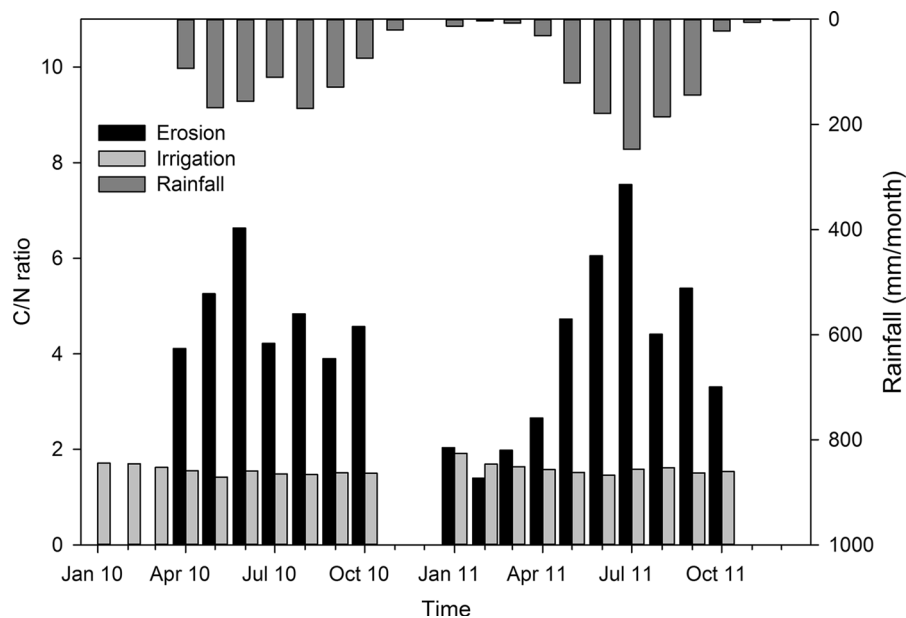
Sediment-associated OC and N paddy inputs from erosion

Nutrient inputs from direct overland flow were much smaller than contributions from irrigation water, amounting to around 10 % of inputs in both years for OC, and approximately 1 % of inputs for N (Tables 2, 3, 4; Figs. 5, 6). Consequently, erosion from upland areas surrounding paddies carried 1.55 Mg or 0.12 Mg ha^{-1} of sediment-associated OC into the rice area in 2010, and 1.35 Mg or 0.10 Mg ha^{-1} in 2011 during rainfall events. For sediment-associated N, the direct erosion based loads amounted to 0.28 Mg in 2010 and 0.20 Mg in 2011, or about 0.02 Mg ha^{-1} a^{-1} in both years.

The percentages of OC in sediments originating from erosion, calculated by dividing the sediment-associated OC load from overland flow by the sediment load from overland flow (Slaets et al. 2015) were 0.83 % in the first and 0.64 % in the second year of the study (Table 5). These percentages are low compared to the OC content of sediments in irrigation water, which averaged 2.15 % in 2010 and 2.37 % in 2011. For N, the difference was even larger, with directly eroded sediments having often a percentage of N an order of magnitude smaller than sediments in irrigation water (Fig. 2b). In general, the percentage of OC in sediments in overland flow was higher in the first months of the rainy season, after a long dry period, consistent with a first-flush effect when a lot of light and fertile material has built up and is available for eroding (Fig. 2a). Average monthly OC to N ratios of eroded material varied from 1.4 in February 2011 to a maximum of 7.5 in July 2011, the month with the largest storm of the study period (on 12/07/2011) in which 70 mm of rain fell in 1 h. In 2010, the OC to N ratio was highest during May and June, the months during which upland fields are prepared for maize planting, resulting in a large supply of loose soil and readily erodible sediment at the onset of the rainy season. In 2011, however, the rains came atypically late, resulting in a shifted peak not coinciding with upland field preparation.

Plant-available nitrogen contributions from irrigation and runoff

As continuous predictions were obtained for both sediment-associated and total N, loads of dissolved N could be estimated as the difference between those two. Irrigation water contributed the vast majority (99 %) of dissolved N inputs to the rice fields (5.56 Mg a^{-1}), while overland flow contributed only 0.01 Mg (1 %) in the first year of the study and no detectable dissolved N in the second year. Paddy outflow contained 3.72 Mg of dissolved N in 2011.
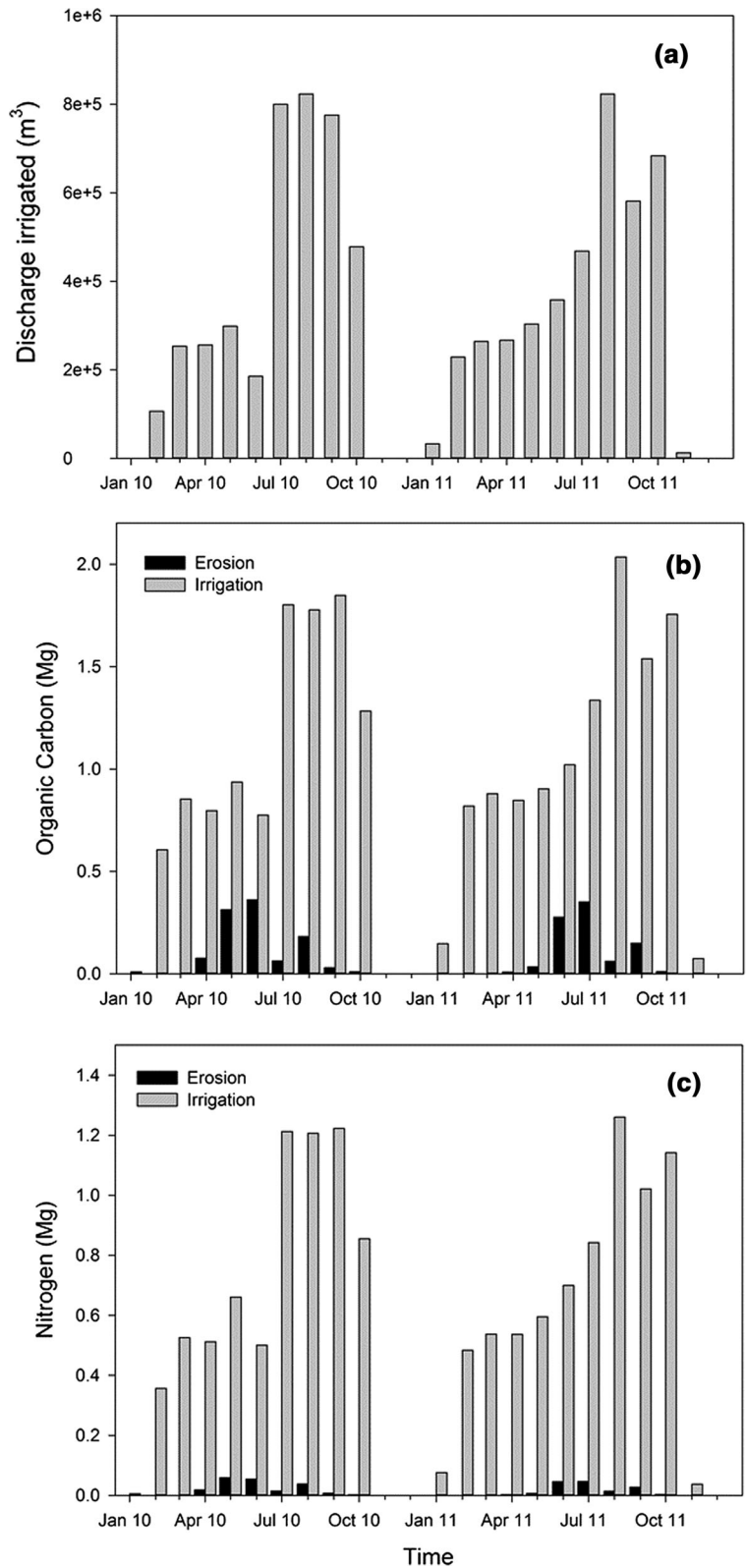
Fig. 5 Sediment-associated organic carbon flow chart for 2011. Bubble size corresponds to size of the OC load (in Mg a^{-1})
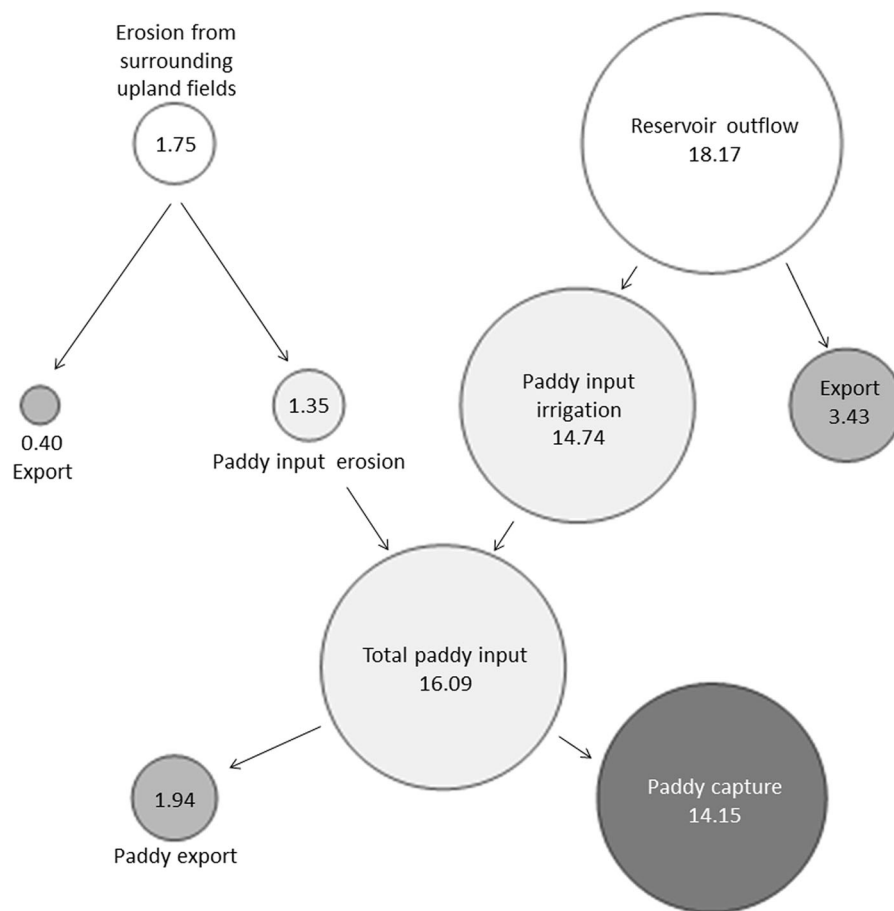
As ammonium (NH_4^+) and nitrate (NO_3^-) are the main plant-available forms of N, a subset of the sediment containing water samples was analyzed for these N forms. No continuous predictions were obtained, but the samples showed seasonal differences in base-flow NH_4^+ and NO_3^- concentrations in the irrigation water (Table 6): NO_3^- concentrations in water samples were particularly high during the months of June and July, coinciding with fertilization with NPK of maize on upland areas surrounding the lake. NH_4^+ concentrations were highest during the spring time, NH_4^+ being the dominant form of inorganic N in an anaerobic environment such as the surface reservoir. During the rainy season, NO_3^- concentrations were higher than those of NH_4^+, with averages over the study period of 0.90 mg L^{-1} for NH_4^+ and 2.94 mg L^{-1} for NO_3^-. During overland flow, storm flow samples contained on average 1.52 mg L^{-1} of NH_4^+ and 6.21 mg L^{-1} of NO_3^- (data not shown).

Organic carbon and nitrogen budgets for irrigated rice

Sediment-associated nutrient losses from outflow from the rice area consisted of 1.94 Mg of OC and 0.68 Mg of N in 2011. For dissolved N, a total of 3.72 Mg (or 0.29 Mg ha^{-1}) was exported via paddy outflow (combining overland flow, baseflow and interflow) in 2011. In 2010, the monitoring station at location B was not yet installed and, therefore, data are not available for this period. The OC in the sediments in paddy outflow averaged 1.07 % in 2011 (Table 5). Balancing losses with total inputs, these estimates resulted in an annual net contribution of 14.15 Mg of OC and 8.89 Mg of N (Tables 2 and 4) from sediments to the nutrient status of the 13 ha paddy area. This contribution corresponded to a trapped amount of 1.09 Mg ha^{-1} a^{-1} sediment-associated OC and 0.68 Mg ha^{-1} a^{-1} of sediment-associated N, revealing that rice fields were a net sink, rather than a net

Fig. 6 Sediment-associated nitrogen flow chart for 2011. Bubble size corresponds to size of the N load (in Mg a^{-1})
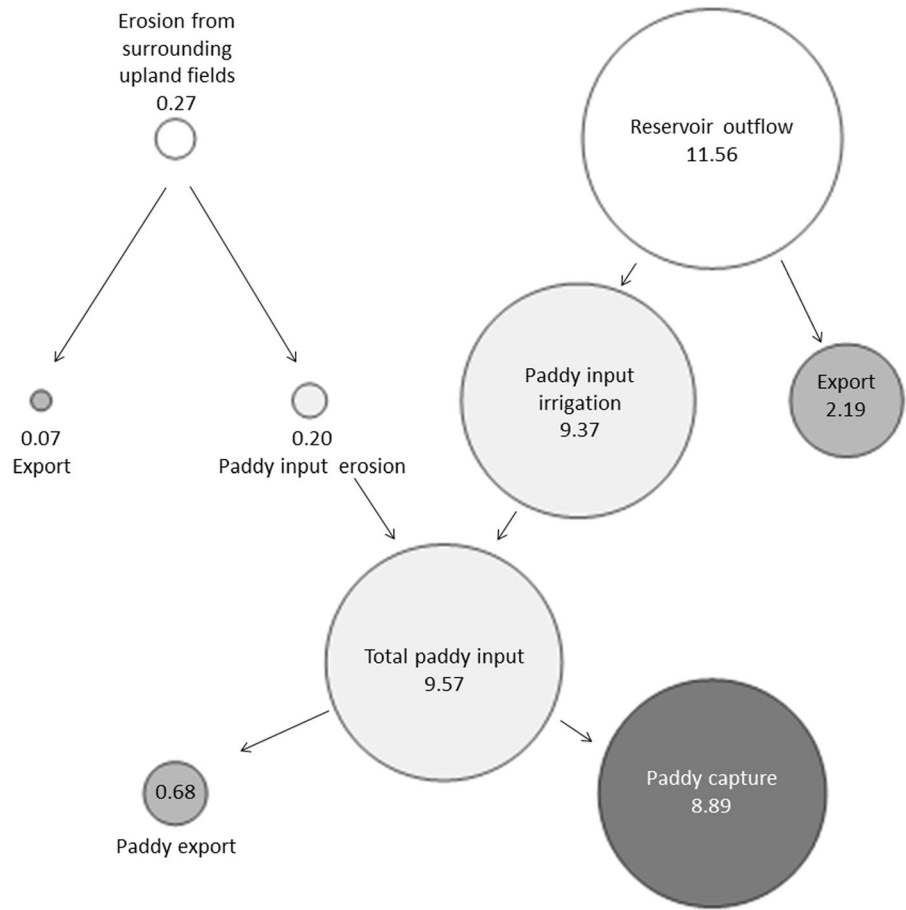
Table 5 Organic carbon (% OC) in the sediments from different components of the paddy sediment balance in 2010 and 2011 based on annual sediment and sediment-associated OC load estimates

Source	% OC	
	2010	2011
Reservoir water		
Irrigation channels	2.15	2.37
Spill-over to river	nd	0.52
Overland flow	0.83	0.64
Paddy outflow	nd	1.07

nd not determined

Table 6 Average (av), minimum (min) and maximum (max) monthly ammonium and nitrate concentrations in irrigation water during the maize cropping season ($n = 42$)

Month	Ammonium (mg L^{-1})			Nitrate (mg L^{-1})		
	min	av	max	min	av	max
April	1.42	1.52	1.62	0.89	1.45	8.56
May	0.08	1.58	1.98	0.82	1.19	9.77
June	0.47	2.11	2.56	0.54	4.79	8.64
July	0.20	0.90	2.25	0.80	4.32	8.33
August	0.19	0.75	1.20	0.53	0.80	12.74
September	0.07	0.32	0.71	0.16	1.04	9.67

source for sediment-associated nutrients, at landscape level.

Multiplying monthly average concentrations of NH_4^+ and NO_3^- in surface reservoir outflow with monitored discharges to the paddies from irrigation, provided estimates of annual inputs to the rice area of 2.82 Mg of NH_4^+-N and 1.07 Mg of NO_3^--N in 2010, and 1.97 Mg of NH_4^+-N and 0.26 Mg of NO_3^--N in 2011. Accounting for the area of the paddies, which is 13 ha, these results correspond to an average annual

input of 0.19 Mg ha^{-1} of NH_4^+-N and 0.09 Mg ha^{-1} of NO_3^--N. This input is the fraction of total N transported into the paddies that is potentially plant-available. Thus dividing by the total N loads (Tables 3, 4), which additionally include organic N, 24 % of total N inputs from irrigation was found to be potentially plant-available in both study years. The plant-available proportion (combining sediment-associated and dissolved NH_4^+-N and NO_3^--N) differed between seasons: during the 2010 spring rice crop, from February till June, over half of irrigation water N inputs to the rice fields were in a direct plant-available form (Fig. 7). In the summer season of 2011, when rainfall did not coincide with upland maize fertilization, 30 % of N inputs were found to be plant available. During both summer cropping seasons, from July till November, overall N inputs from irrigation were larger as more water was irrigated (Fig. 4a), but only 15 % of this contribution was plant available N (Fig. 7).

Relocation of organic carbon and nitrogen to neighboring catchments

Nutrients are not only lost via paddy outflow as quantified in the previous section, which for the entire 13 ha paddy area resulted in the export of 1.94 Mg of OC, 0.68 Mg of sediment-associated N and 3.72 Mg of dissolved N in 2011. They are also exported via the irrigation channel, which leaves the catchment and crosses over into a neighboring catchment. In 2010, these losses amounted to 3.39 Mg of OC and 2.22 Mg of N, and in 2011 a total of 3.43 Mg of OC and 2.19 Mg of N were exported this way (Tables 2, 3, 4). Part of the overland flow that enters the channel during rainfall is also exported in the same way, amounting to 0.50 Mg of OC and 0.11 Mg of N in 2010 and 0.40 Mg of OC and 0.07 Mg of N in 2011. Additionally, watershed losses occurred when excess water was removed from the irrigation supply through the spillover during the rainy season: Outflow from paddy
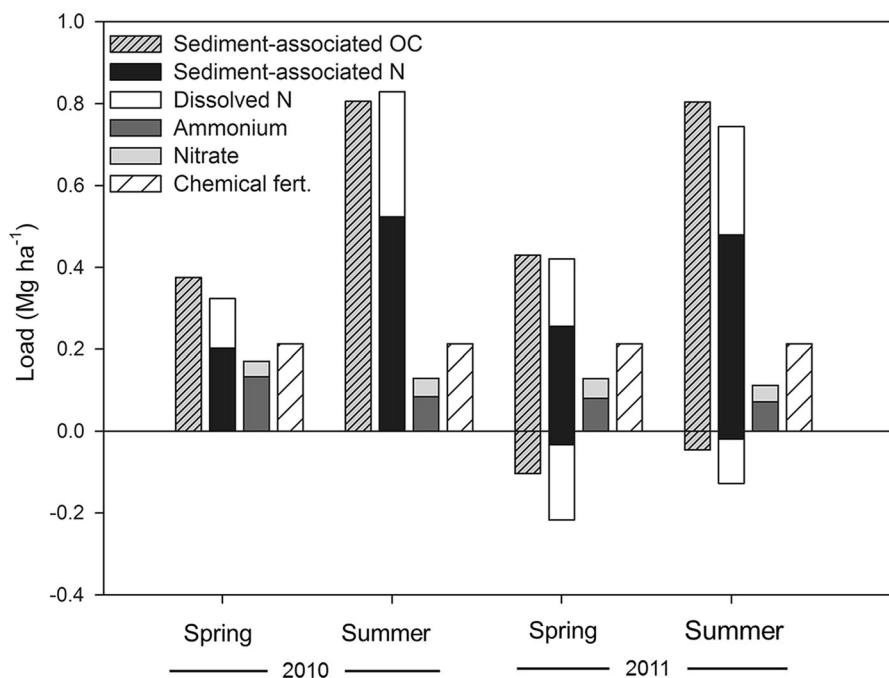
Fig. 7 organic carbon and nitrogen inputs to the 13 ha paddy area (Mg ha^{-1}) per rice cropping season (spring: Feb–June, summer: July–Nov) for both years in the study. Inputs shown are total sediment-associated OC inputs (from irrigation and erosion), N inputs divided into sediment-associated and particulate fractions, and total plant-available N inputs divided into ammonium-N and nitrate-N. The recommended N inputs from chemical fertilizer according to local agricultural extension guidelines are also indicated. Negative loads are nutrient losses via paddy outflow. Losses were only quantified for OC, sediment-associated and dissolved N in 2011 and losses for ammonium, nitrate and chemical fertilizer were not assessed

fields forms 40 % of the total annual discharge at location B in the river—the majority of discharge in the river thus being derived from the reservoir spillover. Via this reservoir overflow mechanism, 6.72 Mg of OC and 0.86 Mg of N left the catchment into the river in 2011.

Discussion

Reservoir influence on upland-lowland nutrient reallocation in irrigated watersheds

Irrigation water is an important medium for redistribution of nutrients at the watershed scale. Previous work (Slaets et al. 2015) has shown that in the same catchment, irrigation mobilized 75 % of sediment inputs into the paddy area while 25 % originated from erosion. For nutrients, the role of irrigation becomes even more pronounced: 90 % of sediment-associated OC and virtually all N, both sediment-associated and dissolved, were brought in by irrigation water while only very little was delivered by erosion (Figs. 5, 6). Substantial contributions to nutrient loads from overland flow were only made in months of high rainfall and large storms, when mobilized material was characterized by high OC to N ratios. Overland flow therefore still played a role in OC transport, but direct overland flow contributed very little to the N inputs of the rice area. The estimated sediment-associated OC contributions from irrigation are higher than the 0.03 Mg ha^{-1} found by King et al. (2009) for a study in Southern California, where regulatory programs protect the reservoir from erosive land use in the contributing area with similar elevation as our study area, showing the importance of the erodibility and land use of the surrounding landscape in irrigated settings. The results are, however, in the same order of magnitude as another study describing nutrient loads from irrigation. Schmitter et al. (2012) recorded 1.30 Mg ha^{-1} a^{-1} of OC (both sediment-associated and dissolved) and 0.72 Mg ha^{-1} a^{-1} of total N in the same study area for the two rice cropping seasons from February till October.

The OC capturing capacity of the rice fields has implications for the preservation of OC at the landscape scale in maize-rice systems. Paddies are flooded, anaerobic environments and will typically slow down breakdown of OM. This preservation could entail that erosion functions as a C sink in this type of settings. There is still much debate regarding the consequences of erosion for the carbon cycle at the global scale (Doetterl et al. 2016; Kirkels et al. 2014). Lal (2001) estimated an erosion-induced source of around 1 Pg per year, while Van Oost et al. (2007) modelled a small sink (0.7 Pg per year). Berhe et al. (2007) similarly quantified C storage due to erosion–deposition, the sink being fifteen times larger in a more disturbed watershed.

The conditions for C storage through erosion are a (partial) replacement of eroded C at the erosion site and a stabilization of deposited C in more passive pools (Berhe et al. 2007). In the maize-rice system in this study, stabilization compared to upland maize fields is probable as 88 % of OC inputs were captured by the paddies and thus deposited in a low-breakdown anaerobic environment. The vast majority of OC inputs, however, did not come from direct runoff during rainfall, but from the surface reservoir. Nadeu et al. (2012) point out the importance of sediment sources for OC cycling, as different erosion processes can result in sediments with different OC characteristics and thus different OC preservation patterns.

Dlugoß et al. (2012) and Fiener et al. (2015) additionally emphasize the importance of the magnitude and frequency of erosion events, as they found few high-intensity events result in less OC loss. Similarly in our study site, direct runoff during large rainfall events contributed very little to the paddy OC inputs, even though these events brought in substantial sediment loads (Slaets et al. 2015). As the largest OC inputs for the paddies came from the surface reservoir, there is further potential for OC burial. Jacinthe et al. (2012) reported that this could be an important mechanism for C sequestration, but methane emissions could offset the storage. Finally interactions with nutrients must be taken into account (Doetterl et al. 2016), as N inputs to these paddies are large and decomposition of organic matter can be limited if N is limiting.

While the reservoir discharged a much larger water volume to the paddies than runoff, the higher OC and N loads contribution of the reservoir is not solely related to the released water quantity. The percentage of OC and N in the sediments coming from the surface reservoir was larger than OC and N in sediments from direct overland flow. Both sources, however, receive a relatively similar quality of sediments (i.e. nutrient

content), as the drainage area to the lake consists of similar soil types and land uses to those of the 31 ha of upland area draining directly to the irrigation channel. The OC content of erosion sediments was around one-third of the OC content in irrigation water, and this difference in nutrient content was therefore caused by biogeochemical processes in the reservoir: breakdown of organic matter and nutrient mobilization in an aquatic environment contribute to the increased nutrient content of the irrigation water. Furthermore, sedimentation of the coarse, sandy material resulted in irrigation water containing fine-textured, fertile sediments higher in OC and N (Lick 1982; Yamada et al. 2015). Results from Slaets et al. (2015) on texture analysis for sediments in the same study site also demonstrated that irrigation water sediments were characterized by a finer texture (average 33 % sand, 33 % silt, 34 % clay) than those in overland flow (average 50 % sand, 30 % silt and 20 % clay).

The surface reservoir additionally buffered the seasonal changes in the quality of sediment inputs to the paddies. Brown et al. (2011) similarly found surface reservoirs to retain approximately 16 % of total N load. While OC to N ratios in sediments from overland flow increased as the rainy season progressed, and light, fertile material disappeared increasingly from the watershed, OC to N ratios of the sediments in the reservoir outflow remained more constant throughout the year. Irrigation water thus provided a constant influx of nutrient-rich sediments beneficial to the rice area, compared to overland flow. Seasonal trends were visible, however, in the plant-available N contribution of irrigation water. In the spring season, the N inputs were dominated by NH_4^+ and NO_3^-, while in the summer, during the rainy season, organic N became more important. This change shows the effect of the N inputs into the reservoir from runoff during the rainy season: runoff during the spring season might easily carry dissolved fertilizer into the reservoir, even if rainfall events are not intense enough to generate substantial erosion.

Irrigation and overland flow in the overall rice organic carbon and nitrogen budget

OC and N inputs from irrigation water were large compared to overland flow, but only part of these inputs will remain long enough on the fields to really be taken up by rice plants. A part will be lost through the quantified pathway of paddy outflow, and also through volatilization or seeping into groundwater. The question therefore remains what was the contribution of irrigation and overland flow to the overall OC and N budget of rice fields in this cascade setting. N inputs from chemical fertilizer to paddy fields vary widely, with average values ranging from 0.06 to 0.15 Mg ha^{-1} per cropping season in Asia (International Plant Nutrition Institute 2002) depending on soil types, climatic conditions, varieties and cropping intensity (Dobermann and White 1998). In Chieng Khoi, the local extension service recommended 213 kg N ha^{-1} per rice crop, thus amounting to 426 kg ha^{-1} of N over a year containing two rice crops. Inputs from irrigation water, estimated at 190 kg ha^{-1} a^{-1} of NH_4^+-N and 90 kg ha^{-1} a^{-1} of NO_3^--N, thus potentially provided a load of plant-available N equivalent to 66 % of the recommended application of nitrogen through chemical fertilizer, based on our results. As N is usually found to be more limiting than phosphorous or potassium in irrigated rice systems (Dobermann et al. 2003; Suprapti et al. 2010), the indigenous nutrient supply has a vital role in maintaining rice yields. These results underscore both the importance of upland-lowland linkages and the vulnerability of rice production and food security to changes in land use, such as deforestation, cropping systems and intensification, in the landscape as a whole. Plant-available N inputs, in the form of NH_4^+ and NO_3^-, showed seasonal trends linked to fertilization of maize on upland areas. Therefore upland-lowland linkages do not only affect spatial variability due to differential deposition of sediments (Schmitter et al. 2010) but also temporal variation. The summer crop was over-irrigated when the reservoir became full during the rainy season. While the spring crop received less irrigation water, and thus less N inputs from irrigation water, it received a larger amount of plant-available N, as the months of May and June coincide with maize cropping on upland areas. Although the majority (93 %) of sediment-associated N inputs were captured in the rice fields, a filtering effect also found by Yan et al. (2010) and Maruyama et al. (2008), the N export from paddy outflow was driven by the dissolved fraction (Figs. 6, 7). As the dissolved N exported from the paddies not only consists of inputs from irrigation water, but also from other sources such as chemical fertilizer, green manure and biological N fixation, the dissolved N in the paddy

outflow can be expected to contain a combination of these inputs. Therefore, it was not possible to quantify the proportion of dissolved N contributed by irrigation that is trapped in the rice fields. Losses, however, will also take place for chemical fertilizer, and these findings demonstrate the importance of upland-lowland linkages in mountainous irrigated watersheds, as maize fertilization on the uplands was linked to a flush of plant-available N into the rice fields. Redistribution mechanisms within watersheds therefore need to be taken into account—not only for site-specific, but also for season-specific fertilizer recommendations. Assuming losses from denitrification of 150 kg ha^{-1} a^{-1} (Yan et al. 2010), a net N plant-available capture of 130 kg ha^{-1} a^{-1} would still remain, and therefore N fertilizer application could be reduced without risking N deficiency issues. These implications are further supported by Schmitter et al. (2011), who compared fertilized and non-fertilized plots and found no significant differences in rice grain yield between the two in the same study area.

Nutrient re-allocation beyond the watershed scale

Nutrients were not only reallocated within the watershed, the irrigation system also exported nutrients out of the watershed. The main source of these losses was through the surface reservoir spillover: when the lake maximum capacity is reached, the spillover starts to function and releases excess water into the river, through which it is removed from the watershed. Both for OC and dissolved N, this release was the largest export pathway, larger than losses from overland flow or paddy outflow. For sediment-associated N, the largest loss was through irrigation water leaving the catchment via the irrigation channel. Both this water, and discharge from the spillover released to the river, were used further downstream to irrigate paddies in a lower lying catchment. Sediments in the irrigation water were characterized by a higher percentage of OC and N and a lower OC to N ratio compared to runoff, illustrating how the filtering effect of the reservoir releasing nutrient-rich sediments propagates beyond hydrological borders and benefits rice production further downstream as well. Furthermore, the combined load of dissolved N released from the watershed amounted to 13 Mg a^{-1}. Assuming a required amount of N fertilizer according to the local recommendations

of 0.43 Mg ha^{-1} a^{-1}, the load of dissolved N lost from the watershed alone could potentially provide enough N for 30 ha of paddy rice downstream, emphasizing the propagating effect of filtering elements in the landscape such as rice fields and reservoirs, also reported by Brown et al. (2011), Lassaletta et al. (2012) and Yoshinaga et al. (2007). The timing of N inputs from irrigation water depends on both upland fertilization and rainfall events. Maize is typically fertilized in June in the study area, coinciding with the highest NH_4^+ concentrations in the irrigation water, while for rice, local recommendations are a split application where the first dressing, at transplanting, contains 56 % N, 100 % P and 34 % K of the total amount of fertilizer applied in the form of NPK and Urea. Second dressing (at maximum tillering) and third dressing (at flowering) provide the remaining 22 % N and 33 % K in the form of Urea and Kali. Therefore, even though irrigation water was found to make a substantial contribution to the indigenous N supply of rice, it cannot fully replace good (and timely) fertilizer management.

If nutrients were not recycled in lower lying paddy areas but rather lost even further downstream, potential environmental impacts could affect long-term depositional water bodies such as lakes, reservoirs and oceans. While phosphorus is typically the source of eutrophication in freshwater bodies, nitrogen is frequently the eutrophication factor in coastal waters. Reservoirs are known to trap a substantial amount of the global sediment, OC and N (Beusen et al. 2016; Vörösmarty et al. 2003). Similarly, in this study, paddies were found to trap sediment-associated N, thus mitigating the increased nutrient loss resulting from the agricultural developments in the uplands. While irrigated rice thus protects lower lying areas, the filtering effect cannot fully compensate for the high runoff concentrations from permanent upland maize cultivation: Beusen et al. (2016) also reported that increased trapping by reservoirs did not compensate for increased nutrient delivery from human activities. Lakes are classified as eutrophic having concentrations of total N over 1.875 mg L^{-1} of total N. The average total N concentrations in the paddy outflow in this study were around 3 mg L^{-1}. The corresponding annual N yield of 16.85 Mg for the 13 ha rice area and 37 ha upland area combined, could thus lead to decreased oxygen levels, algal growth and loss of aquatic flora and fauna for downstream water bodies.

Implications of uncertainty for nutrient balance

Confidence intervals for OC and N load estimates were large (Tables 2, 3, 4). Considering all sources of uncertainty affecting load estimates, including spatial and temporal variability (de Vente and Poesen 2005; Mai et al. 2013), non-linearity of sediment transport processes at different scales (Schreier and Brown 2004) and controls of sediment supply, other than hydrological mobilization and carrying capacity (Gao 2008)—a very small variance would, in fact, be unexpected. In this type of study, seemingly highly accurate predictions are the ones that should invoke closer inspection as they can often be attributed to a lack of validation, an over-parameterization of the model or a too small dataset that simply did not capture the variability in the matter transport.

While the confidence intervals might seem large, especially since they are amongst the first of such results presented, overall, the biophysical interpretation and implications for plant production and sustainability in the area hold. Comparing the confidence intervals for OC and N inputs from overland flow and irrigation water, the contribution of irrigation water remains substantially larger than that of overland flow, emphasizing the dominant role of the surface reservoir in sediment redistribution. The confidence intervals for the sediment loads from irrigation water were wider than those for the load coming from overland flow, confirming that irrigation processes are driving the uncertainty in the OC and N budgets for this watershed. These results further illustrate the importance of high-temporal resolution data and uncertainty analysis, especially for implementing integrated watershed management strategies or soil and water conservation practices at the watershed level.

Conclusions

The sediment-associated organic carbon and nitrogen budget for a 13 ha paddy area in this study showed that rice fields were a net sink for sediment-associated OC and N. The paddies trapped 88 % of OC and 93 % of N, resulting in a net input of 1.09 Mg ha^{-1} a^{-1} of sediment-associated OC and 0.68 Mg ha^{-1} a^{-1} of sediment-associated N. Irrigation water was the dominant driving force of nutrient reallocation within the watershed, contributing 90 % of OC inputs and virtually all N inputs, and provided an additional 0.43 Mg ha^{-1} a^{-1} of N in the dissolved fraction. NH_4^+ and NO_3^- analysis showed that 24 % of the combined sediment-associated and dissolved N input into the paddies was potentially plant-available, and therefore irrigation water contributed a substantial amount of plant-available N to the rice, amounting to 66 % of the recommended application of chemical fertilizer over the whole vegetation period. The higher percentage of OC and N in sediments in irrigation water, as well as the lower OC to N ratios demonstrated the buffering effect of the surface reservoir on sediment-associated nutrient transport in the watershed. As the sediments in the irrigation water stem from the same erosion processes and from similar sediment sources, the difference in quality between irrigation water and overland flow was attributed to the reservoir capturing coarse, unfertile material and slowly releasing nutrients both to the rice fields within the watershed and, via paddy outflow and the reservoir spillover, to downstream areas as well.

The contribution of irrigation water to the plant-available N inputs highlights the importance of quantifying upland-lowland linkages of maize-rice cropping systems, which are very common throughout montane Southeast Asia. Currently, erosion due to unsustainable maize monocropping on the upland fields results not only in a loss of soil fertility in situ, but also in an influx of nutrients to paddy fields. A permanent loss of nutrients from the uplands, for example by removal of the fertile topsoil, would therefore not only result in a loss of income due to a declining yield of the cash crop maize, it would also entail a loss of nutrient inputs to the paddies, associated with a decline of nutrient content of the sediments in the irrigation water. Such upland-lowland linkages demonstrate the vulnerability of rice yields to landscape level nutrient reallocation processes. Surface reservoirs help mitigate these consequences with their filtering capacity, but eventually, only sustainable land use practices can ensure continued food security in these cropping systems.

Appendix: Bootstrap estimates and confidence intervals for sediment loads

Calculating a measure of uncertainty on this sediment load is not trivial. The final value is a sum of instantaneous loads, and those loads are the product of two predicted values, concentration and discharge, which are not independent of each other, as discharge is a predictor variable for concentration. Additionally, the predicted values are on the transformed scale, and there is serial correlation in the sediment concentration data, as samples are taken closely together in time.

In order to calculate 95% confidence intervals on the sediment loads, a bootstrap method was developed that addresses all of these issues (Slaets et al. in revision). The bootstrap is a Monte Carlo-type method that generates the sampling distribution of a statistic by resampling a large number of times, either from the original observations or from a parametric distribution, to obtain new bootstrap datasets, on each of which the sediment load is calculated. This large number of bootstrap sediment loads provides an empirical distribution, which can be used to estimate the 2.5th and 97.5th percentiles. These percentiles are the limits of the 95% confidence interval (Efron and Tibshirani 1993). In our dataset, 2000 bootstrap replicates resulted in smooth histograms and reproducible percentiles. The developed method thus accounts for uncertainty in the parameter estimates of both the discharge and sediment rating curves, and uncertainty due to residual scatter in the sediment concentrations. In this approach, the final bootstrap process consists of three steps:

(1) Non-parametric bootstrapping of the (stage, discharge) pairs in order to obtain 2000 bootstrap stage-discharge equations, and thus 2000 time series predictions for bootstrapped discharge;

(2) Non-parametric bootstrapping of the sediment concentration dataset, by drawing whole events (to keep the serial correlation intact) and individual base-flow samples, resulting in 2000 bootstrap sediment rating curves, and thus

2000 time series predictions of continuous suspended sediment concentration;

(3) Adding a simulated error term to the concentration predictions to account for inherent residual scatter in the data and to facilitate the back-transformation from the log-scale.

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