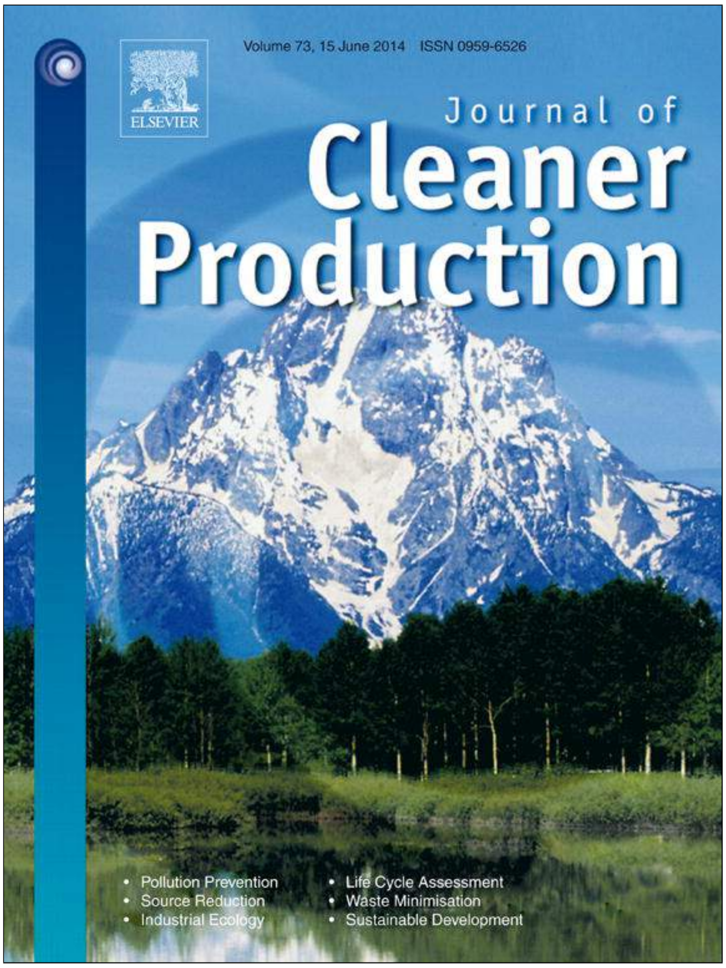

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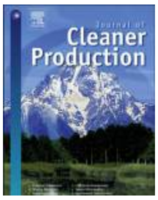

Eco-efficiency of paddy rice production in Northeastern Thailand: a comparison of rain-fed and irrigated cropping systems

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ABSTRACT

Northeastern Thailand is an essential production area for high-quality fragrant rice for both domestic use and export. While rain-fed conditions still largely prevail, plans to extend irrigation are being drafted. This paper compares the advantages of rice production under irrigation and rain-fed conditions in both environmental and economic terms. Indicators of techno-economic performances were combined with environmental impact indicators based upon life cycle assessment, energy and water use analyses. Data were collected in 2010 at the farm level in 43 households of Lam Sieo Yai Basin in North-Eastern Thailand, according to 3 cropping systems, namely wet-season rain-fed (Rw), wet-season irrigated (Iw) and dry-season irrigated (Id) systems. Eco-efficiency indicators were calculated as per impact category. Wide-ranging techno-economic performances and environmental impacts were observed, while cropping practices were found to be homogeneous. Differentiation of systems originated mostly from differences in yield, which were mostly impacted by water supply. Yields vary from 2625 kg/ha in the Iw system to 2375 in the Rw system and 2188 in the Id system. The results highlight the low performances of Id systems in both techno-economic and environmental terms. Id systems require mostly blue water, while the two other systems rely primarily on green water. Id systems also require more energy and labour, due to increased water management needs. Overall, the productivity of most production factors was found to be higher in Rw and Iw systems; this results in return on investment being slightly higher in the Iw system compared to the Rw system (0.12 kg/THB and 0.11 kg/THB, respectively) and is lowest in the Id system (0.1 kg/THB) where THB is Thai baht, currency of Thailand. In Id systems, farmers need to produce twice as much rice (0.41 kg) to obtain 1 THB of net income, compared to 0.23 and 0.25 kg for Iw and Rw respectively. Emissions proved relatively similar across all 3 systems, with the exception of CH_4, which was markedly lower in Rw systems due to specific water and organic residue management. Id systems systematically emitted more nitrates, phosphates and pesticides into water sources. Rw systems showed the lowest environmental impacts per ha and per kg of paddy rice produced. GWP_{100} was higher in Id systems (5.55 kg CO_2-eq per kg of rice) compared to Iw (4.87) and Rw (2.97). Finally, Rw systems were found to be more eco-efficient in most impact categories, including Global Warming Potential. The total value product per kg of CO_2-eq emitted is 4, 2.5 and 2.2 THB in Rw, Iw, and Id systems respectively. This paper further discusses the results in view of contrasting perspectives, including societal objectives, farmer income and environmental integrity, and possible irrigation development in Northeastern Thailand.

1. Introduction

1.1. Rice, poverty, and the environment

Rice (*Oryza sativa* L.) feeds more than 3 billion people globally. Approximately 75% of the 150 million ha harvested worldwide are irrigated and provide food, income, and a diversity of ecosystem goods and services (Bouman et al., 2007a, 2007b), yet they also have negative impacts on the environment (Roger and Joulian, 1998; Tilman et al., 2001; Wenjun et al., 2006). Rice production

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requires large amounts of resources (water, land, energy, and chemicals), and contributes to pollution in all environmental compartments, including water and the atmosphere, due to quasi-permanently flooded (ponding) conditions. Flooded rice grows under anaerobic conditions, which favour methane formation and release. Approximately 120 g of CH_4 are released into the atmosphere for each kg of rice produced; overall, the world's rice cropping under flooded conditions contributes 13% of all anthropogenic CH_4 emissions (IPCC, 2006).

Thailand is the world's 6th largest rice producer and largest exporter. In recent years, annual paddy output has been approximately 30 Mt, with a third being exported. Rice is grown on some 10 million ha of land (or 20% of the country), with more than half grown in the Northeastern region (Isaan), the poorest region of the country. Approximately 9% of Thailand's population still lives under the poverty line; most of this population consists of subsistence-oriented, seasonal rice growers in the Isaan who sell production surplus and rely on multiple income sources for their livelihoods. Also, increasing scarcity of farm labour afflicts the region (ADB, 2012).

As a consequence, any attempt to reduce the environmental impact of rice production (through input reduction or alternative water management) or to develop irrigation should take into account the consequences with respect to economic performances such as changing yields, changing farmer income and higher labour requirements. In addition, in view of plans to extend irrigation in Isaan (Molle and Floch, 2008), there is a need to assess the comparative advantages of controlled irrigation vs. rain-fed cropping (uncontrolled irrigation during the wet season) in both environmental and economic terms.

Rice production in Isaan is currently mostly lowland rain-fed (85% of paddy land area, only in the wet season) and irrigated (15% of paddy land cover during the wet season; only 7.5% during the dry season), and shows low yields of high-quality, high-value varieties (Jasmine fragrant rice for domestic use and export). Northeastern Thailand produces approximately 80% of all jasmine fragrant rice produced nationwide (variety Hom Mali).

Rice production systems contribute 80% of freshwater extractions in Thailand, and pesticide-related toxicity is becoming a major concern. In Thailand, each ha of paddy fields requires approximately 10,000 m^3 of water per season; each kg of paddy rice produced requires 2–3 m^3 of irrigation water, depending on the season (Rahatwal, 2010). Significant increases in rice production through irrigation expansion in the Isaan region can only be achieved through further exploitation of the Mekong and its tributaries and wetlands, incurring the need for massive infrastructures for water diversion and potentially the destruction of natural ecosystems and harmful environmental impacts. There is currently tremendous pressure on Thailand's water resources; the country enjoys high per-capita water availability, but it ranks 14th in the world in organic water pollution and eutrophication (World Bank, 2006). One third of Thailand's surface water bodies are considered to be of poor quality; it is estimated that water pollution costs the country 1.6 to 2.6 per cent of GDP per year (World Bank, 2006). To redress these issues, Thailand has set up ambitious plans geared towards environmental protection, including climate change mitigation measures in agriculture (Office of Environmental Policy and Planning, 2000).

1.2. Eco-efficiency as a metric of sustainability

The rice-environment-poverty nexus described above relates to the sustainability of rice farms and to the possibility of reducing the environmental impact and resource use of rice cropping systems while sustaining the yields and income of farmers and the country's position as a top producer and exporter. A workable approach to sustainability at the farm level consists in evaluating whether producers are making efficient use of resources and minimising environmental impacts while achieving their economic objectives. To that aim, economic-ecological efficiency, known as eco-efficiency (EE), may be a useful operational concept. This concept emerged in the 1990s to allow for a practical approach to sustainability (Schaltegger, 1996; Tyteca, 1996; OECD, 1998; Schaltegger and Synnestvedt, 2002; Bleischwitz, 2003). EE expresses how efficient an economic activity is with regard to its impact upon nature. EE is represented by the ratio “Product or service value/Environmental influence” (OECD, 1998). The concept of eco-efficiency has proven to be a practical tool for enhancing both economic and environmental benefits. To date, it has had a focus on resource use vs. broad economic outputs (e.g., energy use vs. GDP or turn-over), and eco-efficiency has yet to fully develop at the micro level and in the agricultural sector and to consider the diversity of environmental impacts.

1.3. Approaches to economic and environmental performances

Assessing eco-efficiency requires indicators of both economic and environmental performances. Techno-economic assessment of irrigation systems and farms has long been performed. Crop budgeting, resource use analysis, productivity analysis, and farm economic assessment typically result in indicators that reflect water supply performance (Gonzales, 2000; Edkins, 2006), agricultural production performance, and the economic efficiency (productivity) of production factors such as labour, land, water, and other inputs (Ali and Talukder, 2008; Le Grusse et al., 2009; Speelman et al., 2011).

Environmental impact assessment at the same level (farm or cropping system) is much more recent. Among other methodologies, life cycle assessment (LCA) has long been identified as a potential contributor to eco-efficiency analysis (Tyteca, 1996), including in agriculture (Van der Werf and Petit, 2002). LCA application in agriculture has developed over the last 15 years (Audsley et al., 1997) and addressed most agricultural commodities (e.g., Williams et al., 2005). Yet, paradoxically, rice, as a crucial global commodity, has rarely been studied. To date, there is abundant literature on the assessment of greenhouse gas (GHG) emissions from irrigated paddy fields (as reviewed by Blengini and Busto, 2009). Few studies have applied LCA for assessing environmental impacts of rice production in Asia. Most published research essentially focused on GHG and global warming potential (in Japan, Harada et al., 2007; Hokazono et al., 2009), on organic farming of rice (in Japan, Hokazono and Hayashi, 2012), and on weighting and normalization of results (in China, Wang et al., 2010). To the authors' knowledge, there are only three comprehensive published applications of LCA to rice (in Italy, Blengini and Busto, 2009; in China, Wang et al., 2010; in Japan, Hokazono and Hayashi, 2012). Basset-Mens et al. (2010) assessed the scarce rice LCA literature and highlighted the overall paucity and limitations, including a lack of consideration of the actual diversity of field and farm situations and of water and energy use. Until recently, water in LCA was only considered a qualitative compartment susceptible of being impacted upon. New methodologies on water resource depletion in LCA have been extensively investigated recently, with important breakthroughs that suggest using partial water footprinting approach (Mila i Canals, 2009; Pfister et al., 2009). However, empirical validation and local case studies are still lacking. Actual water consumption in agricultural systems is seldom known in developing, gravity-based conditions. Crop water requirements (CWR) and irrigation water requirements (IWR, blue water), both modelled from soil, crop and climate data, are usually used as proxies (Allen et al., 1998). The use of recent versions of FAO's CropWat (Mom, 2007; Chapagain and Hoekstra, 2011), coupled with water balance modelling in ponding conditions (Rahatwal, 2010), shows potential.

To date, only a few research works have mobilised LCA results in eco-efficiency analysis in agriculture (in Canada: Pelletier and Tyedmers, 2008; in New Zealand: Basset-Mens et al., 2009); however, these studies used modelling or scenario-based approaches and did not investigate the diversity of actual cropping systems. To the author's knowledge, no LCA-based eco-efficiency research exists in tropical agriculture under developing conditions or in rice production.

1.4. Research objectives

Given the importance of the rice sector in Thailand and growing concerns about its sustainability, environmental impacts and the embedded poverty of its farmers, this research aims at assessing the eco-efficiency of rice cropping systems in Northeastern Thailand as a main production area. In view of the currently prevailing rain-fed conditions and of existing plans to extend irrigation in Isaan, the research also compares the advantages of rice production under controlled irrigation and rain-fed conditions in both environmental and economic terms.

2. Materials and methods

2.1. Study area description

Lam Sieo Yai basin is located at the heart of the Isaan plateau in Northeastern Thailand (Fig. 1) with an elevation that ranges between 100 and 200 m above sea level. It overlaps with three different provinces (Mahasarakam, Roi Et, Sisaket), and 7 districts of Northeastern Thailand, which are among the poorest of Thailand. Its area is 2875 km^2. The Sieo Yai River is the main river of Lam Sieo Yai basin. It joins the Mun river, then ultimately flows into the Mekong River. The area is exposed to a tropical savanna climate. Its average annual temperature is 18 °C. As shown in Tables 1 and 2, the area is exposed to two contrasted seasons: the dry season between November and April, which commonly includes severe drought conditions, and the monsoon-affected wet season between May and October, which features floods on occasions. Also, the period between December and February is significantly cooler. Annual rainfall amounts to approximately 900 mm on average yet with high inter-annual variability.

Table 1
Rainfall depth in Lam Sieo Yai basin; 30-year averages (1981–2010), and figures of 2010.

Period	Rainfall depth (mm)	
	Average 30 years	2010
Yearly	885.7	1218.93
Wet-season (July–October)	707.7	895.98
Dry-season (February–May)	117.2	191.55

In the Lam Sieo Yai basin, 83% of the total area is agricultural land, of which 96% is covered with paddy fields (Fig. 1). In the basin, 75% of paddy fields fall under the Sieo Yai Irrigation Project and benefit from controlled water supply. The other 25% are rain-fed paddy fields of individual farmers. Lowland rain-fed rice is grown only during the wet season, while irrigated rice may be cultivated during both seasons. However, approximately only half of irrigated land is cropped during the dry season, due to uncertain water supply. Rain-fed conditions refer to conditions of lowland rice that is cropped under flooding conditions with no control of water

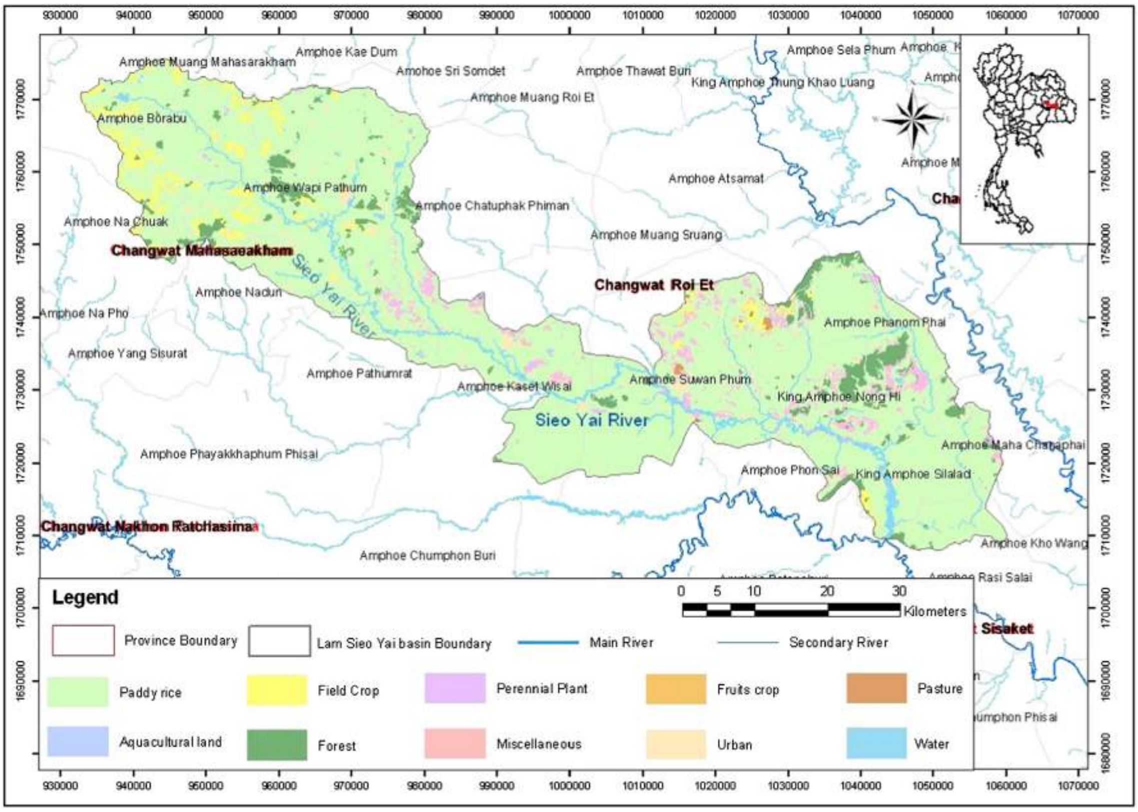

Fig. 1. Map of the Lam Sieo Yai basin; location and land use (Northeast of Thailand).

Table 2
Average monthly rainfall (mm) in Lam Sieo Yai Basin (30-year average, 1981–2010).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly rainfall (mm)	10	2.3	18.5	16.4	80	43.4	142.1	202.9	259.7	103	5.4	2

supply. Rainfall, soil moisture, and natural runoff alone (green water) provide water to the paddy fields. Fig. 2 shows a simplified sketch of water flows in a paddy field. In Fig. 2, the outflow (drainage) is hardly happening because farmers let the water evapo-transpirate and percolate well before the end of the cycle, and usually do not have to pump water off the fields.

2.2. Joint LCA and techno-economic analyses

2.2.1. General approach

The research collected, analysed and combined indicators of techno-economic performances (rice production, costs, and product value) with environmental impact indicators based upon the life cycle approach. Both approaches apply at the same plot level (cropping system level) and complement each other. Techno-economic analysis typically results in monetary values as per factor of production (e.g. labour, land, agro-chemicals) while LCA expresses environmental impacts as per selected functional units (in this case: mass of product and area of land used). The research reported here is problem-oriented; it focuses on midpoint indicators for different environmental impact categories (e.g., global warming potential, eutrophication, or acidification) and resource use (land, water and energy). Overall, the chosen approach is of an accounting nature (as opposed to process change purpose, which would require technological scenarios). The performed LCA is therefore attributional and static. The primary functional unit (FU) for LCA is the mass (1 kg) of raw paddy rice (unmilled) at the farm gate (approximately 15% humidity content). The secondary FU is 1 ha of land used for the production of raw paddy rice (unmilled) at the farm gate. A third "hidden" FU is 1 dollar of profit earned by the farmer, because eco-efficiency is a ratio that expresses how many dollars are made as per impact, which is the reverse ratio of impact as per dollar made, as expressed in LCA. Total value product (or gross income, i.e. market price of product multiplied by mass of product) has been used to represent the total economic value of the product.

All data were collected, calculated or modelled in diverse typical rice farming situations of the Lam Sieo Yai basin in Northeastern Thailand. LCA and economic results were finally used to calculate eco-efficiency indicators as per impact category.

2.2.2. Systems, and systems' boundaries

Three cropping systems were investigated based upon water management system: wet-season rain-fed rice (Rw), wet-season irrigated rice (Iw) and dry-season irrigated rice (Id). Although the traditional transplanting of sprouts from nursery to paddy field may still be observed, the direct sowing of dry seeds has recently become overwhelmingly predominant in Northeastern Thailand. Seventy-five per cent of farms have adopted the technology of dry-seed sowing, which spares time and labour but results in lower yields as shown in Table 3. The results presented here refer to this planting mode, which was carried out in each water management system. Two fragrant rice varieties are chiefly cultivated in Northeastern Thailand: Kao Dok Mali 105 (during the wet season) and RD15 (during the dry season).

Primary data were collected by means of field observations and interviews with farmers; data refer to the two cropping seasons of 2010, including dry and wet seasons. Table 1 shows the precipitation conditions that prevailed during these seasons compared to long-term averages; it highlights the fact that 2010 received more precipitation than 30-year averages, on both a yearly basis and a per-season basis. Thirty farm plots were selected and studied for wet-season rain-fed and irrigated rice systems (15 plots each) and 13 farm plots for dry-season irrigated rice system, based upon local experts' recommendations. Sampling was both purposive and random, since farms were selected randomly among a large number of farms identified by local experts within the three main known cropping systems. Therefore, the selected farms are deemed to represent the common farming situations found in Sam Lieo Yai basin. Sub sample sizes ultimately differ (15, 15, 13, respectively) owing to data quality issues in some farms, which had to be ultimately discarded from analysis. Both environmental impact analysis and techno-economic analysis were performed on all 43 cropping systems.

Results are reported as median values, with minimum and maximum values. The reasons for this are manifold: most underlying biophysical processes leading to agricultural performances and environmental impacts are not linear; the calculations leading to the assessment of direct field emissions and environmental impacts are not of a linear nature either as a result of threshold effects due to discrete scaling factors related to crop and water management practices; and consequently, the results do not follow normal distributions (e.g. in Figs. 4 and 5).

Although LCA conceptually covers the whole life cycle of a product or service, the present study covered the rice production systems from "cradle" (mobilisation of all raw resources and

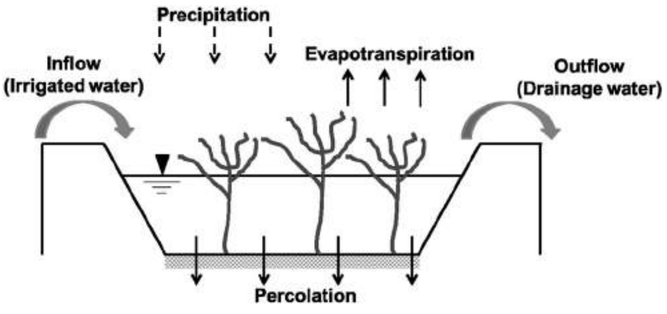

Fig. 2. A representation of water flows in a paddy field.

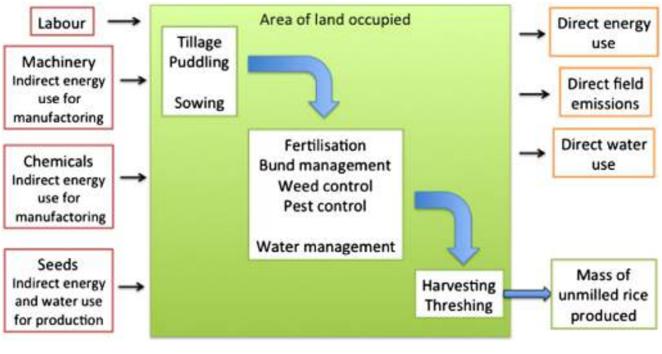

Fig. 3. Flow diagram for the studied rice cropping systems.

Table 3
Average yield (kg/ha) of Lam Sieo Yai basin.

Method to grow Hom Mali rice	Yield (kg/ha)		
	Irrigated		Rainfed
	Dry season	Wet season	Wet season
Sowing by dry seeded	2219	2656	2363
Sowing by wet seeded	2625	3000	2813
Transplanting (Nursery)	2988	3188	3019

equipment) to farm-gate (unmilled rice); we did not consider further rice processing, storage, transport, packaging, consumption, or other aspects (as shown in Fig. 3). This choice was justified by the fact that approximately 60–90% of global warming impact of rice relates to production at field level (Harada et al., 2007; Hokazono et al., 2009); furthermore, Blengini and Busto (2009) found that most other environmental impacts are predominantly generated at the farm level. The flow diagram of the studied systems is shown in Fig. 3, which describes the sequence of typical operations in rice cropping systems of Northeastern Thailand. In Fig. 3, the flows related to machinery and equipment include those resulting from manufacturing, transportation and direct use (fuel consumption). Flows related to seeds and chemicals refer to flows resulting from production and transportation. Human labour is considered only in techno-economic calculations. Rice growers rely mostly on family labour. Labour requirements have significantly reduced because harvesting is mostly mechanized nowadays, and direct-seedling – instead of labour-consuming transplanting- now prevails. In any case, all labour requirements have been monetized at market price for calculations.

2.2.3. Joint inventories

The common technical data and specific data needed for LCI and economic analyses for the main stages of rice production (land preparation and sowing, rice cultivation and field operations, harvesting) are presented in Table 4.

2.2.3.1. Inventory of field operations and performances. The inventory data required to perform both techno-economic analysis and environmental impact assessment comprise the following processes and operations:

- Field operations with machinery (ploughing, puddling-rolling, combine harvesting); data collected include type, weight, scheduling, use time, use costs, and labour requirements,

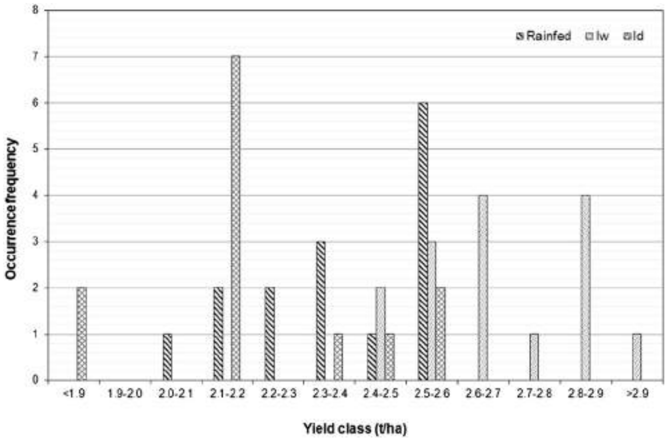

Fig. 4. Paddy rice yields recorded among the 43 rice cropping systems in 2010 (Rainfed, Iw: Irrigated wet season; Id: Irrigated dry season).

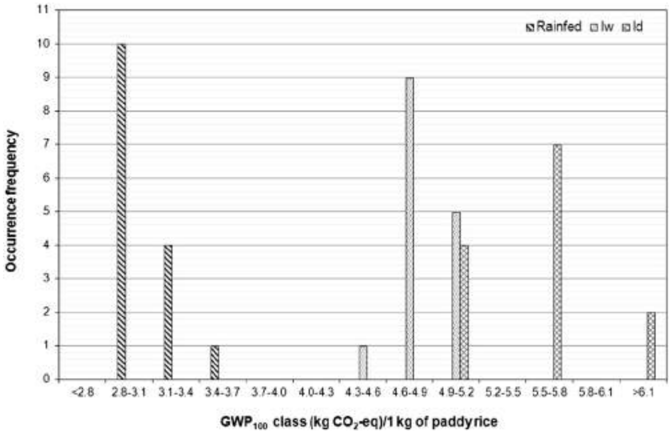

Fig. 5. Global warming potential over 100 years (GWP$_{100}$) per kg of paddy rice produced calculated for the 43 rice cropping systems (wet and dry seasons 2010) (Rainfed, Iw: Irrigated wet season; Id: Irrigated dry season).

- Field operations performed manually (sowing, fertiliser application, bund maintenance, water management, spraying); pesticide-spraying is performed manually with portable equipment; water management at the plot level requires portable water pumps; bund maintenance involves grass-cutting with portable equipment; data collected include type (chemical and equipment if any), capital value, scheduling, use time, use costs, and labour requirements,
- Inputs and agro-chemical use (seeds, urea, 15-15-15, 16-16-8, glyphosate, $CaCO_3$, isoprocarb, metaldehyde); data collected include type (commercial name, brand), cost, doses, scheduling of application, labour requirements,
- Yields and market price at the farm gate; in 2010, the farm gate price of paddy rice was 12,000 THB per metric ton, guaranteed and subsidized by Government, for both dry and wet seasons,
- Local price of seeds and retail white rice; the income generated by paddy production was not calculated from yields only, because farmers keep some paddy rice for self-consumption (2% on average) and seeds for the next season (approximately 9%); therefore farmers' income includes the costs avoided by self-consumption (not buying white rice instead) and by self-production of seeds (not buying seeds for next season); these were factors in all economic calculations, using local market price of seeds (28 THB/kg) and of retail white rice (30 THB/kg).
- Cultivation and harvested areas.

These data were collected through detailed questionnaires and farmer interviews at the farm level (related to a given plot under study) during the 2010 cropping seasons.

Under inundated paddy field conditions, it proves impossible to measure directly real consumptions at field level; also, losses incurred at both plot and conveyance system levels are not measurable. As a consequence, water use was first modelled with CropWat (FAO, 1992), based on the concepts of climatic demand and crop evapotranspiration. Since the whole of Lam Sieo Yai basin is under the same climatic station, hence the same available data, crop water requirements (CWR = blue water + green water) and irrigation water requirements (IWR = blue water) calculated in mm (=0.001 cubic meter per square meter) are the same between systems in any given season. There are only differences between dry and wet season. Second, we had to further analyse water use with *ad-hoc* water balance to take account of specific traits of paddy fields (i.e. quasi-permanent ponding conditions, deep and lateral infiltrations, direct evaporation). Also, losses incurred at system

Table 4
Type and source of data needed for LCI and economic analyses.

	Areas of inventory	Data sources	Unit
Technical data	Input use (seeds, chemicals)	Primary data (farm level)	Kg or g
	Direct energy consumption (machinery, portable equipment)	Primary data (farm level)	MJ
	Water consumption	Modeling from IWR (Water balance model and CropWat)	m^3
	Yield	Primary data (farm level)	kg/ha
	Land use	Primary data (farm level)	ha/production cycle
LCI	Indirect energy consumption (from manufacturing and transport of machinery and chemicals)	Ecoinvent database (in SimaPro)	MJ
	Direct field emissions	Modelling (secondary data IPCC and tier-2 references)	Kg substance per kg of paddy rice
Economic data	Production costs (labour, chemicals, machinery, energy)	Primary data (farm level)	Thai Baht
	Economic value (total value product)	Primary data (market price at farm gate)	Thai Baht
	Labour	Primary data (farm level)	h

Note: only technical data are common to both LCI and economic analysis.

level were modelled. Finally, marginal additional uses such as mixing and dilution of agrochemicals were included as blue water components. Results on IWR were ultimately cross-checked with observations on water pumping practices and specs, and water levels, and proved consistent.

The inventory for the manufacturing and delivery of machinery and agrochemicals equipment, machinery, inputs and energy carriers used during field operations were calculated with SimaPro 7.3.2 from field data and based upon existing conversion rates, methods, and databases (Ecoinvent database).

2.2.3.2. Direct field emissions. The following emissions to air were considered: CH_4, N_2O, NOx, and NH_3. These emissions were modelled based upon the norms established by the International Panel on Climate Change (IPCC, 2006), adjusted with secondary, region-relevant information (Yan et al., 2003a, 2003b). Carbon dioxide was considered neutral (Williams et al., 2005).

IPCC (2006) proposes a model for calculating daily emissions, based upon a baseline emission factor EF_c (Equation (1)).

$$EF_i = EF_C \cdot SF_w \cdot SF_p \cdot SF_0 \cdot SF_{s,r} \tag{1}$$

where:

EF_i = adjusted daily emission factor for a particular harvested area, kg-CH_4.ha^{-1}.d^{-1}
EF_C = baseline emission factor for continuously flooded fields without organic amendments
SF_w = scaling factor to account for the differences in water regime during the cultivation period
SF_p = scaling factor to account for the differences in water regime in the pre-season before the cultivation period
SF_0 = scaling factor should vary for both type and amount of organic amendment applied
$SF_{s,r}$ = scaling factor for soil type, rice cultivar, etc., if available

EF_c refers to the following conditions in a given cropping situation:

- Non-flooded pre-season has been less than 180 days prior to rice cultivation (or field is replanted within less than 180 days after previous flooded cropping; such situation actually refers to double – or multiple- cropping conditions);
- Continuous flooding during rice cultivation;
- No organic fertilization or organic residue incorporation.

The IPCC (2006) suggests a default average baseline emission (EF_c) of 1.30 kg-CH_4.ha^{-1}.d^{-1} (with high variation). Our calculations rather followed Yan et al. (2003a) who recommend $EF_c = 3.12$ kg-CH_4.ha^{-1}.d^{-1} as the baseline emission factor based upon direct field measurements in Northeastern Thailand, where specific conditions prevail (high soil, air and water temperatures and high solar radiation, which have been shown to be determining factors of increased CH_4 emissions). All scaling factors affecting EF_c were taken from IPCC (2006) according to observed local crop and water management practices: rain-fed conditions (uncontrolled, intermittent flooding with multiple aeration phases; non-flooded pre-season of more than 180 days; straw incorporated in the ground more than 30 days before cultivation), and irrigation (with multiple aeration phases; non-flooded pre-season of less than 180 days; straw incorporated in the ground less than 30 days before cultivation).

SF_o is the scaling factor reflecting both type and amount of organic matter applied. Equation (2) determines SF_o (IPCC, 2006).

$$SF_0 = \left(1 + \sum_i ROA_i \cdot CFOA_i\right)^{0.59} \tag{2}$$

where:

SF_0 = scaling factor for both type and amount of organic amendment applied
ROA_i = application rate of organic amendment *i*, in dry weight for rice straw (in ton.ha^{-1})
$CFOA_i$ = conversion factor for organic amendment *i* (in terms of its relative effect with respect to straw applied shortly before cultivation) (IPCC, 2006)

With regards to common practices in the study areas, organic amendments include only rice straw and rooting systems that remain after harvesting. The literature commonly considers a dry grain/dry straw ratio of 1:1. According to average grain yields in recent years in the study area, it was assumed that 2.5 tons of dry straw were incorporated per ha as organic fertiliser (as *ROAi*). Subsequently, the scaling factors that were used are:

- *SFw*: 0.52 in all systems;
- *SFp*: 0.68 in Rw; 1 in Iw and Id;
- *CFOAi*: 0.29 in Rw; 1 in Iw and Id
- *ROAi*: 2.5 ton/ha
- Hence *SFo*: 1.4 in Rw; 2.1 in Iw and Id

According to these conditions and relative scaling factors, the application of the IPCC's CH_4 emission model results in adjusted daily emission factors *EFi* of 1.522 kg-CH_4.ha^{-1}.d^{-1} in rain-fed conditions and 3.397 kg-CH_4.ha^{-1}.d^{-1} under irrigation conditions (for both dry and wet seasons). The observed average length of cropping cycles is 120 days, from sowing to harvesting. It is very homogenous, although dictated by rice ecophysiology and climatic conditions, and also by the availability of harvesting equipment (combine harvester), which is rented to local entrepreneurs (combine harvesters).

Because flooded conditions are unfavourable to nitrification, N_2O and NO_x emissions to air have long been assumed to be negligible in paddy rice production. Yan et al. (2003b) reviewed literature with measurements of N_2O and NO_x emissions from continuously flooded paddy fields and proposed emission models that included both baseline and fertiliser-dependent emissions and were specific to paddy rice produced in South Asia but not Thailand. These models were adjusted to the lengths of cropping seasons in each sampled case (average: 120 days); however, these models failed to consider intermittent flooding conditions with drying periods during which more active nitrification-denitrification occurs, most likely leading to higher N_2O and NO_x emissions.

Yan et al. (2003b) focused their literature analysis on urea-induced NH_3 emissions because urea is the most common chemical fertiliser used by farmers in South and South East Asia (urea and ammonium-based fertilisers form approximately 85% of all nitrogen fertilisers applied to paddy fields in Northeastern Thailand). They proposed a model of urea-induced NH_3 emissions that depends upon the timing and mode of application, which, in turn, have a strong influence on the volatilisation rate. In spite of a paucity of data, the same authors also proposed NH_3 emission factors for other nitrogen-based fertilisers. These models were used, with adjustment to a 120-day cropping season.

Water-soluble nitrates and phosphates have been considered to be the two potential pollutants emitted to the water compartments during rice cropping. A similar approach was carried out for both of these pollutants. Paddy rice consumes significantly more ammonia than nitrates, in contrast to other global crops. Because urea and ammonium-based fertilisers prevail in Northeastern Thailand, direct nitrate emissions result mostly from biochemical transformations (e.g., nitrification) and the whole nitrogen cycle and balance rather than from direct fertiliser loss. The principles underlying the nitrate emission assessment are that (1) nitrates form the remaining components of the overall nitrogen mass balance, the other components of which were determined in earlier sections; (2) these water-soluble nitrates may leach to the water compartment through surface drainage and deep percolation; and (3) such a portion refers to the ratio between water that is not used by the crop and overall water supply; in other words, it relates to water use efficiency.

Accordingly, nitrates potentially leaching from a paddy field are modelled according to a dual N and water mass balance approach suggested by Pathak et al. (2004). N inputs include fertiliser, precipitation, irrigation water and soil (N stock, immobilisation). N outputs include losses in surface runoff, deep percolation, harvested and exported crop components (mostly rice grain), soil losses (erosion), mineralisation, volatilisation and nitrification processes. The difference in N stored in pre-cultivation soil and in post-cultivation soil is considered negligible because these soils have maintained long-term stable nitrogen contents under the same cropping systems for years. Similarly, the organic matter dynamic is deemed balanced over time, with equal mineralisation and immobilisation (straw). Other components, such as biological nitrogen fixation, groundwater contribution, and exports by weeds, are ignored (Pathak et al., 2004).

All components of N balance therefore are known, assumed or neglected, with the exception of N losses to deep percolation and surface drainage as water-soluble nitrates. N inputs from fertiliser have been calculated from the fertilisers' formulae and application doses. N inputs from rainfall and irrigation water were calculated from data on N contents, average precipitation and irrigation data over the period under consideration (cropping cycle). Using data from the Pollution Control Department of Thailand (PCD) and from the Royal Irrigation Department of Thailand (RID), we calculated and used an average NO^{-}_3 concentration of 0.7 $mg.l^{-1}$ in precipitation, and 0.11 $mg.l^{-1}$ in irrigation water. Rainfall data from the Thailand Meteorological Department rainfall stations located in the study area were used (as shown in Table 3).

N uptake from rice plants was calculated from the average N contents of the average mass of exported crop parts (grain and ears). N losses due to emissions to the air in the form of N_2O, NO and NH_3 were calculated as shown in previous sections. N_2 is emitted during the last phases of denitrification. Although not a pollutant, N_2 needs to be assessed to complete the whole mass balance. Brentrup et al. (2000) proposed an emission factor of 9% of all N fertilisation. Although their emission factor corresponded to annual crop conditions under temperate climate, it was used in this study, in the absence of more adapted data.

It was assumed that the remaining components of nitrogen mass balance were nitrates. Water-soluble nitrates may be either absorbed by the crop through evapotranspiration flux or emitted to the water compartment as pollutants via deep percolation and drainage. Following Pathak et al. (2004), it was also assumed that the proportion of nitrates bound to drain or leach to the surface and groundwater compartments during the crop cycle equalled the proportion of water that was unused by crops in the paddy system. Therefore, a water mass balance was needed to ascertain water use efficiency and to determine percolation and drainage components. Runoff was considered nil because in common conditions, paddy fields are flat and managed in a way that prevents water from spilling over bunds; farmers maintain water depth between defined minimal and maximal ponding conditions (generally 0–150 mm). However, at times, and especially at the end of the cropping season, farmers drain the fields off.

Average monthly rainfall data (as shown in Tables 1–2) and reference evapotranspiration data provided by meteorological services were used, as well as typical irrigation data collected in the study area. Crop coefficients (Kc) are required to assess actual evapotranspiration and were drawn from FAO and from local references by the RID. Kc are linked to four crop growth stages, which are initial, development, mid-season and ripening stages. The CropWat platform (FAO, 1992) was used to calculate actual evapotranspiration.

A similar approach was applied to phosphates, under similar assumptions regarding the stability of P contents in the long term, the absence of erosion, and with similar modelling approach (water mass balance). P inputs from fertiliser were calculated from fertiliser formulae and application doses. According to the PCD, the average value of P concentration in precipitation in Thailand is 0.045 $mg.l^{-1}$; according to the RID, the average P concentration in irrigation water in Thailand is 0.125 $mg.l^{-1}$.

In the cropping systems under study, the pesticides typically used include a molluscicide (solid pellets, metaldehyde-based), an insecticide (liquid, isoprocarb-based with $CaCO_3$ as humectant additive) and an herbicide (liquid, glyphosate-based); all are hand-sprayed at different stages while the field is flooded most of the time. It was assumed that 100% of pesticides ultimately end up in both soil and water compartments because none of the pesticide is supposed to concentrate in the rice grain and leave the field at harvest. Straw and rooting systems are left in the field to decay. Under these circumstances, it was arbitrarily decided to split emissions equally between soil and water compartments (50%–50%).

2.2.4. LC impact and eco-efficiency assessment

Impact assessment is the third stage of LCA. Because there is still no consensus on weighting, impact assessment was focused on characterisation, as suggested by Blengini and Busto (2009). The selected indicators include resource-use indicators: energy use (EU), freshwater use (WU) and land use (LU); they also include environmental impact (mid-point) indicators: eutrophication (EP), acidification (AP), global warming potential (GWP_{100}), freshwater aquatic ecotoxicity (FWAE), ozone depletion (ODP). These impact categories were chosen based upon their widespread use in agricultural LCA studies, allowing for comparison. More specifically, FWAE was selected because freshwater is a key feature and compartment of paddy rice cropping systems. Characterisation was performed with the SimaPro platform using CML baseline 2000/world, 1995 methodology.

The GWP for a 100-year time horizon (GWP_{100}) was calculated according to IPCC in kg CO_2-eq. (Guinée et al., 2002). With factors recommended by Guinée et al. (2002), EP was calculated in kg PO_4-eq, FWAE was calculated in kg 1-4 dichlorobenzene (DB) eq, and ODP was calculated in mg trichlorofluoromethane (CFC-11) eq. AP was calculated using the generic method proposed by Heijungs et al. (1992) in kg SO_2-eq. Energy use refers to the depletion of energy resources and was calculated based upon direct and indirect fossil fuel use, including physical (machinery) and chemical (fertilisers and pesticides) energy; all were converted to MJ. Water use refers to the volumetric depletion of water resources and was calculated based upon water footprint concepts. Crop evaporative consumption was modelled with water balance and CropWat models (FAO, 1992); it included the evaporation of rainfall from crop land (green water use, WU_g) and the evaporation of irrigation water from crop land (blue water use, WU_b). Land use refers to the loss of land as a resource in the sense of being temporarily unavailable for other purposes. Details on CML 2002 calculations, impact factors and normalisation may be found in CML (2002). CML 2002 methodologies and necessary databases are included in the SimaPro 7.3.2 modelling platform (Pré Consultants, 2010a; 2010b), which was used for this research. Commercial pesticides were modelled according to their active ingredients and the inventory data from Ecoinvent database within SimaPro 7.3.2.

The eco-efficiency of the rice cropping systems was quantified by expressing the total value generated (gross income or Total Value Product) as per environmental impact created (for each impact category). Net return as per environmental impact was also calculated (net income, or gross income minus total production costs) to represent eco-efficiency from the farmers' perspective. This means that we have considered the value generated from a farmer viewpoint. Any other cost (ecosystem disservice or negative environmental externality) or benefit (ecosystem service) to society has been ignored in the study.

3. Results

3.1. Utilisation of production factors and performances per area cultivated

Table 5a shows the techno-economic performances of the three cropping systems per area cultivated (ha). The results highlight the low performances of dry-season irrigated rice systems (Id), the production factor requirements of which are systematically higher than those of the two other systems; in addition, the Id system yielded markedly lower production. This system also requires mostly blue water (irrigation water), while the other two rely predominantly on green water (natural stocks and flows). The Id system requires 3 pumping episodes on average to replenish ponding conditions in paddy fields; therefore, it requires more labour and energy (pumps).

Labour, energy and pesticide requirements are markedly lower in rain-fed conditions due to lesser water management requirements (no pumping) and an absence of treatment against the golden snail (*Pomacea canaliculata*) which cannot reproduce during the cropless dry season of rain-fed plots. Energy requirements are consistent with the values reported by Pimentel (1980) and consist of approximately 12,000 MJ/ha and 15,000 MJ/ha for rice production in the Philippines in the wet and dry season, respectively (excluding human power).

The high level of homogeneity of fertiliser and pesticide application practices within each cropping system resulted in relatively homogeneous production costs per system; however, there were diverse outcomes in terms of yield (as shown in Fig. 4 for the 43 cropping systems -year 2010) and therefore of gross and net income. Net income per system was wide-ranging, with the Id system being the least profitable and the most variable. Conditions during the dry season are less favourable temperature-wise and more uncertain and variable in terms of water management. Iw systems showed higher homogeneity of results and a potential for the highest yields and net income.

3.2. Productivity of production factors and performances per mass of rice produced

Table 5b shows the productivities of production factors and the techno-economic performances of the three rice cropping systems. Overall, the results confirm that the productivities of most factors are higher in the Rw system, in which farmers produce more rice per labour unit, pesticide unit and total energy unit. Interestingly, the productivities in the Rw and Iw systems are similar for factors

Table 5a
Production factor use and techno-economic performances per area cultivated in selected rice cropping systems of Lam Sieo Yai basin − year 2010.

Production factors and performances	Reference unit	Rain-fed			Wet-season irrigated rice			Dry-season irrigated rice		
		Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.
		Ref. unit/ha								
Land	Ha	1	1	1	1	1	1	1	1	1
Labour	man hr.	8.49	6.63	5.68	15.23	11.95	8.01	16.45	16.45	11.25
Fertiliser	kg of fertiliser	625	625	625	687.5	687.5	687.5	687.5	687.5	687.5
Pesticide	kg of active matter	5.07	5.07	5.07	7.36	7.36	7.36	11.58	11.58	11.58
Total water	m^3	6285	6285	6285	7026	7026	7025	7256	7256	7256
Green water	m^3	6285	6285	6285	6285	6285	6285	1172	1172	1172
Blue water	m^3	0.29	0.25	0.21	740.54	740.54	740.44	6084	6084	6084
Total energy	MJ	17,360	17,281	17,222	19,590	19,530	19,388	20,846	19,783	18,327
Production cost	THB	20,868	20,843	20,822	22,435	22,354	22,243	23,415	22,943	20,884
Gross income	THB	32,018	30,407	26,050	37,607	33,875	31,742	33,045	28,740	23,500
Net income	THB	11,196	9564	5182	15,364	11,521	9193	10,102	5325	2616

Note: THB = Thai Baht, currency of Thailand = approximately 0.033 US$ at the time of data collection (2010).

Table 5b
Production factors' productivities and techno-economic performances in selected rice cropping systems of Lam Sieo Yai basin – year 2010.

Production factors and performances	Reference unit	Rain-fed			Wet-season irrigated rice			Dry-season irrigated rice		
		Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.
		kg of paddy rice/ref. unit								
Land	Ha	2500	2375	2000	2938	2625	2438	2500	2188	1875
Labour	man hr.	440.37	358.49	235.47	366.6	219.69	160	222.22	133	160
Fertiliser	kg of fertiliser	4.00	3.80	3.20	4.27	3.82	3.55	3.64	3.18	2.73
Pesticide	kg of active matter	493.1	468.44	394.48	399.32	356.84	331.35	215.98	188.98	161.99
Total water	m^3	0.40	0.38	0.32	0.42	0.37	0.35	0.35	0.30	0.26
Green water	m^3	0.40	0.38	0.32	0.47	0.42	0.39	2.13	1.87	1.60
Blue water	m^3	12,000	9500	6933	3.97	3.55	3.29	0.41	0.36	0.31
Total energy	MJ	0.15	0.14	0.12	0.15	0.13	0.12	0.13	0.10	0.10
Production cost	THB	0.12	0.11	0.10	0.13	0.12	0.11	0.11	0.10	0.09
Gross income	THB	0.078	0.078	0.077	0.078	0.077	0.077	0.080	0.076	0.076
Net income	THB	0.39	0.25	0.22	0.27	0.23	0.19	0.72	0.41	0.25

such as fertiliser, total water and green water. Return on investment (mass of rice produced per production cost) is slightly higher in the Iw system compared to the Rw system (0.12 kg/THB and 0.11 kg/THB, respectively) and is lowest in the Id system (0.1 kg/THB). Median yields (land productivity) vary from 2625 kg/ha in the Iw system to 2375 in the Rw system and 2188 in the Id system. Finally, the amount of rice per net income unit is markedly lower in the Iw system (0.23 kg per THB earned as net income) and Rw system (0.25) compared to the Id system, in which farmers need to produce twice as much rice (0.41 kg) to obtain the same net income.

3.3. *Direct field emissions and environmental impacts*

Table 6 reports the direct field emissions that were calculated. Emissions to air proved relatively homogeneous across all three systems, with the notable exception of methane emissions. Rw systems emit a median amount of 76 g CH_4 per kg of paddy rice, compared with 158 g and 176 g for Iw and Id systems, respectively. Lower CH_4 emissions in rain-fed conditions relate first to the water regime in the pre-season before the cultivation period (non-flooded conditions for more than 180 days) and second to the management of organic residues (incorporated more than 30 days before cultivation). CH_4 emission figures broadly concur with those of the IPCC (2006), which reports that approximately 120 g of CH_4 are released into the atmosphere for each kg of rice produced; however, our results reveal significant local differences based on cropping systems and water management practices. With regards to emissions to water, Id systems systematically emit more nitrates, phosphates, and agro-chemicals per both functional units, on account of the overall lower productivity of chemical inputs.

Table 7a and breport the environmental impacts for selected impact categories, per ha occupied for cultivation and per kg of unmilled rice produced, respectively. Overall, LCIA confirms the results related to direct field emissions and resource-related results of the techno-economic analysis. On a land use basis (Table 7a), GWP_{100} is markedly lower in rain-fed systems compared to irrigated systems, Iw showing the highest impact. Differences in CH_4 emissions were previously discussed (straw incorporation and water management during pre-cultivation times) and explain this result. In all other impact categories, Rw systems systematically show lower impacts per ha than Iw and Id systems, with the latter having the highest impacts. However, AP, ODP and total water use are of the same magnitude across systems; yet, water use remains appreciably lower in Rw systems.

When impacts are expressed per mass of paddy rice produced (Table 7b), the impacts of Id systems are even higher than those of the two other systems due to the lower yields. GWP_{100} becomes higher in Id systems (5.55 kg CO_2-eq) compared to Iw systems (4.87). Rw systems remain the least impacting with 2.97 kg CO_2-eq. Fig. 5 shows the diversity of GWP_{100} results obtained from calculations on all 43 sampled cropping systems. Although wide-ranging, the results clearly differentiate the three cropping systems. Total energy use is higher in Id systems (9.53 MJ per kg rice) compared to Iw and Rw systems (7.44 and 7.25, respectively).

Fig. 6 shows the diversity of water consumption in the sampled cropping systems. Variations in water use are especially marked in

Table 6
Direct field emissions from the paddy field of Lam Sieo Yai Basin.

Direct emission		Reference unit	Quantity (reference unit/1 kg of paddy Hom Mali rice)								
			Rainfed			Wet-season irrigated rice			Dry-season irrigated rice		
			Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.
Emission to air	Methane (CH_4)	g CH_4	86.7	75.94	73.05	165.49	158.56	148.78	193.61	176.37	163.08
	N_2O	g $N-N_2O$	0.37	0.31	0.3	0.32	0.29	0.26	0.41	0.35	0.31
	NO	g N–NO	0.22	0.18	0.17	0.18	0.17	0.15	0.24	0.21	0.18
	NH_3	g $N-NH_3$	26.61	22.41	21.28	21.91	20.35	18.18	28.48	24.41	21.36
Emission to water	Nitrates	g N	50.42	40.52	37.88	42.69	38.76	33.33	57.34	47.39	39.93
	Phosphorus	g P	19.38	15.53	14.5	18.98	17.26	14.9	26.43	21.94	18.58
	Glyphosate	mg	38.00	32.00	31.00	52.00	49.00	44.00	68.00	58.00	51.00
	Calcium carbonate	mg	40.00	34.00	32.00	33.00	30.00	27.00	71.00	61.00	53.00
	Isoprocarb	mg	7.00	5.90	5.60	5.80	5.40	4.80	12.50	10.70	9.40
	Metaldehyde	mg	–	–	–	32.00	30.00	27.00	42.00	36.00	31.00
Emission to soil	Glyphosate	mg	38.00	32.00	31.00	52.00	49.00	44.00	68.00	58.00	51.00
	Calcium carbonate	mg	40.00	34.00	32.00	33.00	30.00	27.00	71.00	61.00	53.00
	Isoprocarb	mg	7.00	5.90	5.60	5.80	5.40	4.80	12.50	10.70	9.40
	Metaldehyde	mg	–	–	–	32.00	30.00	27.00	42.00	36.00	31.00

Table 7a
Environmental impact indicators in selected rice cropping systems of Lam Sieo Yai basin – year 2010, results expressed per ha cultivated.

Impact indicator		Reference unit	Rain-fed			Wet-season irrigated rice			Dry-season irrigated rice		
			Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.
			Ref. unit/ha								
Output-related indicators	GWP_{100}	kg CO_2-eq	8625	7054	5680	15,040	12,784	10,993	15,500	12,141	9488
	EP	kg PO_4-eq	233	178	141	255	208	167	298	217	158
	AP	kg SO_2-eq	130	104	83	128	106	88	142	107	80
	ODP	mg CFC-11-eq	210	168	133	214	177	148	240	180	135
	FWAE	kg 1,4-DB eq	823	656	522	955	795	656	1078	812	606
Input-related indicators	WU	m^3	6305	6295	6285	7035	7035	7026	7256	7256	7256
	LU	Ha	1	1	1	1	1	1	1	1	1
	EU	MJ	17,360	17,281	17,222	19,590	19,530	19,388	20,846	19,783	18,327

Where; GWP_{100} is Global warming potential, EP is Eutrophication Potential, AC is Acidification Potential, ODP is Ozone Depletion Potential, FWAE is freshwater aquatic ecotoxicity, WU is freshwater resources use, LU is land use and EU is Energy use.

dry-season irrigation, showing diversity of practices in farmers' decisions and strategies regarding water supplies (pumping episodes).

Table 8 reports a contribution analysis on rain-fed paddy rice based on median results, showing the relative contribution of cropping subsystems to each impact category. Direct field emissions to air and water are likely to overwhelmingly contribute to AP, EP, GWP_{100} and FWAE. Field operations, meaning operations requiring the use of machinery and equipment (including water pumping, and the manufacturing of all equipment) contribute 20% of all energy use and a large part of ODP. Fertiliser application and manufacturing contribute a majority of total energy use, a large part of ODP, FWUE, and a marginal amount to AP, EP and GWP_{100}, due to the prevailing direct emissions at field level. Indeed, nitrogen fertilisers contribute much to GWP_{100} through N_2O direct field emissions. Pesticide application and manufacturing contributes marginally to total energy use. Rice seeds also contribute marginally to FWAE and EU. Pesticide application requires small amounts of water, and the main contributor to WU remains crop water use. Overall, direct field emissions are contributing a main part of input-related impact categories at local and regional scales (AP, EP, FWAE) and on the global scale (GWP_{100}); they mostly depend on water management practices for methane emissions, and both agrochemical and water management for other emissions. As stated by Blengini and Busto (2009), this predominant role calls for more reliable and site-specific data. Contribution analysis of the two other irrigated systems shows the same structure and overall contributions, although total water use in Id systems results mostly from blue water use (irrigation water), while WU in Iw systems results mostly from green water use (natural stocks and flows).

3.4. Eco-efficiency and net return to environmental impact

Table 9a reports the eco-efficiency of the three systems as per impact category. Because market price (the market value at farm gate) of paddy rice was identical in all three systems (12 THB per kg in 2010), the results are basically reversed values of the results on impact per kg of rice produced shown in Table 7b. However, there is an interest in reporting eco-efficiency as such, as it represents how cropping systems generate total value per environmental impact unit they create. In that sense, Rw systems are more eco-efficient than others, with the exception of AP, ODP and LU impacts, for which Iw systems perform slightly better. Id systems lag significantly behind the other two systems.

Interestingly, Rw systems value each ton of CO_2-eq emitted at 4040 THB, or approximately 134 US$ per ton. Iw and Id systems value each ton of CO_2-eq emitted at 82 and 72 US$, respectively. These values far exceed the trading price of CO_2 set up by the European Union Emissions Trading Scheme, the first international emission allowance trading system established after the Kyoto protocole, which price is the highest compared to other national systems, and ranged between 16 and 20 US$ throughout 2010.

Table 9b reports the net return on environmental impact, that is, the net income left to farmers per environmental impact unit. It represents how cropping systems generate income for the farmers per environmental impact they create. The results show that Iw systems are more "net return efficient" than others, with the notable exception of GWP_{100} for which Rw still performs better. Id systems still lag far behind the other systems in terms of net return efficiency.

Table 7b
Environmental impact indicators in selected rice cropping systems of Lam Sieo Yai basin – year 2010, results expressed per kg rice produced.

Impact indicator		Reference unit	Rain-fed			Wet-season irrigated rice			Dry-season irrigated rice		
			Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.
			Ref. unit/1 kg of paddy rice								
Output-related indicators	GWP_{100}	kg CO_2-eq	3.45	2.97	2.84	5.12	4.87	4.51	6.20	5.55	5.06
	EP	kg PO_4-eq	0.09	0.08	0.07	0.09	0.08	0.07	0.12	0.10	0.08
	AP	kg SO_2-eq	0.05	0.04	0.04	0.04	0.04	0.04	0.06	0.05	0.04
	ODP	mg CFC-11-eq	8.40E-02	7.10E-02	6.70E-02	7.30E-02	6.80E-02	6.10E-02	9.60E-02	8.20E-02	7.20E-02
	FWAE	kg 1,4-DB eq	0.33	0.28	0.26	0.33	0.30	0.27	0.43	0.37	0.32
Input-related indicators	WU	m^3	3.15	2.65	2.52	2.89	2.68	2.40	3.87	3.32	2.90
	LU	Ha	5.00E-04	4.20E-04	4.00E-04	4.10E-04	3.80E-04	3.40E-04	5.30E-04	4.60E-04	4.00E-04
	EU	MJ	8.68	7.25	6.91	8.04	7.44	6.60	9.77	9.53	7.91

Where; GWP_{100} is Global warming potential, EP is Eutrophication Potential, AC is Acidification Potential, ODP is Ozone Depletion Potential, FWAE is freshwater aquatic ecotoxicity, WU is freshwater resources use, LU is land use and EU is Energy use.

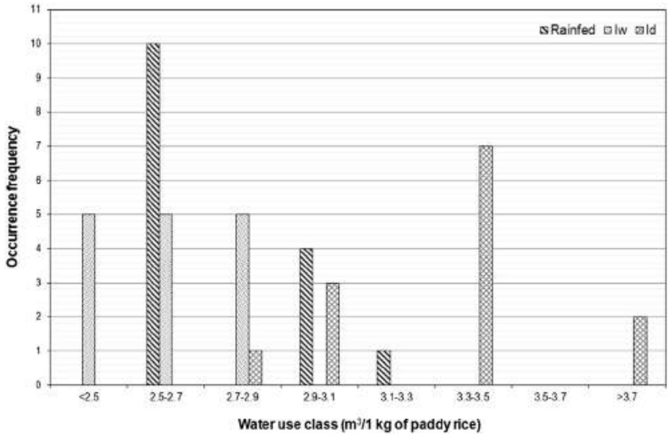

Fig. 6. Total water use (WU) per kg of paddy rice produced modelled for the 43 rice cropping systems (wet and dry seasons 2010) (Rain-fed, Iw: Irrigated wet season; Id: Irrigated dry season).

4. Discussion

4.1. Homogeneity of practices, diversity of performances and impacts

Farmers' practices proved surprisingly homogenous across cropping systems, showing particularly small variations in water use, and application of agrochemicals. The homogeneity in water use between systems in one same season is due to the modelling approach, yet the results are very different between seasons. Production costs per ha illustrate such relative homogeneity of practices. The limited sample size may hide the actual diversity; also, farmers may have responded to questionnaire-based interviews in a generic way, focussing on recommendations they receive rather than on their actual varying practices. Indeed, in Thailand's irrigation projects, technical support is provided by local officers of the RID that manages the projects, in association with agro-chemical retailers; all tend to promote and disseminate blanket recommendations. Further, collective water management in irrigation systems imposes synchronicity and commonality of practice, in single-crop systems where both rice physiology and climatic conditions prevail over individual contingencies and liberty. The homogeneity of practices is less comprehensible with regards to rain-fed cropping systems, performed by individual farmers, least connected to RID. Small-scale paddy farmers often lack the education and own experience to challenge existing norms and to experiment. Thailand rice farmers are generally very abiding of norms and standards set up by authorities. Strikingly, labour use shows much more diversity, although it is also dependant on water management. Labour mobilisation in a cropping system typically refers to one individual farmer's decision and organisation mode; contingencies and strategic choices can more fully materialise.

Table 8
Contribution of sub-systems to the impacts of rain-fed paddy rice production.

Wet-season rain-fed rice							
Subsystems	Percentage of impact to subsystems						
	AP	EP	GWP100	ODP	FWAE	WU	EU
Direct field emissions	82.70	96.36	61.88	0	57.94	0	0
Field operations	12.12	1.76	27.29	48.16	1.90	0	20.00
Fertilisers (manufacturing and transport)	4.64	1.71	8.68	46.17	31.52	0	66.67
Pesticides (manufacturing and transport)	0	0	0.02	0.43	0.31	0	4.44
Rice seed production	0.54	0.16	2.13	5.23	8.32	5.00	8.89
Crop water use	0	0	0	0	0	95.00	0

In spite of the relative homogeneity of cropping practices, overall and per sub-cropping system, outcomes in both economic and environmental terms show significant diversity. Net income and global warming potential are particularly wide-ranging in the different systems. This variation mostly results from large differences in yields, overall and per sub-cropping system. Yields and resulting net incomes are more diverse (less stable over time) in Rw and Id systems compared to Iw systems, due to a lack of control of the water supply and a lack of water, respectively. Attempts to relate farmers' performances to several socio-economic factors at the household level (i.e., experience in farming, age, level of education) proved unsuccessful. Instead, it was observed that, while Id farmers usually try to refill their paddy fields three times per season, many do not actually obtain enough water (e.g., canal tail-enders). The precipitation levels of the dry season of 2010 were relatively high compared to 30-year average precipitation levels; the lack of water for Id system farmers could have been even more damaging to yields in normal or drier years. This would potentially result in lower yields, and increased differences in performances and impacts between wet season and dry season systems. The same reasoning applies to Rw systems, which showed relatively high performances and low impacts in 2010, but would perform well below Iw systems under drier conditions.

4.2. Environmental impacts: convergences and discrepancies with other studies

Three published studies of rice from Italy (Blengini and Busto, 2009), China (Wang et al., 2010) and Japan (Hokazono and Hayashi, 2012) were chosen for the comparison with our study for North East Thai rice. All three studies, although showing contrasted goal and scope, had enough transparency in materials and methods to allow calculating LCA results per kg of rice at-the-farm-gate and in the same units. Interestingly, none of the available studies presented toxicity results and used a reduced selection of impacts categories (4–6).

For water use, our results (2.65–3.32 m^3/kg rice) were much higher than those from Wang et al. (2010) (0.431), yet compatible with those from Blengini and Busto (2009) (4.9). However, apart from WU, our results for Thai rice were either of similar magnitude yet greater (energy use, GWP, ODP), or much greater (Acidification and Eutrophication potentials) compared to the results from other regions. This trend of LCA results per kg of rice being greater in our case study can globally be explained by rice yields being markedly lower in the Isaan region of Thailand as well reflected by the sampled systems. While yields can reach easily 4–6 tons per ha, and even more, in the Central Plains of Thailand and in neighbouring countries, they hardly reach 2.5 tons in Isaan, due to the specific, high-quality, high-value, low-yielding varieties of fragrant rice used (Hom Mali). As showed previously, GWP_{100} per kg of rice in our case study ranged between 2.97 and 5.55 kg CO_2-eq against a range between 1.46 kg CO_2-eq (Hokazono and Hayashi, 2012) and 2.374 (Blengini and Busto, 2009) from the literature. In addition to the lower yields, the greater GWP result can be further explained by the use of the CH_4 baseline emission value suggested by Yan et al. (2003a) that is higher than the generic one suggested by IPCC (2006) for paddy rice, on account of specific pedoclimatic conditions in Isaan. Our results on energy use (7.3–9.6 MJ per kg of rice) and ODP (0.068–0.082 mg CFC11-eq per kg of rice) were similar to those obtained by Blengini and Busto (2009) on Italian rice in highly mechanised field conditions (8.75 MJ for non renewable energy use and 0.06 mg CFC11-eq for ODP). Conversely, our results for AP (0.04–

Table 9

a. Eco-efficiency (total value product per environmental impact, as per category) of selected rice cropping systems of Lam Sieo Yai basin – year 2010. b. Net income per environmental impact (as per category) of selected rice cropping systems of Lam Sieo Yai basin – year 2010.

Impact indicator	Reference unit	Rain-fed			Wet-season irrigated rice			Dry-season irrigated rice		
		Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.
		Baht/ref. unit								
Eco-efficiency										
GWP$_{100}$	kg CO$_2$-eq	4.23	4.04	3.48	2.66	2.46	2.34	2.37	2.16	1.94
EP	kg PO$_4$-eq	170.46	159.79	128.89	175.18	151.71	138.41	142.69	121.09	100.84
AP	kg SO$_2$-eq	289.16	275.23	231.66	332.41	297.03	275.86	281.69	246.41	211.27
ODP	mg CFC-11-eq	179.91	169.97	143.03	198.02	177.52	164.38	167.13	146.16	124.87
FWAE	kg 1,4-DB eq	45.98	43.64	36.70	44.61	39.87	37.04	37.15	32.52	27.91
WU	m3	4.77	4.53	3.81	5.01	4.48	4.16	4.14	3.62	3.10
LU	ha	30,000	28,500	24,000	35,250	31,500	29,250	30,000	26,250	22,500
EU	MJ	1.73	1.65	1.37	1.81	1.60	1.48	1.51	1.25	1.22
Net return to environmental impact										
GWP$_{100}$	kg CO$_2$-eq	1.58	1.36	0.75	1.16	0.90	0.74	0.80	0.44	0.23
EP	kg PO$_4$-eq	63.98	53.69	27.86	75.79	55.56	43.34	48.11	24.58	11.72
AP	kg SO$_2$-eq	106.63	91.52	49.83	145.26	109.72	85.69	93.98	49.67	24.48
ODP	mg CFC-11-eq	66.84	56.72	30.85	85.73	64.54	51.65	56.12	29.68	14.53
FWAE	kg 1,4-DB eq	17.16	14.59	7.88	19.44	14.49	11.60	12.51	6.56	3.24
WU	m3	1.78	1.52	0.82	2.18	1.64	1.31	1.39	0.73	0.36
LU	Ha	11,196	9588	5182	15,380	11,550	9196	10,102	5291	2632
EU	MJ	0.65	0.56	0.30	0.79	0.59	0.47	0.51	0.26	0.14

0.05 kg SO$_2$-eq) and EP (0.08–0.10 kg PO$_4$-eq) were much greater than the values found in the literature ranging for AP from 0.00616 kg SO$_2$-eq for Blengini and Busto (2009) to 0.024 kg SO$_2$-eq for Wang et al. (2010) and for EP from 0.00678 kg PO$_4$-eq for Blengini and Busto (2009) to 0.013 kg PO$_4$-eq for Wang et al. (2010). These impact categories are mostly affected by field emissions of NH$_3$, NO$_3$ to water and P to water. As for CH4 emissions, specific emissions factors or equations were used to estimate field emissions in our case study using equations from Yan et al. (2003b) for estimating ammonia emissions and a combination of nutrient budgets (N or P) and a precise water balance for the studied systems for N and P to water. The greater AP and EP in our study might therefore reflect more favourable conditions (e.g. higher temperatures) for these emissions compared to other situations. However, the insufficient level of detail and transparency in published LCA studies makes also possible certain discrepancies in the methods used across studies. Harmonised methods and assumptions would be desirable to complete LCA study comparisons across contrasted situations.

4.3. *Sustainability and the comparative advantages of rain-fed rice cropping*

The results contribute insights and data to the debate on the need to further develop irrigation in the context of North-eastern Thailand, with necessary precautions due to limited data. Rain-fed systems are reasonable alternatives and compete well against irrigation during the wet season. Proponents of irrigation development in North-east Thailand advocate that rain-fed systems only provide cropping opportunity during the wet season and force farmers to resort to alternative livelihoods in the dry season. In any case, the Isaan region has a long tradition of rural seasonal outmigration during the dry season and of off-farm and on-farm diversification of livelihood systems. It seems that irrigation during the dry season is not very profitable or environmentally friendly; in addition, this cropping system requires significant amounts of blue water, which must be tapped from existing limited resources at the expense of other users or the environment. In North-eastern regions, water supply is a problem for urban areas for instance, since surface water is the only resource, with no major reservoir for storage; further irrigation development in dry season will only make the water scarcity issue more acute.

For a societal objective of higher rice production and limitation of outmigration, irrigation during both seasons guarantees higher production overall, and keeps farmers busy all year round.

From a farmer's viewpoint, dry-season irrigation requires more inputs, higher costs and labour, and ultimately shows lower efficiency. Because of such reasons, and the fact that irrigation water supply is not guaranteed, only half of irrigation farmers grow rice during the dry season. Also, these farmers do not have alternative livelihoods, while wet season farmers are typically migrating during the dry season and/or own livestock.

Furthermore, if eco-efficiency and environmental integrity are factored into decisions, irrigation during dry season is clearly not the best option. In spite of these poor performances, approximately half of the irrigation farmers grow rice during the dry season under irrigation. These farmers manage to access enough water.

Further, the striking shift from traditional transplanting to direct sowing of dry seeds illustrates the fact that rice farmers in Isaan are seeking labour efficiency and time-saving solutions, rather than high yields, in a context of labour scarcity, massive seasonal outmigration, and diversified rural livelihood systems (ADB, 2012). Indeed, direct seedling results in lower yields than transplanting, yet with lower labour requirements. So, beside its higher environmental impacts and costs, rice systems' intensification through irrigation might not be the way chosen by the farmers.

5. Conclusion

This research has implemented a joint approach of techno-economic performances and environmental impacts in a diversity of actual cropping systems classified as wet-season rain-fed (Rw), wet-season irrigated (Iw), and dry-season irrigated systems (Id); data collected refer to 2010 cropping seasons.

According to techno-economic and environmental criteria, all results converge and establish that dry-season irrigated systems are performing less well than other systems. They use blue water (while other systems rely mostly on green water), require more energy, labour and agrochemicals, and ultimately yield lower production. As a result, gross and net incomes are lower. Although these results refer to only one year, they tend to explain why only half of irrigated land is actually cultivated during the dry season.

In addition to the conclusion related to the low performances of Id systems, we found a striking match between Rw and Iw systems. Indeed, performances of rain-fed and wet-season irrigated rice are comparable in both economic and environmental terms. The productivities of most production factors are higher in Rw systems, although Iw systems yield higher production. Yet again, it must be reiterated that 2010 was a wet year, favourable to Rw systems. Drier conditions during the wet season would most likely penalise Rw systems due to uncontrolled water supply, yielding less production.

Direct field emissions are comparable in all systems, with the notable exception of CH_4, which is markedly lower in Rw systems due to water and organic residue management. All environmental impacts are higher in Id systems, whether they are expressed per area used or per mass product.

The type of research performed here is demanding. It is multidisciplinary by nature, requires a huge primary data basis and involves complex modelling. However, such methodological combination shows great potential for multi-criteria assessment of cropping systems and allows for detailed eco-efficiency analyses. Several sensitive aspects and key limitations shall be underlined and possibly addressed for future research undertaken with a similar approach.

First, sample size and sampling strategy require the utmost attention; while sample size must remain manageable (because LCA must be run on each and every unit of analysis), it should also represent the diversity of existing systems in a given area. To address this issue, the research was performed at the level of a small river basin, where rice cropping practices, if not performances, are quite homogeneous. However, the results cannot then purport to be generalisable.

Second, as demanding as it was, our data collection documented only two cropping seasons in one given year. Techno-economic and environmental performances are very dependent upon climatic conditions (through yields, water balance, growing cycle length, scheduling of field operations, etc.). Further research should address other climatic scenarios (e.g., a typical dry year, an average year, a wet year), or even better, a sequence of several years. This research was of a synchronic nature (several systems assessed at one time); further research may consider a diachronic approach (a given system assessed over several cycles).

Third, a thorough inventory cannot compensate for a lack of local references with regards to direct field emissions. In rice cropping, direct field emissions form the bulk of environmental impacts. Although ideal, field measurements (tier-3 data) are hardly feasible in conjunction with a research project such as the one performed here. However, the exclusive use of generic baseline emissions and factors (tier-1 data, such as the ones provided by IPCC) may lead to massive errors. This research tried to adapt IPCC standards and use some tier-2 information (regional data, compiled by Yan et al., 2003a, 2003b); it also attempted to more accurately model emissions to water.

Fourth, results on eco-efficiency are presented per impact category; eight eco-efficiency indicators are calculated and shown for each system. Such profusion is difficult to communicate for decision- and policy-making purposes, especially when ambiguous results or interpretation occur or when EE indicators on a given system show contradicting results. Trade-offs and possibly weighting and normalisation of the impacts are needed. Further research should investigate the development of a single EE index per system for synoptic information of decision-makers, local communities and the general public, following the model of Eco Indicator 99 for single-score environmental impacts (ecopoints). Choices have to be discussed and negotiated with these stakeholders in terms of the selection and weighting of impacts and normalisation.

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