The environmental impacts of lowland paddy rice: A case study comparison between rainfed and irrigated rice in Thailand

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Abstract

North-eastern Thailand is an essential production area for high-quality fragrant rice for domestic use and export. While rainfed conditions largely prevail, plans to extend irrigation are drafted. This article compares paddy rice production under irrigation and rainfed conditions. Techno-economic performances were analysed jointly with environmental impacts, based upon life cycle analysis, and energy and water use analyses. Data were collected in 2010 from 45 diverse rice cropping systems in the Lam Sieo Yai Basin, according to three systems, namely wet-season rain-fed (Rw), wet-season irrigation (Iw), and dry-season irrigation (Id) systems. Wide-ranging performances and impacts were observed, while cropping practices were relatively homogeneous. Differentiation of systems originated mostly from differences in yield, which were largely impacted by water supply. The results highlight the low performances and high impacts of Id systems. They 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. The productivity of most production factors was higher in Rw and Iw systems. Emissions proved relatively similar across 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. Rw systems showed the lowest environmental impacts per ha and per kg of paddy rice produced. The average Global Warming Potential was 2.97 kg CO_2-eq per kg rice in Rw systems, 4.87 in Iw systems, and 5.55 in Id systems. This article further discusses the results in view of contrasting perspectives, including societal objectives, farmer income and environmental integrity, and possible irrigation development in north-eastern Thailand.

Key words: environmental impact; irrigation; life cycle analysis; productivity; rice.

Subjects: natural resources and environment; vegetal productions; water.

Résumé

Les impacts environnementaux du riz de bas-fonds : comparaison de systèmes irrigués et pluviaux en Thaïlande

Le Nord-Est de la Thaïlande est une région essentielle pour la production de riz parfumé de haute qualité à usage domestique et à l'export. Alors que les systèmes pluviaux dominent, des plans d'extension de l'irrigation sont préparés. Cet article compare la production de riz en casier irrigué et en pluvial. Les performances technico-économiques et les impacts environnementaux ont été analysés conjointement, à l'aide des analyses du cycle de vie et des usages de l'énergie et de l'eau. Les données ont été collectées en 2010 dans 45 systèmes de culture du bassin de Lam Sieo Yai, selon trois systèmes : pluvial de saison humide (Rw), irrigué de saison humide (Iw) et irrigué de saison sèche (Id). On observe des performances et des impacts très différenciés, alors que les systèmes sont relativement homogènes. Ces différences entre systèmes proviennent essentiellement des rendements, eux-mêmes influencés par les apports d'eau. Les résultats soulignent les moindres performances et les

impacts forts des systèmes Id. Ils requièrent de l'eau d'irrigation (eau bleue) alors que les autres consomment avant tout les précipitations utiles et le stock d'eau du sol (eau verte). Les systèmes Id consomment aussi plus d'énergie et de main-d'œuvre pour la gestion de l'irrigation. La productivité de la plupart des facteurs de production est supérieure dans les systèmes de saison humide Rw et Iw. Les rejets s'avèrent similaires dans tous les systèmes, à l'exception du CH_4, nettement moins émis par Rw en raison des modalités de gestion de l'eau et des résidus de culture. Les systèmes Id rejettent systématiquement plus de nitrates, de phosphates et de pesticides. Les systèmes Rw montrent les impacts les plus faibles, par hectare et par kilo de riz produit. Le potentiel de réchauffement climatique est en moyenne de 2,97 kg CO_2-eq par kilo de riz dans les systèmes Rw, 4,87 dans les systèmes Iw, et 5,55 dans les systèmes Id. Enfin, l'article discute les résultats, au regard des objectifs sociétaux et de ceux des producteurs, du respect de l'environnement, et du possible développement de l'irrigation dans le Nord-Est de la Thaïlande.

Mots clés : analyse du cycle de vie ; impact sur l'environnement ; irrigation ; productivité ; riz.

Thèmes : eau ; productions végétales ; ressources naturelles et environnement.

Worldwide, paddy rice systems provide food, income, and a diversity of ecosystem goods and services (Bouman *et al.*, 2007), yet they also have negative impacts on the environment (Roger et Joulian, 1998; Tilman *et al.*, 2001). Rice production requires large amounts of resources and contributes to pollution in all environmental compartments. Flooded rice grows under anaerobic conditions, which favours methane formation (IPCC, 2006).

Thailand is the world's sixth largest rice producer and largest exporter. Rice is grown on some 10 million hectares of land, with more than half grown in the north-eastern region (Isaan). 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). Isaan produces approximately 80% of all jasmine rice produced nationwide.

Overall, rice production systems contribute 80% of freshwater extractions in Thailand, and pesticide-related toxicity has become a major concern. There exist recurring plans to extend irrigation in Isaan (Molle and Floch, 2008), which can be implemented only through further exploitation of the Mekong river and its tributaries and wetlands.

Given the importance of the rice sector in Thailand and growing concerns about its sustainability, this research aims at assessing the environmental impacts of rice cropping systems in Isaan as a main production area. In view 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.

Materials and methods

Study area description

The Lam Sieo Yai basin (2,875 km^2) is located at the heart of the Isaan plateau in North-eastern Thailand. The region has a tropical savanna climate, with two seasons: the dry season between November and April, which commonly includes severe drought conditions, and the monsoon-affected wet season between May and October. Annual rainfall amounts to approximately 900 mm on average, yet with high inter-annual variability.

Of the total area, 83% is agricultural land, of which 96% is covered with paddy fields. In the basin, 75% of paddy fields are irrigated (*i.e.* with controlled water supply). The other 25% are rainfed paddy fields. Lowland rainfed rice is grown only during the wet season, while irrigated rice may be cultivated during both seasons. Rainfed conditions refer to conditions of lowland rice that is cropped under flooding conditions with no control of water supply. Rainfall, soil moisture, and natural runoff alone (green water) provide water to the paddy fields.

Joint LCA and techno-economic analyses

General approach

Among other methodologies, life cycle analysis (LCA) has recently emerged as the leading methodology to assess potential environmental impacts in agriculture (Van der Werf and Petit, 2002). This approach is increasingly used in the industry and the agriculture sectors for assessing processes and products and for the development and implementation of environmental policies (EU, 2010a). LCA is a structured, systematic, standardised method (ISO 14040 and 14044) for quantifying the emissions, resources consumed, and environmental and health impacts that are associated with the production and use of goods and services (products). LCA consists of a thorough and systematic inventory (life cycle inventory, LCI) of processes, emissions, resource consumptions, and inputs and outputs related to the provision of a good or service. It then converts the

inventory into impact indicators as per impact categories. This step is the life cycle impact assessment (LCIA) phase (Baumann and Tillman, 2004; EU, 2010b).

LCA application in agriculture has developed over the last 15 years (Audsley *et al.*, 1997) and addressed most agricultural commodities (Williams *et al.*, 2005). Yet, paradoxically, rice has been rarely studied. To the authors' knowledge, there are only three comprehensive published applications of LCA to rice (Blengini and Busto, 2009; Wang *et al.*, 2010; Hokazono and Hayashi, 2012). The two former compare an alternative, supposedly less impacting, cropping system with an existing one. Wang *et al.* (2010) studied only one system. In all cases, the assessments focus on virtual systems that represent average, ideal situations, regardless of the diversity of local situations and practices. Basset-Mens *et al.* (2010) assessed 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.

The research is an attempt to better address the actual diversity of existing systems. It collected, analysed, and combined indicators of techno-economic performances with environmental impact indicators based upon the life cycle approach, at cropping system level. Techno-economic analysis typically results in monetary values as per factor of production while LCA expresses environmental impacts as per selected functional units FU. The FU for LCA is the mass (kg) of raw paddy rice (unmilled) at the farm gate (approximately 15% moisture content).

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). Direct sowing of dry seeds has become predominant in Isaan. The results presented here refer to this planting mode in each water management system.

Primary data were collected by means of field observations and interviews with farmers; data refer to both dry and wet seasons of 2010. Year 2010 received 1,219 mm of precipitation, which is notably more than the 30-year average (900 mm). For each system, 15 farm plots were selected with extension officers and farmers, based upon representativeness and local diversity.

The present LCA study covered the rice production systems from the mobilisation of all raw resources and equipment to farm gate (unmilled rice). *Figure 1* shows the flow diagram used for the study, where both direct and indirect flows were considered in the inventory.

Joint inventories

The common technical data and specific data needed for LCI and economic analyses for the main stages of rice production are presented in *table 1*. The inventory comprises the following processes and operations:
- field operations with machinery;
- field operations performed manually;
- inputs and agro-chemical use;
- yields and market price at the farm gate;
- cultivated areas.

Actual water consumption is unknown in canal, 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). Recent versions of the FAO's CropWat (FAO, 1992; Chapagain and Hoekstra, 2011), coupled with water
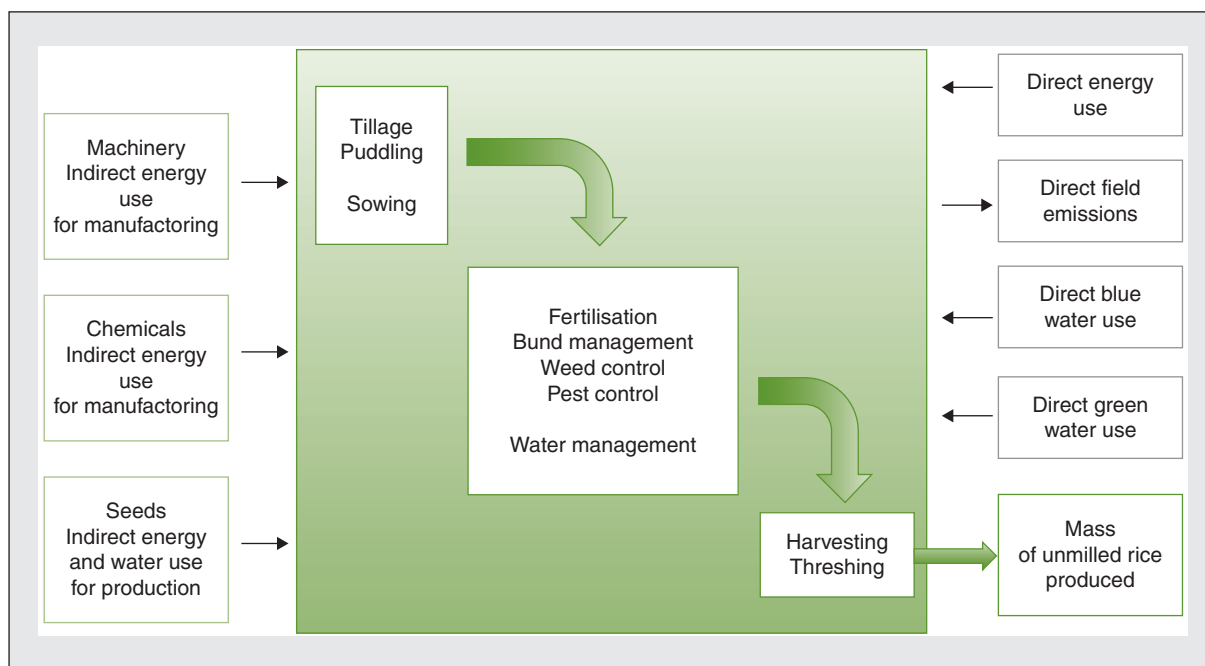
Figure 1. Flow diagram for rice cropping systems: general inventory of inputs and outputs from resources mobilisation to farm gate (unmilled rice).

Figure 1. Diagramme de flux en systèmes rizicoles : inventaire général des intrants et extrants, de la mobilisation des ressources à la porte de la ferme (riz non-décortiqué).

Table 1. Type and source of data needed for life cycle inventory (LCI) and economic analyses.

Tableau 1. Type de données et leurs sources pour l'inventaire ACV (analyse du cycle de vie) et les analyses économiques.

	Areas of inventory	Data sources	Unit
Common 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)	m³
	Yield	Primary data (farm level)	kg/ha
	Land use	Primary data (farm level)	ha/production cycle
LCI-specific data	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
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

IWR: irrigation water requirements; IPCC: International Panel on Climate Change.
Thai Baht (THB): currency of Thailand, equal to approximately 0.033 US$ at the time of data collection (2010).

balance modelling in ponding conditions, have been used.
The inventory for the manufacturing and delivery of machinery, agrochemicals and seeds, equipment, machinery, inputs, and energy carriers used during field operations were calculated with SimaPro 7 from field data and based upon existing conversion rates, methods, and databases (Ecoinvent database). These flows are shown on the left side of *figure 1*. Flows related to direct field emissions, energy use, and blue (irrigation) and green (rainfall) water use are shown on the right side of *figure 1*. Human labour is being considered only in techno-economic calculations.
CH$_4$ emissions were modelled based upon tier-1 methods established by the International Panel on Climate Change (IPCC, 2006) for paddy under different water regimes, adjusted with tier-2 baseline emission factors determined by Yan *et al.* (2003a) for Thailand. For N$_2$O, NH$_3$, and NOx emissions, the methods developed by Yan *et al.* (2003b) were used. They suggested tier-2 methods for flooded paddy fields in South East Asia. Carbon dioxide was considered neutral (Williams *et al.*,

2005). The observed average length of cropping cycles is 120 days, from sowing to harvesting.
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. Because urea and ammonium-based fertilisers prevail in Isaan, direct nitrate emissions result mostly from nitrification and the whole nitrogen cycle and balance, rather than direct fertiliser loss. The principles underlying the nitrate emission assessment are that: i) nitrates form the remaining components of the overall nitrogen mass balance the other components of which were determined in earlier sections; ii) these water-soluble nitrates may leach to the water compartment through surface drainage and deep percolation; and iii) such a portion refers to the ratio between water that is not used by the crop and overall water supply (that is 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 Brentrup *et al.* (2000) and Pathak *et al.* (2004).
A similar approach was applied to phosphates, under similar assumptions regarding the stability of long-term contents, the absence of erosion, and with a similar modelling approach. P inputs from fertiliser were calculated from fertiliser formulae and application doses.
In the cropping systems under study, the pesticides typically used included a molluscicide (metaldehyde), an insecticide (isoprocarb-based with CaCO$_3$), and an herbicide (glyphosate); 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. Straw and rooting systems are left in the field to decay. It was decided to split emissions equally between soil and water compartments (50%-50%).

LC impact assessment

The selected environmental impact indicators first include resource-use indicators: energy use (EU), freshwater use (WU), and land use (LU).

It should be noted that no characterisation towards indicators of potential water resource depletion was used. Current methodologies (Pfister *et al.*, 2009) that calculate regional Water Stress Index (WSI) do not provide satisfactory results in tropical monsoon areas. Indeed, the algorithm considers the high monthly variations of precipitations, and results in artificially high WSI. Second, they include environmental impact indicators: eutrophication (EP), acidification (AP), global warming potential for a 100-year time horizon (GWP_{100}), freshwater aquatic ecotoxicity (FWAE), and 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 compartment of paddy rice cropping systems. Characterisation was performed with the SimaPro platform using CML baseline 2002/world, 1995 methodology. All units are provided in *table 2*. GWP_{100} was calculated according to IPCC (Guinée *et al.*, 2002). EP, FWAE, and ODP were calculated with factors recommended by Guinée *et al.* (2002). AP was calculated using the generic method proposed by Heijungs et al. (1992). Energy use was calculated based upon direct and indirect fossil fuel use, including physical (machinery) and chemical (fertilisers and pesticides) energy. Crop evaporative consumption was modelled with water balance and CropWat models (FAO, 1992); it included the evaporation of rainfall from cropland (green water use, WU_g) and the evaporation of irrigation water from cropland (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 Guinée *et al.* (2002). CML 2002 methodologies and necessary databases are included in the SimaPro 7.3 modelling platform, which was used for this research. Commercial pesticides were modelled according to their active ingredients and the inventory data from Ecoinvent database within SimaPro.

Results

Utilisation of production factors and performances

Table 3 shows the techno-economic performances of the three cropping systems per area cultivated (ha). The results highlight the low performances of Id systems, 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. The Id system also requires mostly blue water, while the other two rely predominantly on green water. The Id system requires three 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.

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 and, therefore, of gross and net income. Net income per system was wide-ranging, with the Id system being the least

Table 2. Environmental impact indicators in selected rice cropping systems in the Lam Sieo Yai basin in 2010.

Tableau 2. Indicateurs d'impacts environnementaux de systèmes rizicoles du bassin de Lam Sieo Yai, année 2010.

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	3.450	2.970	2.840	5.120	4.870	4.510	6.200	5.550	5.060
	EP	kg PO_4-eq	0.093	0.075	0.070	0.087	0.079	0.069	0.119	0.099	0.084
	AP	kg SO_2-eq	0.052	0.044	0.042	0.044	0.040	0.036	0.057	0.049	0.043
	ODP	mg CFC-11-eq	0.084	0.071	0.067	0.073	0.068	0.061	0.096	0.082	0.072
	FWAE	kg 1,4-DB eq	0.329	0.276	0.261	0.325	0.303	0.269	0.431	0.371	0.323
input-related indicators	WU	m^3	3.153	2.646	2.518	2.886	2.676	2.395	3.87	3.317	2.902
	LU	ha	0.00050	0.00042	0.00040	0.00041	0.00038	0.00034	0.00053	0.00046	0.00040
	EU	MJ	8.680	7.252	6.913	8.037	7.44	6.6	9.774	9.529	7.913

Results are expressed per kg rice produced.
GWP: global warming potential; EP: eutrophication; AP: acidification; ODP: ozone depletion; FWAE: freshwater aquatic ecotoxicity; WU: freshwater use; LU: land use; EU: energy use.

Table 3. Production factor use and techno-economic performances per hectare in selected rice cropping systems in the Lam Sieo Yai basin in 2010.

Tableau 3. Utilisation des facteurs de production et performances technico-économiques de systèmes rizicoles du bassin de Lam Sieo Yai, année 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								
Labour	man hr.	8.494	6.625	5.677	15.234	11.949	8.013	16.447	16.447	11.250
Fertiliser	kg of fertiliser	625.00	625.00	625.00	687.50	687.50	687.50	687.50	687.50	687.50
Pesticide	kg of active matter	5.070	5.070	5.070	7.356	7.356	7.356	11.575	11.575	11.575
Total water	m^3	6,285	6,285	6,285	7,026	7,026	7,025	7,256	7,256	7,256
Green water	m^3	6,285	6,285	6,285	6,285	6,285	6,285	1,172	1,172	1,172
Blue water	m^3	0.288	0.250	0.208	740.539	740.539	740.444	6,084	6,084	6,084
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	28,521	27,095	22,817	33,512	29,947	27,808	30,000	26,250	22,500
Net income	THB	7,653	6,252	1,995	11,077	7,593	5,565	6,585	3,307	1,616

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

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.

Table 4 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 with regards to factors 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 (0.117 kg/THB and 0.114 kg/THB, respectively; [1 THB=0.03 US$]) and is lowest in the Id system (0.095 kg/THB). Median yields (land productivity) vary from 2,625 kg/ha in

the Iw system to 2,375 in the Rw system, and 2,188 in the Id system. Finally, the amount of rice per net income unit is markedly lower in the Iw system (0.297 kg/THB earned as net income) and Rw system (0.310) compared to the Id system, in which farmers need to produce twice as much rice (0.662 kg) to obtain the same net income.

Environmental impacts

On a land use basis, LCIA results show that GWP_{100} is markedly different between rain-fed and irrigated systems, Iw showing the highest impact (table 2). Differences in CH_4 emissions (because of straw incorporation and water management during pre-cultivation times) account for 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 (figure 2).

On a rice mass basis, differences are more marked, due to yield differences. In table 2, the environmental impacts for selected impact categories, per kg of unmilled rice produced, are reported. The impacts of Id systems are 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. Total energy use is higher in Id systems (9.64 MJ/kg rice) compared to Iw and Rw systems (7.50 and 7.29, respectively). Figure 3 reports a relative comparison of selected environmental impacts by the three systems, and highlights the same differences, and the high impacts of Id systems.

It was calculated that Rw systems value each ton of CO_2-eq emitted at 4,040 THB, or approximately 134 US$. Iw and Id systems value each ton of CO_2-eq emitted at 82 and 72 US$, respectively.

Figure 2 shows the diversity of water consumption in the sampled cropping systems. Variations in water use are

Table 4. Productivity of production factors and techno-economic performances in selected rice cropping systems in the Lam Sieo Yai basin in 2010.

Tableau 4. Productivités des facteurs de production et performances technico-économiques de systèmes rizicoles du bassin de Lam Sieo Yai, année 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	2,500	2,375	2,000	2,938	2,625	2,438	2,500	2,188	1,875
Labour	man hr.	440.37	358.49	235.47	366.60	219.69	160.00	222.22	133.00	160.00
Fertiliser	kg of fertiliser	4.000	3.800	3.200	4.273	3.818	3.545	3.636	3.182	2.727
Pesticide	kg of active matter	493.10	468.44	394.48	399.32	356.84	331.35	215.98	188.98	161.99
Total water	m^3	0.398	0.378	0.318	0.418	0.374	0.347	0.345	0.301	0.258
Green water	m^3	0.398	0.378	0.318	0.467	0.418	0.388	2.133	1.866	1.600
Blue water	m^3	12,000	9,500	6,933	3.97	3.545	3.292	0.411	0.360	0.308
Total energy	MJ	0.145	0.1379	0.115	0.15151	0.13441	0.12442	0.1264	0.10494	0.1023
Production cost	THB	0.120	0.114	0.096	0.131	0.117	0.110	0.107	0.095	0.090
Gross income	THB	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083
Net income	THB	0.629	0.310	0.274	0.348	0.287	0.229	1.160	0.662	0.380

Note: THB = Thai Baht; currency of Thailand, equal to approximately 0.033 US$ at the time of data collection (2010).
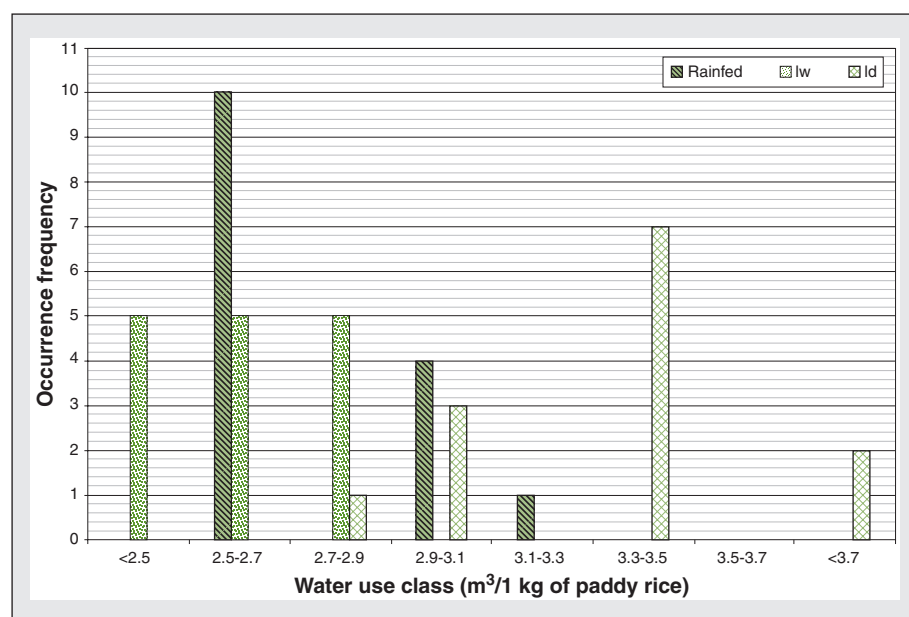
Figure 2. Total water use (WU) per kg of paddy rice produced, modelled for the 45 rice cropping systems (wet and dry seasons in 2010).

Figure 2. Usage total en eau par kilo de paddy produit, modélisé pour les 45 systèmes rizicoles (saisons humide et sèche 2010).

Rainfed; Iw: Irrigated wet season; Id: Irrigated dry season.

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

A contribution analysis showed the relative contribution of cropping sub-systems to each impact category. Direct field emissions to air and water overwhelmingly contribute to AP, EP, GWP_{100}, and FWAE; they mostly depend on water management practices for methane emissions, and both agro-chemical and water management for other emissions. Field operations with machinery and 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}. Rice seeds contribute marginally to FWAE and EU. Pesticide application requires small amounts of water, and the main contributor to WU remains crop water use.
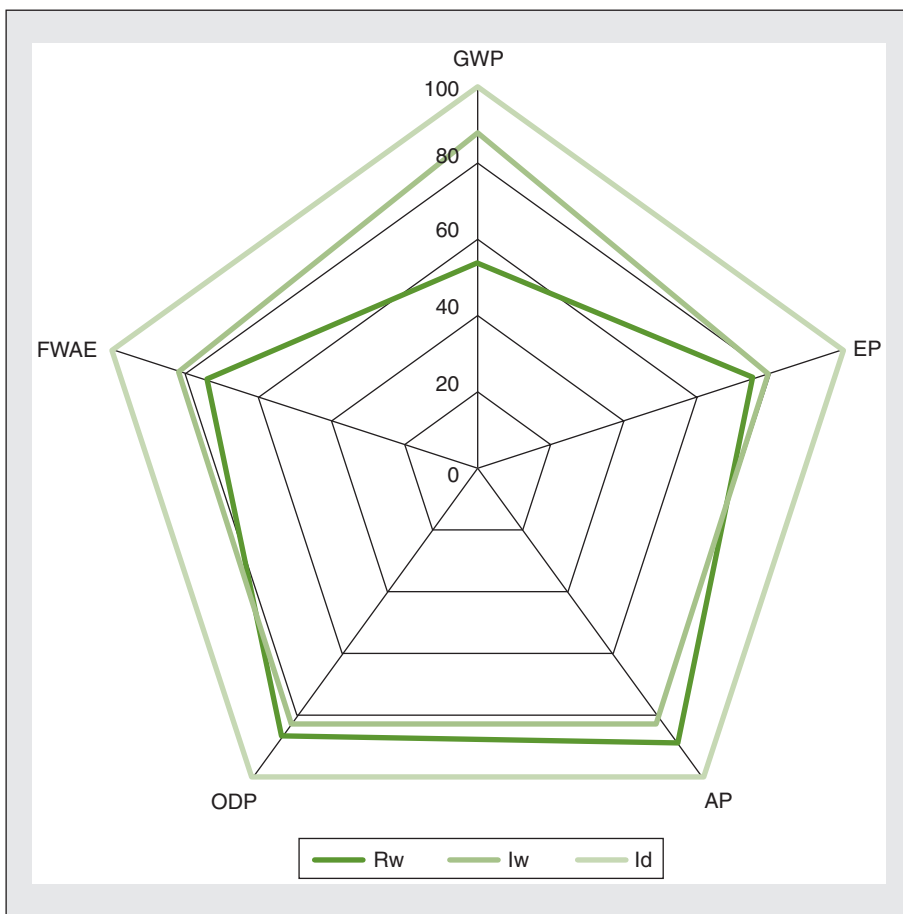
Figure 3. Comparative environmental impacts of the three rice cropping systems.

Figure 3. Comparaison des impacts environnementaux des trois systèmes rizicoles.

Rw: Rain-fed; Iw: Irrigated wet season; Id: Irrigated dry season.
FWAE: freshwater aquatic ecotoxicity; GWP: global warming potential; EP: eutrophication; ODP: ozone depletion; AP: acidification.

Discussion and conclusion

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) 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. 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 rationale applies to Rw systems, which showed relatively high performances and low impacts in 2010, but would perform well below the level of Iw systems under drier conditions.

The results contribute insights and data to the debate on the need to further develop irrigation in the context of Isaan, 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 Isaan 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.

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. Furthermore, if environmental integrity is factored into decisions, irrigation during the dry season is clearly not the best option. Furthermore, the 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. Direct seedling results in lower yields, yet with lower labour requirements.

All results converge and establish that dry-season irrigated systems are performing less well than other systems. They use blue 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 account for why only half of irrigated land is actually cultivated during the dry season.

Also, there is 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.

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, the methodological combination shows great potential for multi-criteria assessment of cropping systems and allows for detailed eco-efficiency analyses. ■

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