Precision land leveling for sustainable rice production: case studies in Cambodia, Thailand, Philippines, Vietnam, and India

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Abstract

Laser-controlled land leveling (LLL) can help improve rice production's spatial and temporal management, leading to optimized water and crop management. This research resulted in sustainable performance indicators to illustrate that LLL is a sustainable technology for rice production. The assessment was conducted in Cambodia, the Philippines, Thailand, Vietnam, and India. Benefits of LLL include saving land use, water, and agronomic inputs, increasing yield, and decreasing postharvest losses resulting in saving energy of 3.0–6.9 GJ ha^{-1} and decreasing emissions by 1151–1486 kg CO_2-eq ha^{-1}. Additionally, LLL application can obtain a net profit of USD 52–84 ha^{-1} per rice production season in the countries studied. The result demonstrated that LLL is a sustainable technology as well as strongly supports sustainable rice production. The study would lead to better adoption of this technology through its evidence-based promotion.

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Introduction

Poor land consolidation, insufficient mechanization, including the lack of precision land leveling, and inefficient use of agronomic inputs are some of the major challenges in rice production. Significant unlevelness in rice field plots causes uneven water distribution leading to adverse effects such as hampered crop establishment and increased use of seed, water, fertilizer, and pesticide to compensate for the effects of an uneven field. Land leveling is an important precondition for land preparation and a good seedbed or for land consolidation in agriculture, particularly for the humid tropics characterized by heavy rains and water scarcity in different seasons.

Most rice fields in the Southeast Asian countries (SEA) are fragmented with small plot sizes of 0.1–2.0 ha (Roslund, 2015). Small-sized and unleveled fields hamper mechanization and cause low energy efficiency and productivity in mechanized operations that can be counteracted by the benefits of using a combine harvester (Gummert et al., 2018). Expanding field size or removing field bunds is one of the key strategies for more effective farming in several countries. For instance, the "small farmer, large field" program is one of the promoted models of agricultural structural transformation in Vietnam (Rosellon, 2015). A similar farming model has also been piloted recently in India (Mohanty et al., 2017). However, expanding field size is hindered by physical barriers such as unlevelness or topography. For a given slope of a field, as it becomes larger, the differences in elevation also also get bigger, resulting in more adverse effects on the management of water, and other agronomic inputs.

On the other hand, the global rice value chain was recently driven by the need for sustainable production and consumption (Devkota et al., 2021; My et al., 2018; SRP, 2020). Therefore, identifying the sustainable technologies is essential to upgrade the value chain and benefit farmers and related stakeholders. The Sustainable Rice Platform established twelve sustainable performance indicators representing sustainable impact areas (SRP, 2020). Of which, profitability, agronomic use efficiency, and GHG emission are commonly used as the economic and environmental indicators of a technology (Nguyen-Van-Hung et al., 2020).

Land leveling is one of the major factors affecting spatiotemporal yield variability (Simmonds et al., 2013). In addition, leveling index significantly affects uniform crop establishment and boosts the potential yield of rice production (Abu-Bakar et al., 2019). Laser-controlled land leveling (LLL) is a technology used for leveling a field within a certain degree of the desired slope throughout the field. Using laser beam from a transmitter and receiver attached to leveling bucket, the control box interprets the signal either to lift or not the leveling bucket attached to a tractor (RKB, 2017). Its function is to detect automatically the unevenness in altitude of the field in order to move soil correspondingly from higher to lower spots attaining leveled field with very high precision. LLL therefore can help to optimize the field's slope for optimum water management and crop growth. For example, an evenly flat surface is better for irrigated rice as most rice varieties can well grow in fields with standing water. On the other hand, some other crops, such as maize and sugarcane, need a leveled field to avoid erosion, and with a certain slope to enable irrigation and drainage (Naresh et al., 2014; Misra et al., 2020). In addition, LLL helps optimize water management for the terrace field cropping system (SRP, 2020). Furthermore, with precisely leveled fields, the water can be controlled timely and optimally matched with the crop growth requirements. These advantages of LLL result in increasing water-use efficiency, crop productivity, and grain quality and decreasing weed problems (Abdullaev

et al., 2007; Agarwal & Goel, 1981; Aryal et al., 2015; FAO, 2020; Naresh et al., 2017). In the same way, the benefits of improved spatial and temporal management, increased of agronomic use efficiency and reduction of irrigated water are significant increase of energy efficiency and reduced GHG emissions in rice production. In particular, less water substantially reduces methane emission from rice production (Sander et al., 2014). LLL, therefore, plays a vital role in precision agriculture for spatial and agronomic input optimization as discussed in Johansen (1996), Kitchen et al. (1996), Pierce & Nowak (1999), Whelan & McBratney (2000), Dobermann et al. (2004), and ISPAG (2021).

Developments in LLL controlled systems were reported in Zheng et al. (2007), Mohtasebi et al. (2007), Si et al. (2007), Qingfei and Gang (2008), Bansal et al. (2014), and Dao-Duy-Vinh et al. (2014) while optimizations of LLL operations were presented in Dedrick et al. (2007), Nguyen-Van-Hung et al. (2010), Mahdi et al. (2014), and Manpreet-Singh et al. (2019). The technology was originally developed around the world for the construction sector and large-scale agriculture and was adapted for use on smallholder farms in Asia around 2000. Given the benefits of LLL, this technology is considered an important technology for agriculture. The technology and benefits of LLL have been popularized through publications and project reports. However, limited research reports exist on the LLL practices in the specific regions and sustainable indicators of LLL. Therefore, this study was conducted with the following objectives: (i) assessment on LLL practices in Cambodia, Philippines, Thailand, Vietnam, and India; and (ii) testing a hypothesis that LLL is a sustainable technology for rice production based on the indicators of agronomic input use efficiency, energy efficiency, greenhouse gas emissions, and cost–benefit.

Materials and methods

Scope of research

The performance of LLL for rice production in the countries studied was evaluated based on a life-cycle assessment (LCA) approach (Gallen, 2010; Nguyen-Van-Hung et al., 2020) with the research scope shown in Fig. 1. The performance of the application of LLL in rice production was investigated based on energy balance, GHG emission balance, and cost–benefit accounted for 1 hectare (ha) of rice production. The inputs of LLL were accounted for machine production distributed in its depreciation, fuel consumption, and labor. On the other hand, outputs of the system include saved energy, profits, and reduced GHGE translated from the benefits such as the reductions of water and agronomic input uses and postharvest losses, and increase of yield. The data were mainly collected through assessments in the implementation of projects of the International Rice Research Institute (IRRI) which include LLL activities from 2016 to 2020 and queries from experts.

Description of the technology

Precision land leveling can be conducted with an LLL system with its main components shown in Fig. 2. A laser transmitter placed at the side of the field projects a laser light or beam that is rotated with a speed of 300–600 RPM to create a horizontal laser plane. The laser beam is intercepted by the laser receiver mounted on the leveling bucket. The receiver can detect the laser beam rotating 360° and in a vertical range of about 0.30 m. A control panel mounted on the tractor interprets the signal from the receiver
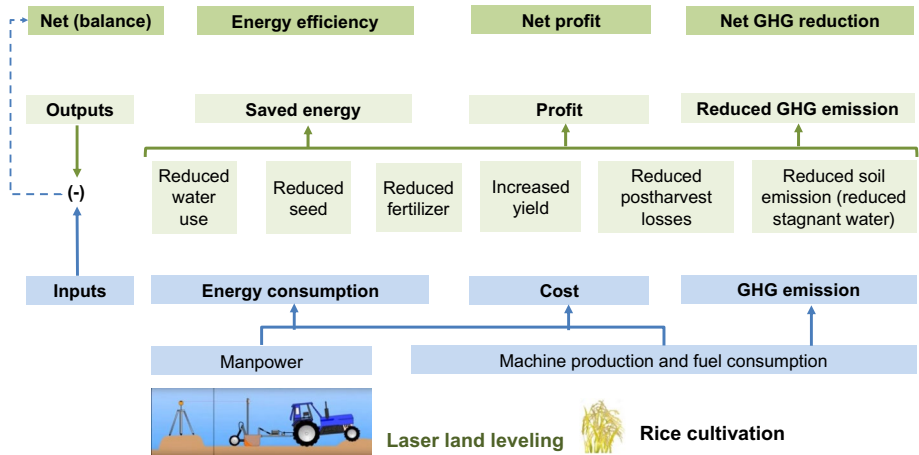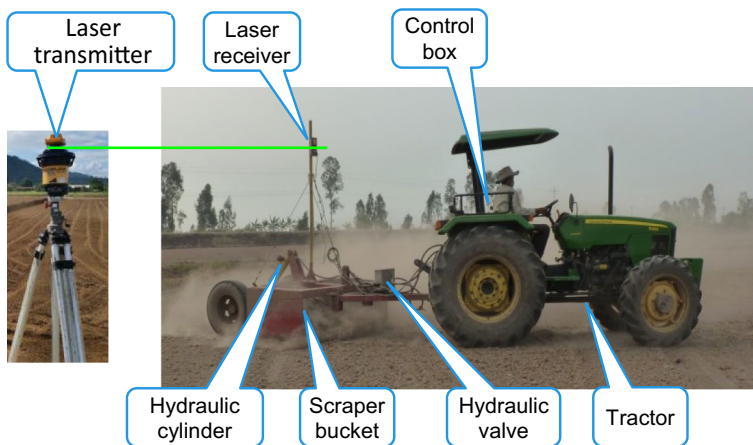
Fig. 1 The research boundary

Fig. 2 Components of laser land leveling system

and opens or closes the solenoid hydraulic control valve, which will raise or lower the leveling bucket. The tractor supplies hydraulic oil through its hydraulic pump. A tractor with 36.8–58.8 kW (50–80 HP) is commonly used in leveling rice fields in Asia. The pressurized hydraulic oil flows through the solenoid control valve and activates the hydraulic cylinder to control the vertical positions of the leveling bucket. The control will keep the scraper bucket always at the same height relative to the laser plane (correct position), resulting to soil being scraped off and collected from the elevated areas and dumped to lower areas in the field. Since the leveling bucket pulled by the tractor is controlled automatically, the tractor operator can drive randomly in the field until the required elevation difference across the entire field is attained. However, random driving pattern during LLL operations may have low efficiency because filling and emptying the bucket are not optimized, thus having idle time while the tractor is running.

Benefits of LLL in terms of agronomic inputs and rice yield

Figure 3 shows the principle of improving land-use efficiency and crop management by precision land leveling. For a field with a certain slope, the larger dimension in length or width can lead to an increase in elevation difference, resulting in more difficult management of water, fertilizer, and pesticide, and crop lodging. LLL technology can attain the levelness of the field surface to a 1–2 cm elevation difference and can be used, even in a large field of 3 ha. It can also be used to create a slope in the field (IRRI, 2020). Application of this technology can lead to an increase in land-use efficiency by 3–6% when consolidating several small fields into one larger field (Jat et al., 2015; RKB, 2017;). LLL can also help in increasing irrigation water efficiency by 12–40%, increasing fertilizer-use efficiency by 10–13%, and increasing rice yield by 5–15% (Jat et al., 2015; Phan-Hieu-Hien et al., 2014; RKB, 2017). The reduction of standing water in the rice field leads to reduced methane emissions, by atleast 20%, as discussed by Sander et al. (2014). In addition, with precision land leveling, crop stand is more uniform and has less lodging at harvest that leads to a decrease of postharvest losses by 2–5% (Jat et al., 2009; Phan-Hieu-Hien et al., 2014).

Table 1 shows rice production factors of the baseline (business as usual) scenarios in the countries covered by the study. In particular, 0.03 L m^{-3} diesel for water pumping was based on a common practice in Asia and assumed to be the same for all countries. The soil methane emission was based on the default data reported in IPCC (2019). The baseline data was then used to calculate the benefits resulting from LLL application for 1 ha of rice production.

Table 2 shows the benefits of LLL corresponding to different agronomic factors established based on a collation between secondary and primary data. The secondary data came from studies of well-known LLL experts and organizations, while the primary data was collected from a key informant survey for 18 farmers in Vietnam in 2020. There were various responses from the interviewed farmers. For example, most of the interviewed farmers were not able to differentiate the effect of laser leveling from other good practices such as "One Must Do,
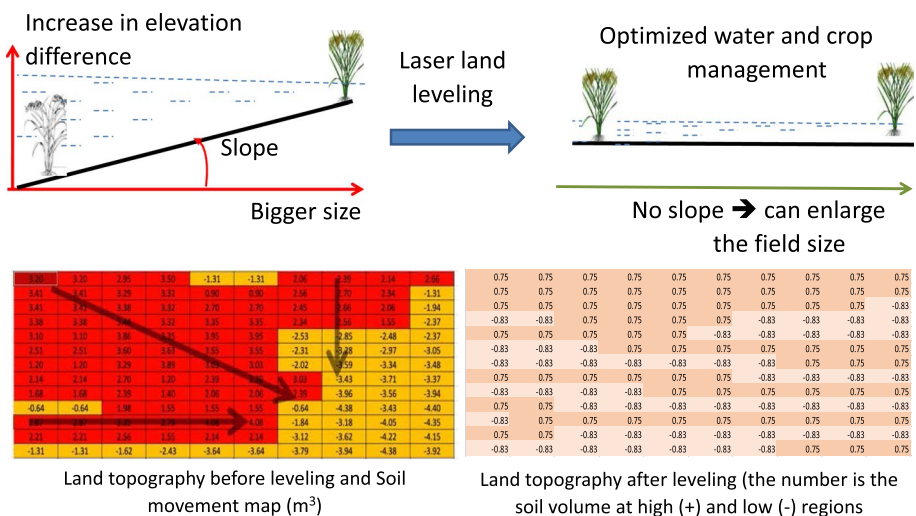
Increase in elevation difference — Slope — Bigger size

Laser land leveling

Optimized water and crop management

No slope ➜ can enlarge the field size

Land topography before leveling and Soil movement map (m³)

Land topography after leveling (the number is the soil volume at high (+) and low (-) regions

Fig. 3 Principle of improving land-use efficiency and crop management by precision land leveling

Table 1 Production factors of rice production

Production factors	Business as usual scenario					
	Unit	Cambodia	Philippines	Thailand	Vietnam	India
Land use efficiency						
Water productivity	kg rice m^{-3}	0.11–0.24[a]	0.29–0.58[b]	0.20–0.58[c]	0.30–0.48[c]	0.24–0.57[h]
Diesel for water pumping	L m^{-3}	0.03[e]	0.03[e]	0.03[e]	0.03[e]	0.03[e]
Seed rate	kg ha^{-1}	100–180[f]	60–70[g]	120–170[h]	100–150[h]	40–60 [i]
Fertilizer	kg ha^{-1}					
N		80–110[f]	80–100[g]	60–120[h]	70–130[h]	50–100 [i]
P_2O_5		50–90[f]	10–20[g]	30–60[h]	10–80[h]	20–70 [i]
K_2O		4–18[f]	8–18[g]	12–40[h]	12–24[h]	20–70 [i]
Yield (14% MC)	kg ha^{-1}	4000[f]	4000[g]	4800[h]	5500[h]	5000[i]
Soil methane emissions	kg CH_4 ha^{-1} day^{-1}	1.22[j]	1.22[j]	1.22[j]	1.22[j]	0.85[j]
Cultivation period	Day	102[j]	102[j]	102[j]	102[j]	112[j]

[a]Smith and Christen (2013)

[b]Bouman et al. (2006)

[c]Mainuddin and Kirby (2009)

[d]Sharma et al. (2018)

[e]Based on an assumption of using a 12-HP two-wheel tractor's engine, which consumes about 18 L of diesel for pumping 60 m^3 of water in an hour

[f]Castilla et al. (2019)

[g]Quilty et al. (2014)

[h]Devkota et al. (2019)

[i]Devkota et al. (2019)

[j]IPCC (2019)

Five Reductions or 1M5R" in Vietnam. 1M5R promotes six core principles: 1 Must Do=Use certified seed; 5 Reductions=seed rate, fertilizer use, pesticide use, water use and postharvest losses (Flor et al., 2021). Nevertheless, farmers agreed that LLL is an important precondition to reduce agronomic inputs and postharvest losses. Within this research, minimum levels of the benefit values integrated from secondary and primary data were used to further analyze sustainable indicators.

Analysis of energy and GHG emission balances

The net energy value (NetE) was calculated based on the net change that resulted from balancing their consumption of inputs versus the benefits of the systems per ha of rice production (Eq. 1). The output energy value (EV_{output}) was accounted for the LLL benefits, including increases in land-use efficiency and yield and decreases in agricultural inputs and postharvest losses. On the other hand, the input energy value (EV_{input}) was accounted for machine production, fuel consumption, and labor.

$$NetE = E_{output} - E_{input} \quad \left(GJ\, ha^{-1} \right) \tag{1}$$

Table 2 Benefits of LLL

Production factors	Benefits of laser land leveling (%)			
	Secondary data	Primary data (Vietnam)[*]	Selected benchmark for analysis	Factors resulted in benefits
Increased land use efficiency	3–6[a,b,c]	2–5	2	Land consolidation (bund removals or enlarged field size)
Reduced water use	10–40[a,b,c,d,e]	18–50	10	Enable optimized water management (less pumping)
Reduced seed	30–50[b,c,d,e]	27–46	27	Avoid the practice that farmers use high seed rate for the unleveled field to compensate for seed and seedling loss
Reduced Fertilizer	10–13[a,b,c,d]	10–20	10	As a consequence of the lower seed rate
Increased yield	5–15[a,b,c,d,e]	3–25	3	More uniform, better grain quality
Decrease in postharvest losses	2–5[b,c,d]	5–10	2	Reduce the risk of lodging causing harvest and postharvest losses
Decrease in soil methane emission	20-30[f]		20	Reduce stagnant water

[a]RKB (2017)

[b]Jat et al. (2009)

[c]Jat et al. (2015)

[d]Phan-Hieu-Hien et al. (2014)

[e]Sander et al. (2014)

[f]Bautista et al. (2020)

[*]Key performance interview in 18 farmers in Vietnam, 2020

Similarly, the GHGE balance (*NetGHG*) was calculated based on the net differences between the outputs and inputs of the system (Eq. 2). The outputs (*GHG_output*) was the GHGE decrease accounted for the increase of yield, reductions in agricultural input use, postharvest losses, and soil emissions. In contrast, the inputs (*GHG_input*) was accounted for machine production and fuel consumption. The energy and GHG emission conversion factors for these inputs and outputs are presented in Table 3.

$$NetGHG = GHG_{output} - GHG_{input}\left(kg\ CO_2 - eq\ ha^{-1}\right) \tag{2}$$

Cost–benefit analysis

Cost–benefit was analyzed for two value-chain actors that were farmers using LLL in their fields and LLL service providers. The cost–benefit ratio for the farmers was calculated based on balancing input costs for hiring the LLL service (service fee) and financial profits obtained from the LLL application per ha (Table 4) in terms of higher yield. The input cost for an LLL service provider was calculated based on depreciation and maintenance of the system, fuel consumption, and labor for all related operations. Within this research, the analysis was for only one type of LLL system produced by a

Table 3 Conversion factors for energy and GHG emissions

Parameters	Energy			GHG emissions		
	Unit	Value	Source	Unit	Value	Source
Consumptions for LLL						
Diesel consumption	MJ L^{-1}	44.8	a,b	kg CO$_2$-eq MJ^{-1}	0.08	a,b
Machine production	MJ L^{-1}	15.6	C			
Labor for driving LLL	MJ h^{-1}	0.44	d,e			
Labor-supporting operations	MJ h^{-1}	0.89	d,e			
Benefits (parameters for saved or decreased)						
Land use	MJ ha^{-1}	–	a,b	kg CO$_2$-eq ha^{-1}	173	a,b
Water pumping	MJ m^{-3}	1.81	F	kg CO$_2$-eq m^{-3}	0.15	f
Seeds	MJ kg^{-1}	26.7	a,b	kg CO$_2$-eq kg^{-1}	1.68	a,b
Rice production	MJ kg^{-1}	28.0	a,b	kg CO$_2$-eq kg^{-1}	2.05	a,b
Nitrogen (N)	MJ kg^{-1}	67.7	a,b,g	kg CO$_2$-eq kg^{-1}	10	a,b
P$_2$O$_5$	MJ kg^{-1}	34.1	a,b,g	kg CO$_2$-eq kg^{-1}	1.91	a,b
K$_2$O	MJ kg^{-1}	4.0	a,b,g	kg CO$_2$-eq kg^{-1}	0.347	a,b
Methane emissions				kg CO$_2$-eq kg^{-1}	30.5	a,b

[a]RKB (2017)

[b]Jat et al. (2009)

[c]Jat et al. (2015)

[d]Phan-Hieu-Hien et al. (2014)

[e]Sander et al. (2014)

[f]Bautista et al. (2020)

[*]Key performance interview in 18 farmers in Vietnam, 2020

Table 4 Parameters for LLL cost–benefit analysis in different countries

Items	Unit	Cambodia	Philippines	Thailand	Vietnam	India
Operational features and service fee						
Time for LLL operation per year	days year^{-1}	60–90	120–150	120–150	60–90	60–90
Unevenness before LLL	cm	5–20	10–30	15–20	15–20	8–25
Unevenness after LLL	cm	2–3	2–3	2–3	2–3	1–2
Capacity of LLL (assumed the same for all countries)	ha h^{-1}	0.1	0.1	0.1	0.1	0.1
Service fee for LLL	USD ha^{-1}	250–300	250–300	250–300	200–250	120–150
Consumption or inputs						
Diesel	USD L^{-1}	0.80	0.55	0.80	0.57	1.00
Tractor rental (including diesel and driver)	USD h^{-1}	20–25	20–23	15–20	10–15	7–10
Labor	USD h^{-1}	1.50	1.00	1.90	1.10	2.00
Financial benefits of LLL application						
Land use	USD ha^{-1} year^{-1}	100–200	120–240	200–400	200–300	200–400
Seed	USD kg^{-1}	0.80	0.80	0.60	0.60	0.80
Paddy	USD kg^{-1}	0.25	0.35	0.25	0.20	0.25
Fertilizer	USD ha^{-1}	150–200	100–200	150–200	170–250	100–150

manufacturer (TRIMBLE, 2020) whose equipment was mostly involved in the assessment. The investment cost of an LLL system (excluding the tractor) varies from USD 6000 to 12,000, depending on the manufacturer and location. However, within this research, the same investment cost (USD 12,000) was used for all scenarios to have a fair comparison. The LLL capacity is 0.1 ha h^{-1}. The life span of the equipment is assumed to be 5 years, which is normally used for agricultural machinery. The bank interest is 12% per year. On the other hand, the service fee is the financial benefit of the service provider.

Wet leveling applied for rice production needs to be done every cropping season, but the LLL applied on dry land to reform the field just needs to be done once every five years, which is assumed to be equal to 10 cropping seasons as is a common practice in SEA and India. The annually available time for dry LLL operation is in a range of 60–150 days for different countries (Table 4). Based on the assessments and LLL trials conducted over an approximately 10-year time frame in the region, it was assumed that the field was re-smoothed using wet leveling every season, resulting in 20% additional input cost for each season following LLL operations. Input costs and profits for farmers and service providers were calculated using Eqs. 3–6. The net profits are calculated based on the net of corresponding outputs and inputs. In addition, a sensitivity analysis was conducted on net profit and payback period by the operation capacity of LLL service providers for the cases in different countries.

$$InCost_{farmer} = Fee_{service}(1 + 0.2 * 9) \tag{3}$$

$$Output_{farmer} = Profit_{season} * 10 \tag{4}$$

$$InCost_{service} = Cost_{Depreciation + Interest + Labor + Fuel + Tractor\,rental + Management} \tag{5}$$

$$Output_{service} = Fee_{service} \tag{6}$$

While $InCost_{farmer}$ is the input cost that the farmer is paying for LLL application in 5 years or 10 cropping seasons (USD ha^{-1} 5 $years^{-1}$), $Output_{farmer}$ is the profit generated from rice production in 10 cropping seasons (USD ha^{-1} 5 $years^{-1}$), $InCost_{service}$ is the total input cost of the LLL service provider including the cost of depreciation, interest, labor, fuel, tractor rental, and management (USD ha^{-1}), and $Output_{service}$ is the service fee received from the farmer (USD ha^{-1}).

Calculation of sustainable performance indicators

The study investigated the five agronomic indicators such as water-use efficiency, nitrogen-use efficiency, phosphorous-use efficiency, productivity (grain yield), and GHG emission. These sustainable performance indicators were established by the Sustainable Rice Platform (SRP) and presented in the SRP version 2 (SRP, 2020). Agronomic input efficiency was calculated based on the corresponding application rates and yields in the countries studied. The element form of phosphorus (P) rate was translated from the amounts of P_2O_5 for each fertilizer application multiplied by a factor of 0.4364 (SRP, 2020). On the other hand, GHG emission was calculated based on the emission factors and growing periods of rice production corresponding to the countries studied.

Data collection and software

The benefits of LLL were established using the secondary data collated with an additional assessment. The assessment was conducted for the case in Vietnam based on the key informant interview approach (USAID, 1996). This research used minimum levels corresponding to the LLL benefits as benchmarks to analyse the sustainable indicators. The results correspondingly indicate the at-least values of LLL sustainability.

The LCA tools incorporated in SIMAPRO software (SIMAPRO, 2020) were used to quantify energy efficiency and GHG emissions. The conversion factors for energy and GHG emissions came from ECOINVENT (2020). Energy (MJ ha^{-1}) was analyzed based on the Cumulative Energy Demand 1.09 method (Gallen, 2010), and GHG emissions (kg CO_2-eq ha^{-1}) were analyzed based on the protocol of global warming in 100 years (GWP_{100a}) (IPCC, 2013).

Results

LLL application and performance

LLL performance and adoption vary in different countries (Table 5). There were 8–40 LLL units in each country of SEA, much lower than in India, with about 17,000 LLL machines working in the Northwest Indo-Gangetic plains. Consequently, crop field-applied LLL was 500–4,000 ha per SEA country, much lower than the approximately 11 million ha of applied LLL in India. There were various tractors with capacities ranging from 35 to 110 HP that were used for LLL. However, the 50–80 HP 4-wheel tractors were commonly used for LLL in the countries studied. The structure of LLL services also varied in different countries. For example, a LLL service only included land leveling operations in Cambodia and Thailand, but it additionally coverd ploughing before leveling in the Philippines, Vietnam, and India. On the benefits per ha of rice production, LLL reduced 1.5–2.8 m^3 water, 14–39 kg seed, and 8–10 kg N, 80–110 kg grain loss, and 19–25 kg CH_4; while increasing 120–150 kg grains.

Energy and GHG emission balances

Figure 4 shows the energy and GHG emission balances of LLL application per ha of rice production in one season for different countries. Total input energy and GHG emissions for LLL machine production and operation in negative (−) values were 5.7 GJ ha^{-1} and 268 kg CO_2-eq ha^{-1}, respectively. On the other hand, applying this technology resulted in savings expressed as positive (+) output values of 8.7–12.6 GJ ha^{-1} and 1,419–1,754 kg CO_2-eq ha^{-1}. These outputs generated net benefits of 3.0–6.9 GJ ha^{-1} and 1,151–1,486 kg CO_2-eq ha^{-1}. Of the total outputs, the highest portion of energy saving came from the yield increase, which contributed 27–39%, while that of GHG emission decreases came from the soil methane emission, which contributed 14–22%.

Table 5 LLL performance and benefits in different countries (data collected through the country extension systems in 2020)

Parameters	Unit	Cambodia	Philippines	Thailand	Vietnam	India
LLL performance (data collected through the country extension systems in 2020)						
No. of LLL units in the country		30	28	8	40	17,000
Ha of applied LLL in the country	ha	3500	550	530	4000	10,800,000
No. of LLL service providers		23	1	4	20	2,136
Operations included in LLL service		Separate plowing and LLL	Plowing and LLL	Separate plowing and LLL	Plowing and LLL	Plowing and LLL
Tractor used for plowing	HP	35–100	35–100	50–90	35–80	35–55
Tractor used for LLL	HP	70–100	35–100	60–110	45–80	35–110
LLL benefits per ha of rice production (computed from Tables 1 and 2)						
Reduced water use	$m^3\ ha^{-1}$	2,824	1,103	1,477	1,692	1,481
Reduced seed rate	$kg\ ha^{-1}$	38	18	39	34	14
Reduced fertilizer use						
N	$kg\ ha^{-1}$	10	9	9	10	8
P_2O_5	$kg\ ha^{-1}$	7	2	5	5	5
K_2O	$kg\ ha^{-1}$	1	2	3	2	5
Increased yield	$kg\ ha^{-1}$	120	120	144	165	150
Reduced postharvest losses	$kg\ ha^{-1}$	80	80	96	110	100
Reduced soil methane emission	$kgCH_4\ ha^{-1}$	25	25	25	25	19
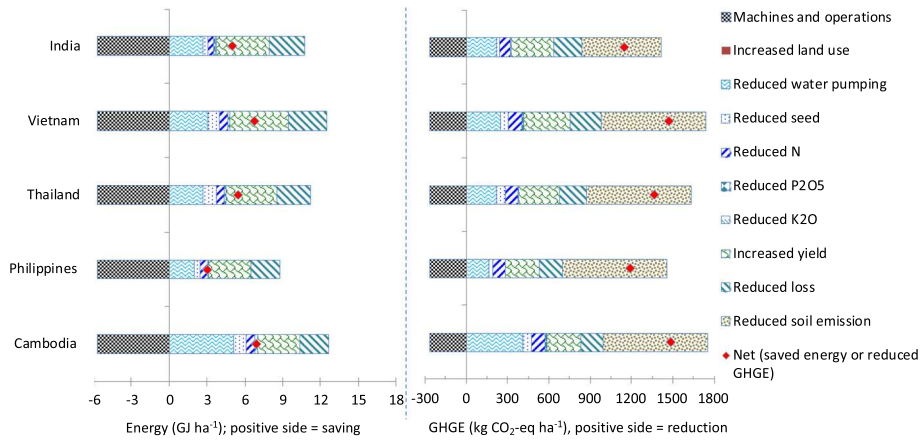
Fig. 4 Energy and GHG emission balances of LLL

Cost balance

Cost–benefit of LLL application for farmers

Figure 5 shows the cost and financial benefit for applying LLL in a 5-year cycle that was analyzed for farmer cases in different countries. LLL cost, including plowing and the leveling service fee that farmers have to pay in negative (−) value, was in the range of USD 270–603 ha^{-1} for a 5-year cycle of rice production. On the other hand, cost savings representing the added value obtained from LLL application were in the range of USD 1110–1331 ha^{-1} 5 years^{-1} depending on the price and inputs of land use, seed, and fertilizer and price, yield, and postharvest losses of rice produced. These costs and benefits generated a net profit of USD 523–840 ha^{-1} for a 10-season or 5-year cycle or USD 52–84 ha^{-1} season^{-1} of rice production in the countries of this study.
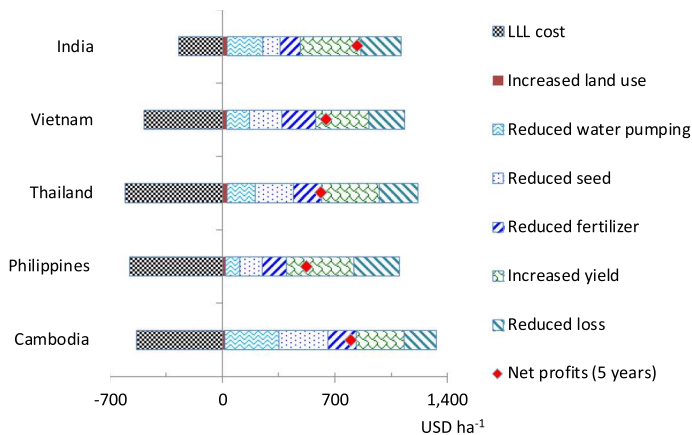
Fig. 5 Cost–benefit (USD ha^{-1}) of LLL application for a 5-year cycle of rice production

Financial analysis for LLL service providers

Figure 6 shows the net profit and payback period for an LLL service as a function of its annual capacity. The net profit of the service providers was highest in Thailand and lowest in India, depending on the service fee and LLL cost, including depreciation, maintenance, interest, fuel, labor, and tractor rental. The breakeven point of the LLL-custom service business model is reached when the service capacity reaches approximately 90 ha year^{-1}, resulting in a payback period of 3.8, 3.0, 1.3, 1.6, and 6.7 years for Cambodia, the Philippines, Thailand, Vietnam, and India, respectively.

Sustainable performance indicators of rice production applying LLL

Table 6 shows the sustainable performance indicators or rice production with applied LLL across the countries studied. LLL added benefits to rice production, leading to increased agronomic use efficiencies, decreased GHG emissions, and generated net income; are presented in the parentheses.

Discussion

The usual practice in SEA is that LLL is applied to reform the field in dry soil conditions to have higher input-use efficiency. This study was therefore conducted assuming dry-land leveling with specified conditions, such as leveling the field with a final elevation difference of 20–30 mm compared with the 150–250 mm unevenness in the original field

Fig. 6 Net profit and payback period of LLL service by capacity
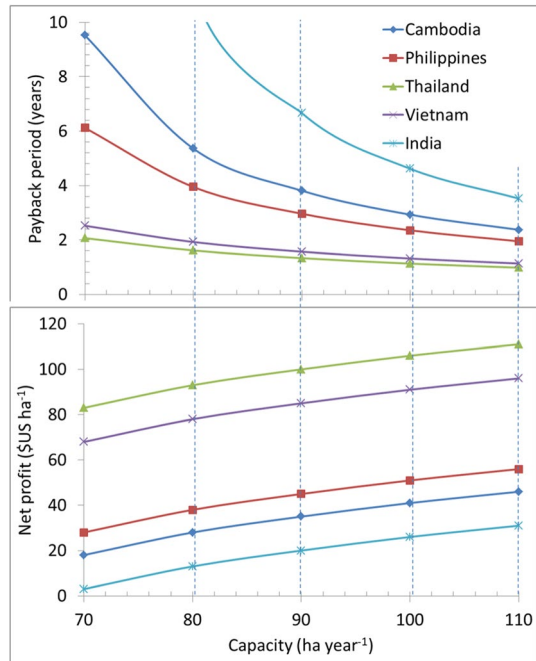
Table 6 Sustainable performance indicators of rice production applied with LLL

Sustainable performance indicators	Unit	Cambodia		Philippines		Thailand		Vietnam		India	
Water-use efficiency	kg(rice) m^{-3}	0.170	(0.003)	0.435	(0.009)	0.390	(0.008)	0.390	(0.008)	0.405	(0.008)
Nitrogen-use efficiency	kg(rice) kgN^{-1}	42.11	(4.21)	44.44	(4.44)	53.33	(5.33)	55.00	(5.50)	66.67	(6.67)
Phosphorus-use efficiency	kg(rice) kgP^{-1}	129.9	(13.0)	606.1	(60.6)	242.4	(24.2)	277.8	(27.8)	252.5	(25.3)
Grain yield	kg ha^{-1}	4000	(120)	4000	(120)	4800	(144)	5500	(165)	5000	(150)
GHG emission	kgCO$_2$-eq ha^{-1}	3484	(-697)	3484	(-697)	3484	(-697)	3484	(-697)	2666	(-533)
Net income	USD ha^{-1}	N/A	(80)	N/A	(52)	N/A	(61)	N/A	(65)	N/A	(84)

The numbers in parentheses are the value benefited by LLL: (+) = increased agronomic use efficiency and yield; (−) = reduced GHG emission; N/A = not available data

without LLL. Many other factors affecting the analysis, such as soil conditions, equipment quality, operation of the technology, etc., were not considered. For example, in India, the capacity of LLL for some specific soils and fields is 0.2 ha h^{-1} for the first time of leveling the field. This will substantially increase the net profit of service providers. This also explains why the number of pieces of LLL equipment and service providers in India is much higher than that in SEA. The significantly higher adoption of LLL in India could be explained by the laser leveling cost in India being half of that of the other countries (Table 2). Also in India, equipment is heavily subsidised at about 50% by the government, which helped spur adoption.

As the analysis showed significant positive net balances of energy, GHG emissions, and cost–benefit ratios in its 5-year cycle of application, is a demonstration on how LLL is contributing to the sustainability of rice production. Besides the quantified benefits described in the analysis, LLL application enables farmers to enlarge field size by consolidating small fields into larger ones, and this allows the mechanization of rice production, leading to other benefits such as better crop stand and pest management, solving labor shortages, and increasing productivity, efficiency, and effectiveness. This analysis illustrated that applying LLL in rice production can decrease the total energy required for rice production in SEA by 20–30% (Nguyen-Van-Hung et al., 2019; Quilty et al., 2014). Similarly, LLL application can diminish GHG emissions of rice production by 20–40%, as shown from a comparison between GHG emission decreases in this research and those reported in Nguyen-Van-Hung et al. (2019) and Romasanta et al. (2017). The added value from LLL applied for rice production (USD 90–118 ha^{-1} per season) is in agreement with that reported in Jat et al. (2015). This is 10–13% of the total income of rice production in SEA (Devkota et al., 2019; Stuart et al., 2018).

LLL has already been widely adopted in developed countries such as the United States and Australia and recently in some Asian countries such as India and China. However, it is still not significantly adopted in countries such as Cambodia, the Philippines, Thailand, and Vietnam. The major reasons may be the lack of demonstration, operation, and management capability; little understanding of the benefits; the need to depreciate the relatively high cost for the service over a 5-year period; and the lack of policy advocacy to promote this technology.

LLL can be more effective with the support of modern technologies. For example, a field topographic survey can be conducted through drone technology and fringe projection profilometry (Anguiano-Morales et al., 2018). Furthermore, digital agricultural solutions such as EasyHarvest, which includes a module for optimized scheduling of LLL (IRRI, 2020; Yahaya et al., 2019), can help to increase LLL effectiveness.

Conclusions

This study confirmed that laser land leveling can improve spatial and temporal management of rice production. Moreover, it illustrated that LLL strongly complements sustainable rice production practices as verified by its sustainable performance indicators. Despite the required inputs for machine production (depreciation) and fuel consumption of LLL, the net income, and balances of energy and GHG emission are substantially improved. LLL can help increase water, seed, and fertilizer use efficiency by at least 12, 27, and 10%, respectively. In addition, it helps to reduce at least 20% of GHG emissions from the reduction of standing water in the field. These outputs generated net energy of 3.0–6.9 GJ ha^{-1};

reduced GHG emission of 1,151–1,486 kg CO_2-eq ha^{-1}; and added an income of USD 52–84 ha^{-1} $season^{-1}$ of rice production in the countries of this study.

The result demonstrated that LLL is a sustainable technology as well as strongly supports sustainable rice production. The study would lead to better adoption of this technology through a concerted effort of an evidence-based promotion and dissemination.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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