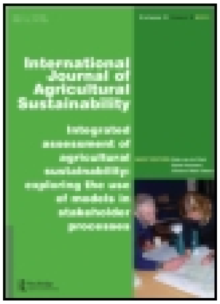

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Profitability and opportunity of conservation agriculture in acid savannah grasslands of Laos

Pascal Lienhard[a,b]*, Khamkéo Panyasiri[b], Sengphanh Sayphoummie[c], Bounma Leudphanane[c], Guillaume Lestrelin[b,d], Lucien Séguy[e] and Florent Tivet[a]

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In north-eastern Laos, the savannah grasslands of the Plain of Jars cover vast areas of potentially cultivable land. However, soil acidity, low inherent fertility, and the absence of alternatives to tillage represent significant constraints to the development of sustainable smallholder agriculture. Our objective was to evaluate the potential for conservation agriculture (CA) to enhance soil productivity and farming system profitability. A three-year rotation of rice/maize/soybean was tested under three fertilization levels and four agricultural systems: one conventional tillage-based (CT) system and three CA systems based on no-tillage with cover crops. After four cropping seasons, our results show that, compared with CT, CA systems led to similar-to-higher grain production, similar-to-higher profits, higher opportunity of livestock system intensification, and higher labour productivity regardless of fertilization levels. While CA represents a relevant alternative to current practices, our results suggest that its contribution to the emergence of a sustainable smallholder agriculture is conditioned by broader institutional transformations, including the enrolment of local manufacturers and traders for deploying no-till implements and seed market channels for cover crops, long-term public support to maintain active research and technical mentoring to farmers, and possibly the integration of ecosystem services in agricultural policy.

Keywords: acid tropical soils; no-till; cover crops; soil productivity; system profitability; rainfed agriculture; crop–livestock systems; smallholders; two-wheel tractors; scaling-up conditions

Introduction

The rapid increase in global food demand recorded over the past 50 years and the projected doubling of this demand over the next 50 years put land resources under very significant pressure to increase and sustain agricultural production (Tilman *et al.* 2002). This pressure is further accentuated by a rapidly growing demand for non-food agricultural products (Lal 2008). Increase in agricultural production can be achieved through intensification and diversification of farming systems on existing cultivated land and expansion of agriculture on marginal lands (IAEA 2000). One of the greatest potentials for expansion lies in savannah regions of humid and subhumid tropical areas. These regions comprise a sizeable amount of land resources in many countries of Africa, Latin America, and include also the largely anthropic savannahs of tropical Asia (NASA 2012). They are suitable for rainfed cropping conditions, yet considered marginal due to low inherent fertility and susceptibility to rapid degradation (IAEA 2000, Fageria and Baligar 2008). In particular, the cultivation of these soils under intensive tillage-based agricultural

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practices can result in accelerated rates of soil erosion (Montgomery 2007), soil organic matter mineralization (Lal 2008, Corbeels *et al.* 2006), and soil biodiversity losses (Kladivko 2001, Govaerts *et al.* 2007). Low- or minimum-input cropping systems are not sustainable on strongly acid and weathered soils, but with sufficient investment and adequate technologies, these soils can be highly productive (Séguy *et al.* 2006). Thus, there is a need to develop/improve management practices and define minimal investment requirements for sustainable agricultural production in tropical acid savannah grasslands.

Based on the three principles of minimal soil disturbance (no-till), permanent soil cover (mulch), and diversified crops rotations, the concept of conservation agriculture (CA) has gained increased public attention over the past decade as an economically and ecologically sound alternative to tillage-based agriculture (Hobbs 2007, Triplett and Dick 2008, Kassam *et al.* 2009, Derpsch *et al.* 2010, Jat *et al.* 2012). In particular, CA is being advocated for enhancing soil health and long-term crop productivity (Hobbs 2007, Govaerts *et al.* 2007, Tivet *et al.* 2013). In large-scale agriculture, CA has been demonstrated to have long-term positive effect on farm incomes, resulting mainly from a reduction in field operational costs, and, to a lesser extent, from increases in soil productivity (Dixon 2003, Bolliger *et al.* 2006, Séguy *et al.* 2006, Triplett and Dick 2008). Comparatively, data on the effect of CA on soil productivity and profitability in small-scale agriculture are much more limited (Dixon 2003).

In this context, our objective was to evaluate the early effects of conservation vs. conventional agricultural management on soil productivity and profitability in the context of smallholder farming constrained by low soil fertility. The case study was conducted in the Plain of Jars, an altitude savannah grassland of about 80,000 ha located in Xieng Khouang Province, north-eastern Laos. Traditional farming systems in the area are based on lowland paddy rice cultivation and extensive livestock production in surrounding grasslands (Hacker *et al.* 1998, Lienhard *et al.* 2006). With limited opportunities for agricultural expansion in the lowlands, the development of rainfed agriculture in the uplands is a key challenge for increasing local agricultural production. However, low pH (5.0), high aluminium saturation ($>$77%), and severe nutrient deficiency represent important agronomic constraints for this expansion (Gibson 1997, Hacker *et al.* 1998). Attempts to develop rainfed production started in the early 1980s and were all based on ploughing and limited-to-no soil amendments; this latter explains mostly the slow expansion of rainfed cultivated areas during the last decade (Kongay *et al.* 2010). To respond to the challenge of developing sustainable rainfed cropping systems in the region, we initiated in 2008 a three-year rotation of rice (*Oryza sativa* L.), maize (*Zea mays* L.), and soybean (*Glycine max* (L.) Merr.) under four management practices (conservation vs. conventional tillage (CT)-based agriculture) and three levels of mineral fertilization (moderate to high). The effects of management practices on soil productivity and economic returns were evaluated four years after conversion of native grasslands into agricultural land. The results are presented and discussed in the first section of this paper. In the second section, we discuss the conditions for emergence of a sustainable smallholder agriculture based on CA in Laos' savannah grasslands.

Material and methods

Experimental design

Experiments were conducted in Poa village (Lat. 19°33′N, Long. 102°59′E) at 1,130 m AMSL. The climate is tropical and mountainous with a six-month (April–September) wet and hot season and a six-month dry season including three months of cold (December–February). The mean annual precipitation is 1400 mm. The soils at the site are red clayey Oxisols (USDA classification). Rice and maize are the main staple and commercial crops cultivated in the area (Lienhard *et al.* 2006). Soybean is cultivated to a lesser extent, but was integrated into the rotation sequence due to the

Table 1. Experimental design and treatments selected for the study.

	Modalities	
Factor	Nb	Description
Starting crop	3 (1[a])	Rice[a], or maize or soybean
Cropping system	4[a]	Three-year rotation of rice, maize, and soybean under: ■ One CT system : ploughing with discs × burying of former crop residues × no cover crops ■ Three CA systems (CA1, CA2, and CA3): no-tillage × maximum soil cover × cover crops associated prior to and with main crops: prior to: Fm + Pp, Fm + stylo, and ruzi + Pp for CA1, CA2, and CA3, respectively. with rice: stylo for all CAs. with maize: Fm + Pp, stylo, and ruzi for CA1, CA2, and CA3, respectively. in succession of soybean: oat + buckwheat for all CAs.
Annual fertilization	3 (2[a])	F1[a]: 60–80–60 kg/ha of N–P_2O_5–K_2O (*N limited to* 32 kg/ha *for soybean*). F2[a]: 120–160–120 kg/ha of N–P_2O_5–K_2O (*N limited to* 32 kg/ha *for soybean*). F3: F2 during the two first years; F1 after that.

Main crops: rice cv. Sebota1, maize hybrid LVN10, soybean cv. Asca. Cover crops: Fm, finger millet (*Eleusine coracana* Gaern); Pp, pigeon pea (*Cajanus cajan*); stylo, *Stylosanthes guianensis* cv. CIAT 184; oat, *Avena sativa* L.; buckwheat, *Fagopyrum esculentum* Moench; ruzi, ruzi grass (*Brachiaria ruziziensis*). Fertilization: N comes from urea (46% N), P_2O_5 from thermo phosphate (16% P_2O_5, 28% CaO, 18% MgO), and K_2O from KCl (60% K_2O).
[a]Modalities selected for the study.

large demand of neighbouring countries (e.g. Vietnam). The three-year rotation of rice, maize, and soybean was conducted in a split–split plot experimental design combining three factors (Table 1) with three replications of 270 m^2 each for a total of 108 sub-sub-plots. The analysis was limited to rice-starting treatments (Table 1), rice being the most acid-tolerant crop (Fageria and Baligar 2008), and to the two extreme fertilization levels (F1 and F2; total of eight treatments and 24 plots).

All treatments received an initial application of 2 Mg/ha of locally produced lime (27% of CaO) to increase soil pH and limit aluminium toxicity. Sulphur powder (30 kg/ha, 99.5% S), manganese sulphate (20 kg/ha, 25% Mn), zinc sulphate (20 kg/ha, 25% Zn), and borax (10 kg/ha, 15% Bo) were also applied to correct micronutrient deficiencies observed in previous experiments (Lienhard *et al.* 2008). Soil mineral amendments were buried by ploughing under CT and broadcasted on the soil surface under CA. Annual mineral fertilization rates (Table 1) were calculated according to grain yields expectations: F1 represents a moderate fertilization level that was expected to compensate nitrogen (N) exportations related to cereal production (about 12–16 kg of N exported per Mg of rice or maize grains exported, CIRAD-GRET 2002), and compensate potassium (K) exportations related to soybean production (about 23 kg of K_2O exported per Mg of soybean exported, CIRAD-GRET 2002). The higher fertilization level, F2, was expected to ensure higher yields and a positive balance of N and K in soils.

Land preparation under CT was performed by local contractors on a fee-for-service basis and consisted of one annual disc ploughing with a 90 hp tractor in April at the beginning of the rainy season. It was followed by one light offset disc harrowing before sowing. In 2010, ploughing was also realized in November to limit weed flowering and spreading. Land preparation under CA systems consisted in the rolling of cover crops and crops residues in March and April, using a locally made rolling knife for two-wheel tractors (Figure 1a), and in the spraying of total

Figure 1. CA implements used for land preparation and sowing: (a) locally made rolling knife for two-wheel tractor, (b) 20-l-wheel sprayer (Knapick, Brazil), and (c) one-row NT planter (Fitarelli, Brazil) adapted for two-wheel tractor.

herbicides (glyphosate and 2.4D-amin) 20–30 days before sowing, using a 20-l-wheel sprayer (Knapick, Brazil, Figure 1b).

All crops were sown using a one-row no-till (NT) planter (Fitarelli, Brazil) initially designed for animal traction and locally adapted for two-wheel tractors, which are popular among smallholders in the area. The direct seeder has a coulter, which cuts into the mulch, a double disc opener, which opens a small rip-line, a seed, and fertilizer hopper, and finally a drive wheel that activates seed and fertilizer release and covers the seed at the same time (Figure 1c). In 2007, cover crops were cultivated prior to main crops under CA systems (Table 1) as a preliminary 'biological' tillage (e.g. soil structure improvement by mulch, roots, macrofauna, and microbial activity) in replacement of traditional ploughing under CT. In 2007, finger millet, ruzi grass, stylo, and pigeon pea (Table 1) were sown in the beginning of July (late establishment) at a sowing density of 10, 12, 6, and 18 kg/ha, respectively, and harvested in October, November, and February, respectively (no harvest of stylo legume). Finger millet and pigeon pea productions were used to feed pigs in partial replacement of maize and commercial protein supplement, respectively. Ruzi grass seed production was sold locally to development projects working on cattle fodder system intensification. Rice, maize, and soybean were sown in rows in May using the same NT planter, with 35, 75, and 40 cm between rows and a sowing density of 55, 20, and 60 kg/ha, respectively. Rice and maize were harvested in October, soybean in September, and all productions were sold locally. Stylo legume, ruzi grass, and finger millet (Table 1) were broadcasted in rice and maize 30 days after main crop sowing, at a sowing density of 8, 10, and 10 kg/ha, respectively. Pigeon pea (22 kg/ha) was manually sown in maize inter-row 30 days after maize sowing, by using a bamboo stick. Oat (80 kg/ha) and buckwheat (15 kg/ha) were broadcasted in soybean, after the first leaves of soybean started to fall. In 2009, stylo legume and ruzi grass associated with maize in CA2 and CA3 systems (Table 1) were manually cut and exported to feed local bulls maintained in stalls for a 110-day fattening period.

Soil productivity

Grain yield and aboveground dry matter (AGDM) production were used as indicators of soil productivity. AGDM productions included weeds and cover crops contributions and were estimated twice a year: at main crops harvest and before land preparation. Measures were made in each plot on six subplots of 4 m^2 each randomly chosen. A random lump crop residue sample of 2 kg was taken from the six subplots to determine dry biomass. In 2009, stylo legume and ruzi grass biomasses exported for cattle fattening were measured at plot scale (270 m^2). Grain yields were measured annually at plot scale.

Cropping system profitability

Net income, net present value (NPV), return on investments, and labour productivity were used as indicators of the cropping systems' profitability. Net income was calculated as the difference between production value and production costs per unit area. The NPV of an income stream is the sum of the present values of the individual amounts in the income stream (Baker 2000) and was calculated as follows:

$$\text{NPV}(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

where t is the time of the cash flow, N is the total number of periods (3 for CT, 4 for CA systems), R_t is net cash flow (i.e. cash inflow − cash outflow) at time t, and i is the discount rate (i.e. the rate of return that could be earned investing the money someplace else; also referred to as the opportunity cost of capital). Here, we used a discount rate of 7%, which is the casual interest rate in local commercial banks for long-term deposit. Investments (e.g. fencing, machinery) were calculated based on the expected useful life and depreciation of the equipments. Labour productivity was calculated as the net income to labour ratio. Inputs and labour were annually collected at plot scale. In the absence of local markets for forage grains, the economic value of finger millet and pigeon pea used for pigs was calculated by substitution: finger millet, which replaced maize in pig daily food intake, was given 50% of maize purchasing price. Similarly, pigeon pea was given 50% of commercial protein supplement price. The benefits from bulls fattening activity were shared between CA2 and CA3 systems according to the relative contribution of stylo legume and ruzi grass, respectively, to overall animal protein supply. The latter was calculated as the total amount of dry matter supplied, multiplied by the mean protein content of the forage measured on lump forage samples at the Vietnamese soil and Fertilizer Research Institute (mean protein content of 22 and 13% for stylo and ruzi, respectively). Economic calculations were made using constant mean price in US$ over the 2007–2010 periods to avoid bias related to price variations over the years. Annual data were aggregated to calculate total grain and stubble productions, production costs, net incomes, and mean labour productivity.

Statistics

The effects of agricultural management on soil productivity and economic returns were tested separately for each fertilization level by one-way analysis of variance. Differences between means were tested by paired multiple comparison using Fisher's test (least significant difference) ($P < 0.05$).

Results

Effects of agricultural systems on soil productivity

Grain yields

Four years after the conversion of savannah grassland into agricultural land, we observed significant differences in grain yields according to fertilizer use with a total mean grain production for the three main crops of 6.8 and 11.2 Mg/ha under F1 and F2 fertilization levels, respectively (Table 2). However, the gains in productivity related to increased fertilization were different according to crops: in the early stage of cultivation, hybrid maize appeared as the most sensitive to variations in nitrogen, phosphorus, and potassium (NPK) supply with almost two-fold higher maize yields observed under F2 as compared with F1 (Figure 2a). The effect of higher fertilization

Table 2. Soil productivity per fertilization level and cropping system (total 2007–2010).

Agricultural system	Grain yield (Mg/ha)		Stubble yield (Mg of DM/ha)	
	(1)	(1) + (2)	(1)	(1) + (2)[a]
F1				
CT	6.4 ± 0.6[b]	6.4 ± 0.6[c]	10.3 ± 1.0[b]	13.8 ± 0.7[c]
CA1	7.9 ± 0.7[a]	9.3 ± 0.8[a]	12.3 ± 1.3[a]	20.5 ± 1.4[b]
CA2	6.8 ± 0.7[ab]	8.0 ± 0.9[b]	10.8 ± 0.3[ab]	19.1 ± 0.4[b]
CA3	6.2 ± 0.5[b]	6.3 ± 0.5[c]	9.7 ± 0.7[b]	23.1 ± 0.7[a]
F2				
CT	11.6 ± 1.1[ab]	11.6 ± 1.1[bc]	17.7 ± 0.9[ab]	20.5 ± 0.8[b]
CA1	12.3 ± 0.7[a]	14.3 ± 0.8[a]	19.1 ± 0.8[a]	31.9 ± 0.9[a]
CA2	11.2 ± 1.2[ab]	13.1 ± 1.4[ab]	17.3 ± 0.9[b]	28.9 ± 1.5[a]
CA3	9.9 ± 1.3[b]	10.1 ± 1.3[c]	14.5 ± 1.0[c]	30.4 ± 1.1[a]

Fertilization level: F1, medium; F2, high. Cropping systems: CT, conventional tillage; CA (1, 2, and 3), conservation agriculture systems. DM, dry matter. Letters between brackets indicate significant differences according to Fisher's test ($P < 0.05$).
(1), main crops; (2), cover crops.
[a]Weeds biomass.

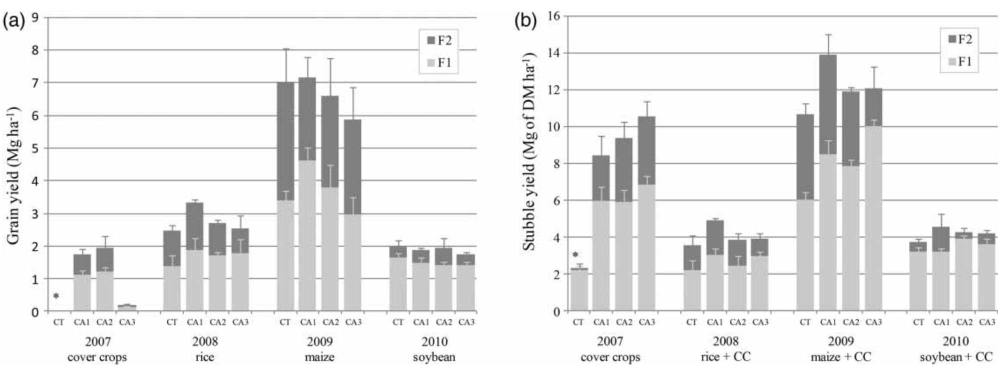

Figure 2. Grain (a) and stubble (b) yields per fertilization level, cropping system, and crop. Fertilization level: F1 (medium) and F2 (high). Cropping systems: CT, conventional tillage; CA (1, 2, and 3), conservation agriculture systems. Error bars indicate standard deviations of the means, $n = 3$. DM, dry matter; CC, cover crops. *savannah grassland.

on grain yield increase was less important on rice (40–80% increase under F2 as compared with F1) and soybean (20–40% increase).

The analysis of cropping systems' effect on grain yields showed that grain production decreased along the gradient CA1 $\geq$ CA2 and CT $\geq$ CA3 (Table 2). This trend logically increased when considering the grain production of cover crops associated prior to and with main crops in CA systems (Table 2).

Stubble yields

As for grains, we observed significant differences in stubble yields according to fertilizer use with 1.5-fold higher biomasses produced under F2 than under F1 (Table 2). In addition, the use of cover crops prior to and with main crops under CA systems modified significantly biomass production between agricultural systems, with 1.5-fold higher total AGDM observed under all CA systems as compared with CT (Table 2). The mean AGDM exported in 2009 under CA2 and CA3 for cattle fattening was 1.1 and 3.1 Mg/ha under F1 for stylo and ruzi, respectively, and of 0.8 and 2.7 Mg/ha under F2 for stylo and ruzi, respectively (data not shown).

Effects of agricultural systems on economic return

Production costs

We observed logically significant differences in production costs depending on fertilizer use with total mean production costs of 1760 and 2450 US$/ha under F1 and F2, respectively (Table 3).

We observed higher initial investments under CAs (from 730 (F1) to 1020 (F2) US$/ha) than under CT (from 530 (F1) to 700 (F2) US$/ha), due to cover crops cultivation prior to rice cropping and the need for specific implements like rolling knife or cutting disc for seed drill (Figure 3). Despite higher initial investments under CAs, the total production costs were significantly higher under CT than under CA systems (Table 3), due to lower annual variable costs, in particular for land preparation and weed management (Figure 3).

Regardless of the cropping system, fertilizers represent the main production cost and account for 45% (CT × F1) to 65% (CAs × F2) of total production costs (Figure 3).

Net incomes and NPVs

We observed a positive but highly variable effect of agricultural systems on profits, with total net incomes ranging from 200 to 1300 US$/ha depending on the fertilization level, cropping system, and the integration of cover crops value into the economic calculations (Table 3). We found 1.5- to 3-fold higher net incomes under F2 than under F1 (Table 3), mainly due to the positive grain yield response of maize to increased fertilization (Figure 2a). Without cover crops, net incomes decreased along the gradient CA1 > CA2 and CT ≥ CA3 (Table 3), due to lower production costs (Table 3) and similar (CA2, CA3) to higher (CA1) grain production under CA systems (Table 2). The significant differences in net incomes observed between CT × F2 and CA3 × F2 (Table 2) are explained by differences in soybean production (Figure 2a) in context of high

Table 3. Profitability per fertilization level and cropping system (total 2007–2010).

	Cropping system (1) + (2)	Production cost (US$/ha) (1)	Net income (US$/ha) (1) + (2)	NPV (US$/ ha) (1) + (2)	Labour (wd/ ha) (1) + (2)	Labour productivity (US$/wd) (1) + (2)
F1						
CT	1897 ± 14[a]	223 ± 89[b]	223 ± 89[c]	168 ± 65[c]	227 ± 14[b]	1.0 ± 0.3[c]
CA1	1671 ± 26[c]	612 ± 81[a]	834 ± 93[a]	596 ± 61[a]	234 ± 13[b]	3.6 ± 0.8[a]
CA2	1753 ± 15[b]	265 ± 62[b]	507 ± 73[b]	332 ± 52[b]	252 ± 17[a]	2.0 ± 0.5[b]
CA3	1710 ± 28[c]	201 ± 97[b]	837 ± 96[a]	617 ± 32[a]	261 ± 27[a]	3.2 ± 0.8[a]
F2						
CT	2522 ± 16[a]	759 ± 84[b]	759 ± 84[c]	593 ± 79[c]	247 ± 17[c]	3.1 ± 0.3[c]
CA1	2404 ± 29[b]	969 ± 80[a]	1241 ± 88[a]	920 ± 71[a]	255 ± 12[bc]	4.9 ± 0.7[a]
CA2	2442 ± 54[b]	772 ± 96[b]	1056 ± 102[b]	749 ± 88[b]	271 ± 18[ab]	3.9 ± 0.6[b]
CA3	2413 ± 47[b]	444 ± 98[c]	1095 ± 121[b]	812 ± 63[b]	277 ± 23[a]	4.0 ± 0.8[b]

Fertilization level: F1 (medium) and F2 (high). Cropping systems: CT, conventional tillage; CA (1, 2, and 3), conservation agriculture systems. Net income: difference between production value and production costs. NPV: sum of the present values of the individual annual cash flows. Labour productivity: net income to labour ratio. wd, working day. Letters between brackets indicate significant differences according to Fisher's test ($P < 0.05$).
(1), main crops; (2), cover crops.

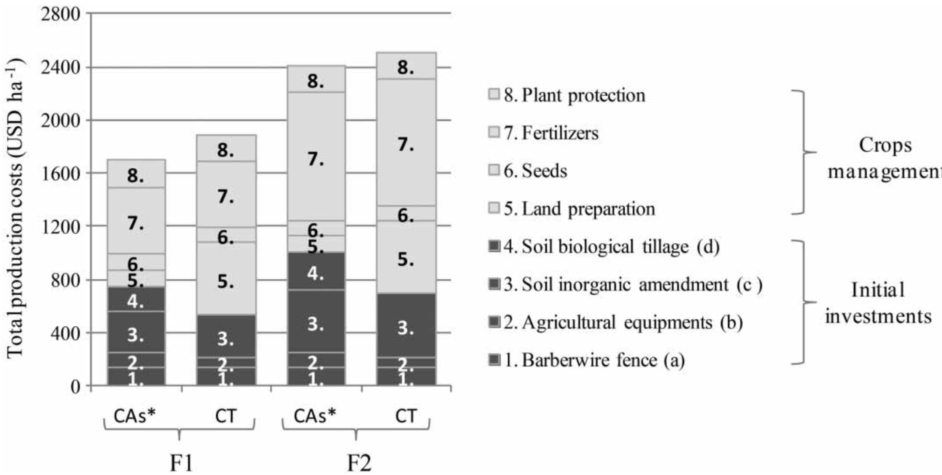

Figure 3. Production costs distribution per fertilization level and cropping system (total 2007–2010). Fertilization level: F1 (medium) and F2 (high). Cropping systems: CT, conventional tillage; CA (1, 2, and 3), conservation agriculture systems. *Mean value of the three CA systems. (a) Four-line barber wire fence with wood pots every 2 m, expected useful life of eight years, depreciation value of 15%; (b) one-row Fitarelli seed drill adapted for a hand tractor with cutting disc and disc openers (500 US$ in 2006), expected useful life of 10 years, depreciation value of 15%; performance of 10 ha/year (capacity of 0.5 ha/day for a 20–25 days sowing period); 20-l-Knapick wheel sprayer (250 US$ in 2006), expected useful life of 10 years, depreciation value of 15%; performance of 20 ha/year (capacity of 2 ha/day for a 10–15 days spraying period); rolling knife for hand tractor (only for CA systems, 300 US$), expected useful life of 15 years, depreciation value of 10%; performance of 40 ha/year (capacity of 2 ha/day for a 20–25 days rolling period); (c) F1: 2 Mg/ha of local lime, 1 Mg/ha of thermo phosphate and 80 kg/ha of micronutrients (S, Bo, Mn, and Zn); F2: similar fertilization except for thermo phosphate (2 Mg/ha); (d) cover crops cultivated in 2007 in CA systems in replacement of soil ploughing: include land preparation, seeds, and NK fertilizers.

soybean sale prices (mean value of 690 US$ Mg^{-1} during the experiment phase). When considering cover crops additional economic value, net incomes decreased along the gradient CA1 and CA3 > CA2 > CT (Table 3), due to the additional benefits from pigs (CA1) or cattle (CA2, CA3) fattening activities and forage seeds sales (CA3).

The NPVs decreased along a gradient similar to the one observed for the cumulated net incomes (Table 3). However, we observed lower differences of NPVs between conventional and CA systems as compared with the cumulated net incomes, due to the one-year cultivation of forage crops prior to rice cultivation under CA systems (Table 3).

Labour requirements and labour productivity

We observed significant differences in labour requirements depending on fertilization levels. Due to higher requirements for grain harvest and post-harvest processing, more labour was required over the four cropping seasons under F2 (262 wd/ha) than under F1 (244 wd/ha) (Table 3). Labour requirements were significantly higher under CA2 and CA3 than under CA1 and CT (Table 3), due to increased labour for the slashing of stylo (CA2) and ruzi (CA3) for 2009 cattle fattening activities. Annual mean labour force ranged from 55 to 90 wd/ha depending on fertilization level, cropping systems, and cultivated crops, but the labour requirements at the beginning of the rainy season (April–June) never exceeded 25 wd/ha regardless of the agricultural system (data not shown).

We observed variable effects of agricultural systems on labour productivity according to fertilization level and agricultural systems, with mean labour productivity over the four-year period ranging from 1.0 to 5.0 US$ per wd (Table 3). Mean labour productivity was found 1.5- (F2) to 3-fold (F1) higher under CA systems than under CT (Table 3).

Discussion

Conservation vs. tillage-based agricultural systems

Effects on soil productivity

Our four-year experiment shows that total grain production was similar (CA2 and CA3) to higher (CA1) under CA systems than under CT independently of the fertilization level (Table 2). These results contrast with studies showing that crop productivity is reduced under NT systems, especially during the first years of conversion towards CA (Corbeels *et al.* 2006, Ogle *et al.* 2012). Instead, they highlight that soil productivity is either not or positively affected by CA management, being similar in this to several studies (Abrol *et al.* 2005, Séguy *et al.* 2006, Derpsch *et al*. 2010, Johansen *et al.* 2012).

In addition, larger differences in soil productivity between CT and CA systems could be observed in the coming years. Indeed, Lienhard *et al.* (2013) have shown on the same experimental site that CT was leading to a rapid degradation of the physico-chemical properties of top soils (e.g. decreased aggregate stability, reduced organic carbon and nitrogen contents) as well as a decrease in microbial abundance (e.g. reduced total biomass, bacterial and fungal densities). These impacts jeopardize long-term agricultural sustainability (Kladivko 2001, Govaerts *et al.* 2007).

Finally, compared with CT, CA systems offer a more diversified grain production. In turn, this production can contribute to livestock fodder system intensification and could potentially be valorised through new seeds market channels (e.g. forage seeds, oat, and buckwheat).

In addition, grain productivity can still significantly be improved since, under similar ecological conditions (i.e. tropical acid savannahs of the Brazilian Cerrados) and with similar fertilization levels, Séguy *et al.* (2006) reported grain yields higher than 6 and 4 Mg/ha for rice and soybean, respectively. Further experimentation to select adequate varieties, sowing dates, cropping itineraries, and more diversified leguminous cover crops could help further improve soil productivity.

While natural savannah grasslands show a mean annual AGDM production of 2.6 Mg/ha (Lienhard *et al.* 2013), their conversion to agricultural land led to mean annual AGDM productions ranging from 4 to 8 Mg/ha (Table 2). This represents a substantial increase in biomass production, both in terms of quantity and diversity. Compared with CT, CA systems were found to produce 1.5-fold higher AGDM biomass and appear therefore more capable to ensure sustainable production and income diversification. Most of this biomass was used for in situ recycling and has been shown to contribute to enhancing soil chemical, physical, and biological properties (Lienhard *et al.* 2013). A small part (5–15% of total AGDM production) was also used under CA2 and CA3 systems (during the maize intercropping sequence) as fresh forage for cattle feeding.

As in many developing countries (Lal 2005, Kassam *et al.* 2009, Johansen *et al.* 2012, Valbuena *et al.* 2012), the share of crop residues and cover crop biomass between in situ recycling, livestock, and other options like energy supply is a key issue influencing the effects of CA systems on soil productivity and profitability in the Plain of Jars. CA requires a critical level of crop residues to maintain soil properties and prevent land degradation (Govaerts *et al.* 2007, Blanco-Canqui and Lal 2009, Kassam *et al.* 2009). At the same time, livestock plays a

Figure 4. Manual wheel NT planter (Brazil) suitable for the sowing in line of various crops under limited soil mulch conditions.

crucial role – as a source of food, income, and living capital – in the traditional farming systems of the Plain of Jars (Gibson 1997, Lienhard *et al.* 2006). The intensification of the cattle industry is also a priority of Lao authorities to alleviate poverty (Gol 2004). Finally, new opportunities are emerging in the Plain of Jars (Lienhard *et al.* 2006) and, more generally, in southeast Asia (Lal 2005) for using crop residues for energy supply such as biofuel and biogas. Thus, further research would be needed to improve AGDM production, notably during rice and soybean cropping sequences for which low AGDM production was observed (<5 Mg/ha, Figure 2b). For instance, AGDM production could potentially be improved by replacing the broadcasting of cover crops with more effective sowing methods. Boulakia *et al.* (2008) showed the effective establishment of stylo into rice by sowing stylo at rice tillering early stage using a two-row NT planter for hand tractor. The use of simple and cheap manual wheel NT planter (Figure 4) may also help improving the establishment of cover crops and subsequent biomass production.

Effects on profitability

After four cropping seasons, our results show that total net incomes were similar (CA2 and CA3 without cover crop value) to higher (CA1, CA2, and CA3 with cover crop additional value) under CA systems than under CT (Table 3). These results are linked to similar-to-higher grain productions (Table 2), lower production costs (Table 3), and higher opportunities for income diversification under CA systems. Similar observations were made in studies conducted in both large-scale (Dixon 2003, Hobbs 2007, Triplett and Dick 2008, Derpsch *et al.* 2010) and small-scale (Abrol *et al.* 2005, Johansen *et al.* 2012) mechanized farming systems. While the latter studies highlight that the main interest of farmers for adopting CA relates to reduced field operational costs (e.g. fuel conservation, labour cost reduction, longer machinery life), reduced production costs in our study were mainly related to land preparation, with higher fees for tractor ploughing under CT than for rolling and herbicide spraying under CA (Figure 3). At the same time, if implementation costs were significantly lower for CA systems, initial investments were higher compared with CT (Figure 3). Higher initial investment requirements under

CA as compared with CT have been described as a major constraint for CA adoption in other small-scale agricultural conditions (Kassam *et al.* 2009, Chabierski *et al.* 2011), but is often neglected in most comparative costs–benefits analysis (Hobbs 2007, Triplett and Dick 2008).

Compared with CT, CA systems offer higher opportunities for income diversification in relation to forage seeds sales (CA3), forage grains used for pigs production (CA1, CA2), and forage used for cattle fattening (CA2, CA3) (Table 3). These results are in line with other studies showing the economic interest of using part of the cover crops production for livestock farming activities (Husson *et al.* 2003, Jullien *et al.* 2008; Landers 2007). Thus, the design and promotion of integrated crop–livestock farming systems represents undoubtedly an interesting pathway for the dissemination of CA systems in the Plain of Jars. The development of markets for cover crops constitutes also an important precondition for the diversification of agricultural systems and the adoption of intercropping practices (Lienhard *et al.* 2008, Lestrelin *et al.* 2012b).

A key challenge for many rural households of southeast Asia is certainly how to optimize the use of limited labour force (Garrity 1996). The effect of agricultural systems on labour requirements and labour productivity is therefore a relevant economic tool to evaluate the potential interest of innovative agricultural systems for smallholders. In contrast with many studies (e.g. Hobbs 2007, Triplett and Dick 2008, Kassam *et al.* 2009), our experiments show that the establishment and management of cover crops can engender higher total labour requirements under CA than under CT (Table 3). However, with mechanized land preparation and sowing operations, all agricultural systems tested required fairly limited labour (<25 wd/ha) at the beginning of the rainy season (April–June). These systems allow thus to avoid competition with lowland paddy rice establishment, which remains a priority for the smallholders of the region (Lienhard *et al.* 2006). Finally, CA systems appeared more labour-effective with a mean labour productivity 1.5- to 3-fold higher under CA than under CT (Table 3).

Jobard (2010) estimated that the annual income of rural households in the area ranges between 1200 and 2700 US$. The promotion of the most effective CA crop–livestock systems (CA1 and CA3) tested in the present study would allow generating mean annual net income of 300 US$/ha, hence contributing to improve household income by 10–25% for each hectare cultivated under CA.

Facilitating the emergence of a sustainable CA-based smallholder agriculture in the savannah grasslands of Laos

The results of our study suggest that CA could represent a relevant alternative to current tillage-based agricultural systems for expanding smallholder agricultural production in a marginal environment like the acid savannah grasslands of the Plain of Jars. Beyond the agro-ecological dimension however, various studies suggest that the dissemination of CA practices among smallholders may also require broader organizational, institutional, and policy transformations (e.g. Erenstein 2003, Knowler and Bradshaw 2007, Lestrelin *et al.* 2012a, 2012b).

Enhancing local access to CA-specific implements

As indicated above, the cultivation of lowland paddy rice remains a priority for the rural households of the study area. Households with access to lowland paddy fields allocate most of their labour force to this production at the beginning of the rainy season. As a result, innovative farming systems in the uplands have limited chance to expand without specific, small-scale equipment for land preparation and sowing operations. Yet, the absence and the cost of suitable implements are often described as a key bottleneck for CA wide adoption worldwide (Abrol *et al.* 2005, Kassam *et al.* 2009, Derpsch *et al.* 2010, Johansen *et al.* 2012). In our experiments, for instance, the NT planter and wheel sprayer

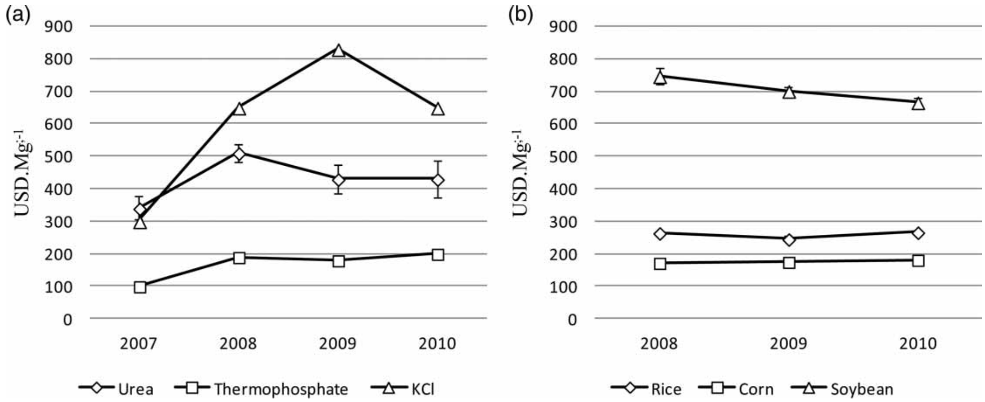

Figure 5. Local prices evolution of: (a) mineral fertilizers (N, P_2O_5, and K_2O), and (b) main crops (rice, maize, and soybean). Bars indicate standard deviation values.

were imported from Brazil, making the acquisition and maintenance processes very complex and costly. Thus, an increased enrolment of local manufacturers would be needed for developing and deploying affordable and effective CA implements.

Reducing fertilization costs

In our experiment, fertilizers represented the main production cost and accounted for 45–65% of the total production costs (Figure 3). Due to the oil crisis, fertilizer prices have experienced a sharp increase after 2007 (Figure 5a), while agricultural prices have been steady or decreasing (Figure 5b). As a result, fertilization cost increased by 80% between 2007 and 2010, jeopardizing the economic benefits in the absence of a similar increased value of the production. A regional study on fertilizers' diversity, price, and accessibility would allow choosing the cheapest NPK formulation. The identification of an increased number of regional traders and the negotiation of more important volumes might also help reducing fertilizers unit prices. Finally, the recent opening of a potassium (K) factory[1] in Laos may also help reducing the cost of K_2O supply, this latter showing the highest price increase (+116% in four years, Figure 5a).

A reduction of K_2O supply to cereal may have little effect on soil nutrients balance and productivity, unless cereal straws are returned to the soils (5 kg of K_2O exported per Mg of rice or maize grains exported, but 10–30 kg of K_2O exported per Mg of rice or maize straws exported, CIRAD-GRET 2002).

The main strategy to reduce fertilizer use and cost is to increase the amount and diversity of plant material returns to the soil. Cover crops could notably be more diversified and include legumes such as hairy vetch (*Vicia villosa*), faba bean (*Vicia faba*), and/or grass pea (*Lathyrus sativus*) to increase the N pool directly accessible for rice and maize (Séguy *et al.* 2006).

Improving first year economic return

In our experiments, forage crops cultivated prior to rice cropping under CA systems for soil biological tillage were harvested and economic returns were related to forage grain sales or use for pig feeding. In the absence of forage seed market and/or subsidies for soil improvement, the cost of this first cropping year is a major constraint for the diffusion of the CA systems tested. It decreases the NPV of CA systems and increases the economic risks for farmers and credit suppliers. However, in situ experiments have shown that the direct seeding of rice after the chemical control of native grass could give similar grain productivity (Jobard 2010, Lestrelin *et al.* 2012a). Thus, one option would be to replace this first year of soil biological improvement by the direct seeding of rice associated with forage species (e.g. ruzi grass, stylo legume).

Reshaping institutions and policies

CA systems are capital-intensive for smallholders and may therefore require some level of financial support to be promoted and implemented. In particular, with limited guarantees (e.g. permanent land titles) to support their demand, many smallholders from our study area encounter difficulties in gaining access to bank loans that are, in any case, subject to high interest rates (14–18% per year, Lienhard *et al.* 2008). The one-year refund period generally applied by creditors in the Plain of Jars is also poorly adapted to the timeframe of the integrated crop–livestock systems tested by our research team. Facilitated access to mid-term credit (five years) with low interest rate (3–5%) would be necessary to support investments like barbed wire, CA-specific equipments, and soil amendments for correcting soil nutrient deficiencies representing an initial charge of ~600 US$/ha (Figure 3).

The establishment of producer groups could facilitate smallholders' access to credit (collective guarantee) and equipments (collective use). As illustrated by the history of CA in Brazil (Bolliger *et al.* 2006) and in line with Laos' recent policy decisions promoting agricultural cooperatives (GoL 2010), farmer-led organizations could provide a strong basis for the establishment of innovations like CA-based cropping systems. In particular, they could enhance local access to information, farm inputs, and market channels and empower smallholders which are increasingly confronted to land speculators and large agribusinesses (Lestrelin *et al.* 2012a). Further devolution of land tenure and the establishment of land titles would also facilitate access to financial capital, allowing farmers to provide stronger guarantees to creditors. It could also contribute to encourage smallholders to engage in long-term agricultural investments. Increased involvement of the private sector and the development of contract farming arrangements, for example, could also enhance smallholders' access to financial capital and improve technical support.

Finally, the dissemination of CA-based farming systems could also be enhanced through payments for ecosystem services. Assessment of the services provided by CA is often largely based on socioeconomic indicators such as incomes, labour productivity, and food security. Yet, as pointed out by Lal (2008), when integrated in broader agro-ecosystems, CA can contribute to producing various ecosystem services (e.g. sequestrating soil organic C, enhancing water availability, strengthening nutrient cycling, increasing biodiversity). Obviously, additional research and experimentation would be needed to identify and, as far as possible, quantify the services that CA could actually provide in the particular context of the Plain of Jars. Reflections should also be engaged on the institutions and mechanisms that could be designed to monitor service provision and deliver payments. However, an approach based on payments for ecosystem services could definitely be employed to encourage and/or reward smallholders' shift towards more sustainable agricultural practices.

Conclusion

Four years after the conversion of the native savannah grasslands into agricultural land, the evaluation, in controlled experimental plots, of CA vs. CT effects on soil productivity and system profitability shows that CA systems are leading to similar-to-higher grain production, similar-to-higher net income, higher opportunity of income diversification towards livestock production, and higher labour productivity. On this basis, CA appears as a relevant option for the development of sustainable smallholder agriculture in the acid savannah grasslands of Laos. For this to happen however, broader institutional transformations would be needed, including: (i) the enrolment of manufacturers and traders for deploying NT implements, markets for cover crops and contract farming arrangements, (ii) long-term public support to the maintenance of active research and technical mentoring to farmers, and (iii) possibly the integration of payments for ecosystem services into agricultural policy. These transformations and supports are urgently needed to limit current large-scale land grabbing by private investors.

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Note

1. *Vientiane Times*, Feb 13, 2012. 'The Lao government has given permission for the Vietnam Chemical Group (Vinachem) to excavate and process potassium in Khammuan province.'

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