Assessing land use and ecosystem carbon stock from space - from a case study in slash/burn ecosystems in Laos -

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Abstract: In the tropical mountain of Southeast Asia, slash-and-burn (S/B) agriculture is an important food production system and widely practiced in many countries. The ecosystem carbon stock in this land use is linked not only to the carbon exchange with the atmosphere but also to the food and resource security. In this study, we revealed the land use and ecosystem carbon stock in the northern part of Laos at a regional scale based on the synergy of satellite remote sensing and *in situ* measurements. Chrono-sequential change of S/B land use and community age of fallow vegetation were derived successfully from the time-series satellite imagery, and combined with simple carbon models to assess the ecosystem carbon stock. Results suggested the carbon-sequestration potential of ecosystems is strongly affected by land-use and ecosystem management scenarios. Alternative land use and ecosystem management scenarios with higher carbon stock and productivity were also proposed. These quantitative estimates would be useful to better understand and manage the land use and ecosystem carbon stock in the slash-and-burn regions of tropical mountains in Southeast Asia. This case study clearly shows that the use of geoinformation technology (remote sensing, GIS and modeling) is crucial for a wide range of agro-environmental issues. Timely, regional, and systematic monitoring is essential for "agro-ecosystems intelligence", i.e., to analyze, understand, and predict the dynamics of agro-ecosystem resources, and to assist the strategies for both domestic and international food and environmental security. It is necessary to foster an international collaboration scheme for agro-ecosystems intelligence based on satellite sensor networks.

Keywords: agro-ecosystems, carbon, eco-informatics, geoinformation, remote sensing, satellite, shifting cultivation

1. Introduction

Quantitative assessment of carbon exchange between various ecosystems and the atmosphere has been one of the critical subjects in environmental policy-making [e.g. 1, 2, 3] as well as in related sciences since the carbon stock in terrestrial ecosystems plays an important role in the global carbon cycle [e.g. 4]. Nevertheless, scientific data and assessment of the long-term and wide-area changes in land use and carbon balance at the ecosystem scale are very limited [5]. Few accurate statistics on the dynamic change in land use are available.

In the tropical mountains of Southeast Asia, slash-and-burn (S/B) agriculture, i.e. shifting cultivation is an important food production system, and widely practiced in mountainous regions of Vietnam, Laos, China, Bangladesh, Myanmar, and northern India [6]. In S/B agriculture, a patch of vegetation is cleared, burnt, and used to grow crops for a few seasons, and then abandoned for regeneration of vegetation. Hence, dynamic and large-scale changes in the ecosystem carbon stock occur over the cropping (C) + fallow (F) cycles. It has been pointed that the S/B agriculture is a rational crop production system to utilize hilly lands with a little input, and used to be sustainable while the fallow period was long enough to recover the plant biomass and soil fertility [7, 8]. The fallow biome also provides various non-timber forest products (NTFP) that play an important role in rural livelihoods [9].

Nevertheless, increasing population pressure and land-use regulation have forced shifting cultivators to expand S/B areas and to shorten the fallow period [10, 11]. Consequently, the negative effects on crop productivity such as decreasing soil fertility and increasing weed problem has been reported [8], but also the negative impacts on biological resources and the atmosphere are seriously concerned. Therefore, alternative land-use and ecosystem management scenarios are urgently required to improve food and resource security [9] as well as for carbon sequestration. However, quantitative information on the chrono-sequential change of land use and ecosystem carbon stock in the region is not available. Limited accessibility to the mountainous areas as well as the limited availability of statistical data for the regions has hampered the scientific investigations, especially at regional scales [7, 8].

Use of satellite imagery is one of the viable options for such investigations. A great deal of efforts have been made to estimate biophysical variables such as biomass, net primary productivity (NPP) and light use efficiency as well as land-use change in a wide range of ecosystems [e.g. 12]. Spectral assessment of photosynthetic efficiency and capacity is one of vital interests in remote sensing and ecosystem science communities [e.g. 13]. Assimilation of remotely sensed data into biophysical process models would be another promising approach [e.g. 14, 15]. In spite of its usefulness, availability of optical satellite imagery is strongly limited due to the tropical climate conditions in the region, and the use of radar imagery (SAR) remains challenging due to the steep topographic conditions. Therefore, the simple approach using time-series satellite imagery examined by Inoue et al. [16, 17] may be feasible for the geo-spatial assessment of land use and carbon stock in S/B ecosystems under such unfavorable conditions.

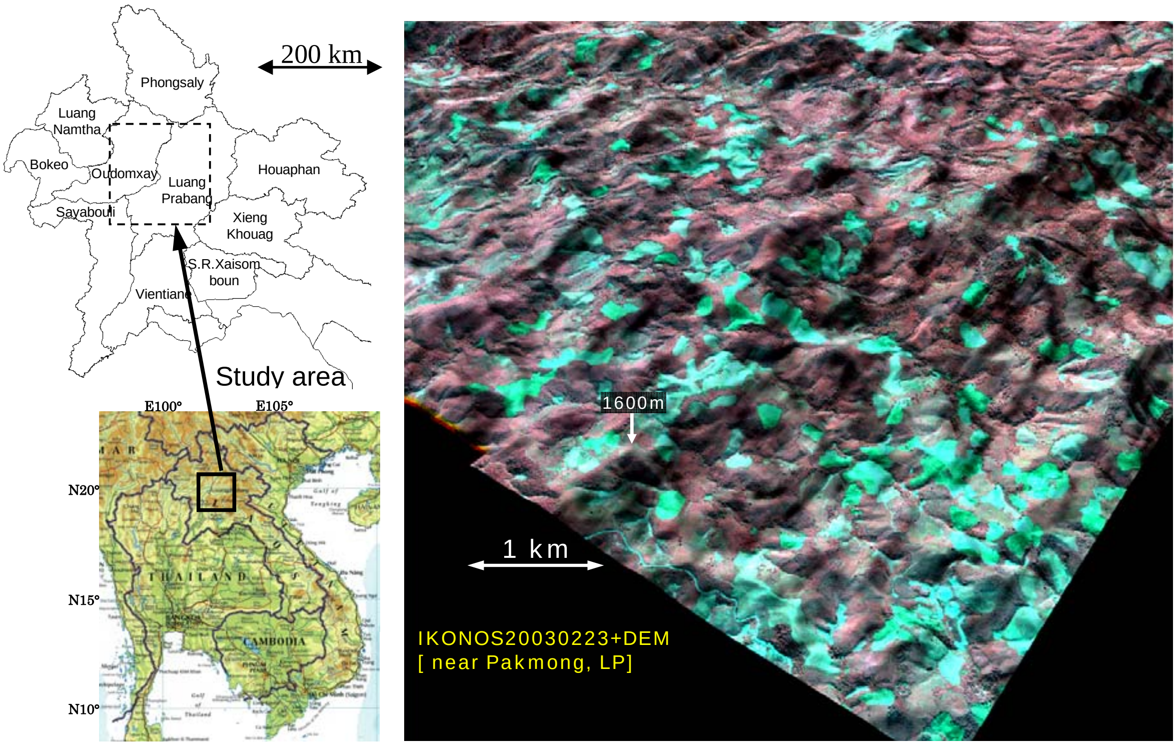


Fig. 1. The study area in northern part of Laos. A 3-D view generated from an image by a satellite IKONOS and digital elevation map shows one of for one of the typical S/B regions in Luang Prabang province (February 23, 2003). The green, red, and near-infrared wavebands are assigned to B, G, and R colors, respectively.

Thus, the main objective of this study was to provide basic information on the land use and ecosystem carbon stock in the region by linking time-series satellite imagery with an ecosystem carbon model derived from *in situ* experiments. Another objective was to infer the impacts of various land-use and ecosystem management scenarios on the potential of carbon sequestration at a regional scale. The importance of geoinformation for agro-ecosystems intelligence is also discussed.

2. Methodology

1) Study Site

The central part of northern Laos was selected as a study area (150×150 km; Fig. 1), because S/B agriculture is the major agricultural system there, and the area is typical of similar ecosystems in the mountainous mainland region of Southeast Asia [6]. The area is centered around 102°03'48.9" E, 20°13'12.8" N and is covered by a scene of Row46/Path129 of Landsat-TM. An intensive study was conducted in a selected site in Luang Prabang Province (17.5×20 km). The elevation ranges from 300 to 2000 m, with a slope from 40 to 100 %. The mean annual rainfall for the area is about 1300 mm with the annual variability (SD) of 260 mm, but more than 90% of the rainfall is during the wet season from May to October. Soils of most S/B fields are classified as Orthic Acrisols, with a reddish-brown color, clay contents > 30%, and a slightly acidic pH. Figure 1 shows the close bird's-eye view of a typical S/B region that was generated from digital elevation map and high-resolution satellite imagery. Overall, in this example, the emerald-green patches were used for slash-and-burn cropping during 2002, and reddish color indicates the densely vegetated areas, respectively. In general, new land patches are slashed during mid-February to early-March, burnt by mid-April, seeded during mid-April to May periods, and harvested during October to November periods. The most important crop in the area is upland rice, and some other crops such as Job's tear, sesame, and paper mulberry are also grown.

2) Data and approaches

An approach to estimate S/B land use from satellite imagery

The region consists of some limited types of land use, i.e. S/B patches, fallow vegetation areas, conservation forests, spiritual forests (cemetery), roads, houses, paddy fields, teak plantations, and water bodies (river, pond). Conservation forests consist of the areas where S/B land use is basically prohibited by local government. Most dynamic spatio-temporal changes in land use occur among the S/B and fallow vegetation areas, while spatio-temporal changes as well as percentage area of the other types are minor. The S/B land use areas consist of a variety of cropping and fallow (C+F) patterns, and their area ratios are a crucial basis in this study. Although it is not feasible to identify the age of fallow vegetation (the number of years after abandonment) in a single satellite image, the S/B patches each year can be discriminated with high accuracy polygon-based classification [16, 17]. First, vector layers of polygons are generated from individual satellite images based on segmentation procedures using spectral signatures and morphological features. Next, the polygons are used for extracting S/B cropping patches based on supervised classification.

Landsat-MSS, TM and ETM+ satellite images (Row46/Path129) and high resolution images from IKONOS and QuickBird satellites over 33 years were used. High resolution images were acquired to cover several areas within the whole study region, and used for detailed analysis as well as for checking the classification results of Landsat images. S/B patches were extracted based on polygon-based classification of each Landsat image, and then used to produce a binary (S/B or non-S/B) image. The binary images over consecutive years were stacked and used to trace the chrono-sequential change of S/B land use on a pixel basis. Consequently, the C+F land-use patterns (community age of fallow vegetation as well as timing and duration of S/B cropping) were derived at a pixel basis from the time-series analysis of satellite imagery only.

An approach to estimate ecosystem carbon stock at a regional scale

Direct quantification of biomass, height, or age using satellite optical signatures remains a challenging task for any types of remotely-sensed signatures even in simple tree stands [e.g. 18]. Hence, we used the community age derived from the analysis of time-series satellite images as a clue to link the land-use patterns and *in situ* measurements for estimating the ecosystem carbon stock in the region. This approach is rather simple but no similar attempts have been reported before.

Regional ecosystem carbon stock C_R (MgC ha^{-1}) was estimated from the area A (ha), area ratio R_k (%) and ecosystem carbon stock C_{Ek} (MgC ha^{-1}) for each land-use pattern (C+F cycle) *k* using the following equations;

$$C_R = A\sum_k [R_k \cdot C_{Ek}] \quad (1)$$

$$C_E = C_V + C_S \quad (2),$$

where C_V (MgC ha^{-1}) is the carbon stock in crop or fallow vegetation including biomass, dead biomass, litter fall and roots, and C_S (MgC ha^{-1}) is the carbon stock in the soil at the depth of 0.3 m. The ecosystem carbon stock C_{Ek} in various C+F cycles (*k*) was estimated by combining simple semi-empirical models for C_V and C_S both of which were expressed as a function of community age. The R_k was estimated from the polygon-based classification of time-series satellite imagery as explained in the previous section. These partial models were derived respectively from the concurrent experimental studies on site. Details are reported in Kiyono et al. [19] and Asai et al. [20, 21]. These experimental plots were carefully selected in typical area considering slope, aspects, elevation, vegetation and accessibility. The procedures to derive those semi-empirical models were conventional and model equations were fitted well to measured data. Nevertheless, due to constraints in logistics, the number of plots and thus the representativeness of the data and models are limited. Results have to be interpreted and utilized on the premise of the inherent uncertainty due to these limitations and assumptions. These semi-empirical models for C_V and C_S were synthesized, and linked with R_k by way of the community age derived from satellite image analysis in order to estimate the ecosystem carbon stock at a regional scale. This approach may provide new information for inferring the dynamics in regional ecosystem carbon stock as affected by land use.

Basis for scenario comparisons

Regional landscape consists of various land-use patches at a range of stages in C+F cycles. Therefore, in order to investigate the potential effects of land-use scenarios on the ecosystem carbon stock at a regional scale, we compared the regional average of ecosystem carbon stock under various combinations of major C+F patterns. In the simulations hereafter, recent land-use situation (designated as scenario P) was represented by the results in 2003 and 2004, and the total potential S/B area was assumed to be 67.4 % of the whole region derived from the analysis in 2003. Thus, each land-use scenario indicates how the potential S/B area (67.4 % of the whole region) is assigned to various C+F patterns and/or non S/B use. Some other scenarios MIN#, MAX#, ALT, p, min#, max#, and alt, were designed by altering some parts of the P scenario. In scenarios MIN# and MAX#, minimum and maximum fallow lengths are restricted to # years, respectively; e.g. in MIN5 all areas with the fallow shorter than 5 yr are assigned to 5 yr fallow area, whereas in MAX8 all areas with the fallow longer than 8 yr are assigned to 8 yr fallow area. The ALT scenario assumes an alternative 2C+10F pattern enabled by new cropping technologies discussed later, while other scenarios assume traditional cropping practices. Scenarios p, min#, max#, and alt are similar to P, MIN#, MAX#, ALT, except that 20 % of total potential S/B area (67.4 % of the whole study area) is reserved for conservation forest and never used for S/B.

On the other hand, we attempted to provide some reference information on the feasibility of such land-use scenarios from a viewpoint of livelihood. The gross regional income was compared for some selected scenarios (P, MAX8, p, ALT, and alt) based on preliminary simulation. Basic data and information for the simulation such as crop yield, prices of products, cost of input materials, labor cost, etc. were collected from the reconnaissance and the on-site experiments [21, 22]. The rice yield was assumed to be 1.7 and 2.55 Mg ha^{-1} in indigenous and improved cultivars, respectively. Standard yield of paper mulberry 1.2 Mg ha^{-1} was used. Price of rough rice and bark of paper mulberry was 0.117 US$ kg^{-1} and 0.35 US$ kg^{-1}, whereas the cost for seedlings and seed for was negligible since they are native to the region. The values of annual labor for agricultural management (seeding, weeding, harvesting, etc.) and wages for the labor were assumed to be 278 man-days yr^{-1}, and 1.2 US$ d^{-1}, respectively. In all scenarios, no agro-chemicals were used as in the present situation. Fertilizer is not used in the region because fertilizer application has never been profitable. Possible income from carbon gain was not accounted in this calculation. Use of fossil fuels and machinery were not involved in these scenarios.

3. Results and discussion

1) S/B land use in the region

The recent status of major land-use types in the intensive study area (350 km^2; Luang Prabang Province) was analyzed using high resolution satellite imagery (QuickBird; October 23, 2003). Table 1 shows the detailed classification results for the study area in 2003, where the monitoring plots for *in situ* measurements were established. The major types of land use, i.e. S/B patches, fallow vegetation areas, conservation forests including spiritual forests, teak plantations, paddy/croplands, water bodies, and road/bare soil/houses were discriminated by supervised classification using ground-based survey. Overall accuracy was about 90%, and producer's accuracy and user's accuracy for the S/B patches were as high as 100% and 86 %, respectively. Nevertheless, results suggest that accurate discrimination of fallow periods or even the differences between short-fallow, long-fallow and conservation forest may be difficult even with high resolution imagery. The areas for S/B cropping, short fallow (1-3years), and longer fallow patches in 2003 were 12.9 %, 34.8 %, and 19.6 %, respectively. Since the longest fallow periods identified by ground-based survey was 20 years in this classification, the total of these area 67.4 % may have experienced the S/B land use in the past two decades, and likely be used periodically for S/B in the future. Results suggest that the sum of these categories (tree-dominant biome), 97.7%, could potentially be the forest if no human disturbance is applied. The area of paddy and other cropland was limited to the narrow flat areas along streams.

Overall, the patch size around 0.6-1.2 ha was the majority (38 ± 2 %), and 83 ± 3 % were smaller than 2 ha, whereas only 5 ± 2 % were larger than 3 ha. Since polygons were created based on spectral similarity and continuity of boundary, these patch size may not always be equivalent to those of management unit linked to ownership, but regional tendency can be inferred from the distribution. For example, 95 % the patches were smaller than 1.2 ha in Oudomxay, whereas 38 % were larger than 3 ha in Muang Houn, respectively. These differences may be related to local variability in indigenous management practices, ownership system, family structure, and ethnic traditions.

Figure 2 shows the temporal change of the S/B cropping area in the intensive study area. The cropping area by S/B practice in each year increased rapidly from around 5 % in 1970's to 12 % in 2000s. The increase during 1990s was remarkable, while it was still small before mid-1980s. The annual increment rate during the decade after 1990 was about 3.8 % for the study area. Similar analysis conducted in several other areas within the whole study area

Table 1. Land use in the intensive study area (350 km^2; Luang Prabang Province) estimated from classification of high-resolution satellite image acquired on October 23, 2003 by a satellite QuickBird.

	Land use	Polygons	Area (ha)	Area (%)	Producer's accuracy (%)	User's accuracy (%)
1	Slash-and-burn (S/B)	4,031	3,952	12.9	100.0	86.0
2	Fallow [1-3 years] (FS)	5,348	10,656	34.8	91.3	80.8
3	Fallow [4< years] (FL)	3,467	6,010	19.6	63.6	70.0
4	Consevation Forest (CF)	4,704	7,759	25.4	83.3	70.0
5	Teak plantation	824	1,515	5.0	62.5	71.4
6	Paddy/Other cropland	177	202	0.7	83.3	90.9
7	Water (river/pond)	85	174	0.6	100.0	100.0
8	Road/Bare soil/House	603	326	1.1	81.8	100.0
	Total	19,239	30,595	100.0	Overall accuracy = 89.5%	
	SB + FS + FL	12,846	20,618	67.4	Kappa = 0.878	
	SB+FS+FL+CF+Teak [potential forest area]	18,374	29,892	97.7		

showed the annual rate of 3-5 % for the decade. Although the recent trend suggests somewhat slowing down, yet, no decreasing trend has been found during the period of analysis. These estimates support the descriptive information from reconnaissance at various sites in the region [e.g. 8, 9].

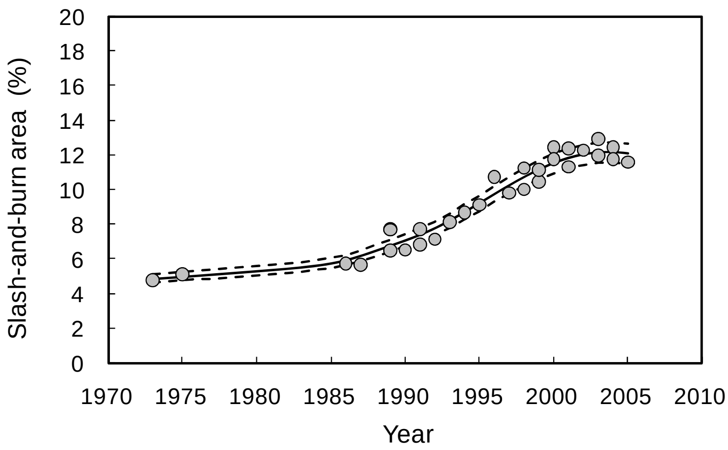


Fig. 2. Temporal change of slash-and-burn cropping area in each year in the intensive study area (350 km^2) in Luang Prabang province. Dotted lines indicate ±5 % range.

2) Community age of fallow vegetation

The S/B or non-S/B land-use history could be traced at a pixel basis for the area of interest, so that the important land-use parameters such as duration of consecutive cropping period or community age of fallow vegetation were derived systematically from the dataset. This was the most crucial role of time-series satellite images in this analysis although few reports on similar approach are found.

First, we examined the land-use intensity in the region by tracing the consecutive S/B use. Figure 3 shows the relative area (%) of consecutive S/B cropping periods (yr) among the total S/B cropped area in each year. The "1 yr" means that a pixel was newly used for S/B in the year, and "2 yr" indicates the second year of S/B use, and so forth. Some parts of "1 yr" pixels are to be used in the next year again for S/B, so counted as "2 yr", accordingly. For the period from 1993 to 2005, the average (± standard deviation) for 1, 2, and 3 y was 74.7 ± 6.8 %, 18 ± 5.2 %, and 4.6 ± 1.8 %, respectively. Results suggest that the relative ratio of consecutive S/B periods is rather stable even though the total S/B area has been changing as shown in Fig. 2. There is a trend of increase and decrease of 1 yr as well as the associated inverse trend in 2yr, and there is some increasing tendency of 2 yr after 2002, but it is not clear if these trends are significantly different from the period before. On average, 75 % of S/B area in each year was newly slashed patches, 76 % out of which is abandoned after a single year of cropping. Long S/B consecutive use (>4 yr) is very minor in the region.

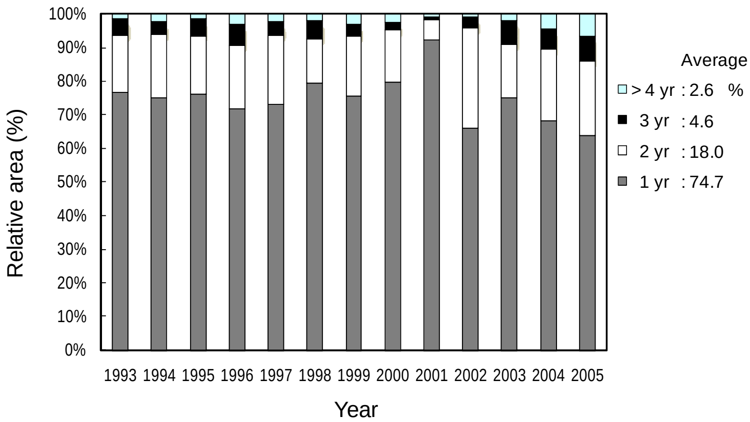


Fig. 3. Relative area of consecutive S/B land use among the S/B cropping area in each year.

Next, we examined the fallow length in the region. Community age of fallow vegetation can be calculated at a pixel basis by tracing back to the last S/B use on each pixel. Area distribution (%) of each community age in the whole area was derived in 2003 and 2004, respectively, and their average was used to represent the recent land use (Fig. 4a). The graph shows that the area for age = 0 (S/B) was largest (11.24 % of the whole area) whereas the area for community age of 1-3 yr was 28%, and 50 % for 1-12 yr, respectively. These values proved comparable with the classification results using the high resolution imagery (Table 1), although some uncertainty remains since the community age larger than 13 years could not be traced due to missing year in time-series Landsat imagery. Since no other information on community age was available, we used the result of community age in 2003-2004 (Fig. 4a) for comparative analysis of land-use scenarios, assuming it is representative of the recent land-use condition in the region.

From Fig. 4a, we estimated the recent situation of S/B land-use patterns, i.e. the fallow length in the study area in case this situation would continue. The differential between the areas of consecutive community ages was assumed to be the area converted to cropping after the specific fallow length. For example, the differential between the community ages 4 yr and 3 yr implied that this differential area has been converted to S/B cropping after 3 yr fallow period. In other words, if the differential is zero (area for 3 yr = area for 4 yr), all area of 3 yr was kept fallow condition to the next year. Accordingly, Figure 4b shows the relative area for each fallow length in 2003-2004 periods. The most common fallow length was 3 yr (20%) followed by 2 yr (17.5 %), that is, the major C+F cycle is 1 yr cropping - 3 yr fallow (1C+3F) pattern followed by 1C+2F pattern. The area for short fallow (1-3F yr) was up to 45 %, while the area for 5-11 yr fallow was 27 %. It was also confirmed that long-fallow areas (>11 y) are still used in part (9 %) for S/B cropping. These findings agreed well with the general information from ground-based reconnaissance, which also support the qualitative descriptions on overall trend of S/B land use in the region [7, 8, 10]. When the time-series satellite images are available over extended periods, the same approach would provide more useful information on the dynamic land-use history.

3) Chrono-sequential change of ecosystem carbon stock in various land-use patterns

The chrono-sequential change of ecosystem carbon stock was simulated under various combinations of C+F patterns. Since the region has been under S/B land use long time, effects of repeated land-use cycles were not taken into account explicitly in this approach assuming that such effects are included in each partial model. Figure 5 shows the chrono-sequential change of ecosystem carbon stock under some typical C+F cycles. The initial value was set to be a typical value measured just before cropping (42.0 Mg ha^{-1}) estimated from in situ measurements [20], which is comparable with the reported range [23]. Obviously, the major increase in ecosystem carbon stock is brought by biomass growth of fallow vegetation (secondary forest), while the drastic drop is caused by S/B practice. Even within the selected C+F patterns, the average value over 35 years varied up to 33 MgC ha^{-1}. In case of 1C+3F pattern (i.e. a cycle of 1-yr cropping with 3-yr fallow), the temporal average during 35 years was 41.7 MgC ha^{-1}, which is nearly the same as the initial values, but in the 1C+2F cycle, the temporal average 34.9 MgC ha^{-1} was lower than the initial carbon level by 7.1 MgC ha^{-1}. For example, the temporal average of carbon stock in 2C+10F cycle was larger than that in 1C+3F by 21 MgC ha^{-1}, which suggests that this amount could be sequestrated into the ecosystem from the atmosphere by changing the land-use pattern from 1C+3F to 2C+10F. The bottom points in each line indicate the carbon level just after S/B practice.

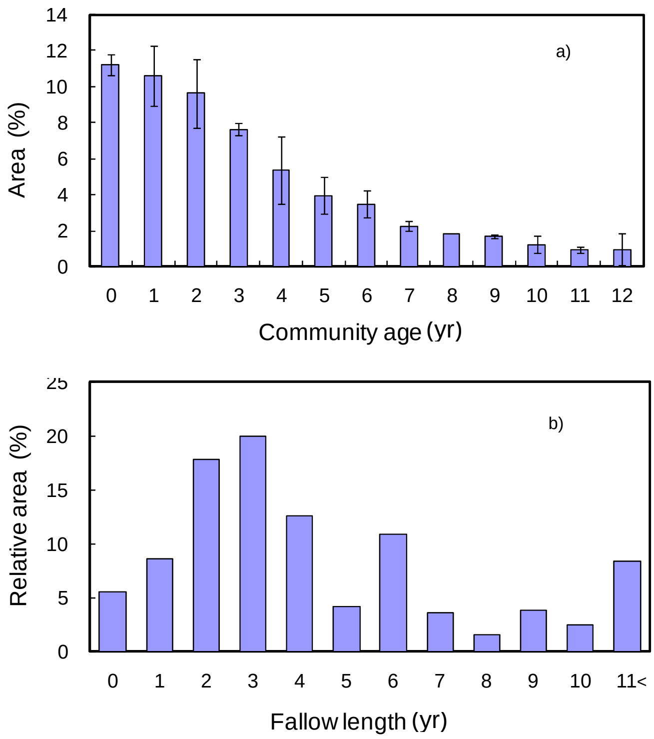


Fig. 4. Areas for each community age of fallow vegetation within the whole region (a), and relative areas for different fallow lengths (b) during 2003-2004 periods.

The decreasing trend was obvious in short fallow patterns, but also some slight decreasing trend was still found even under the 10 yr fallow patterns (e.g. 1C+10F). In this assessment, the same carbon model was applied during the repeated C+F cycles assuming that the plant growth was not affected by the level of soil carbon. However, a positive correlation found between soil carbon content and rice yield at the study site [21] suggests that the vegetation growth may be lowered than the model estimates due to decreased level of soil carbon. Although there are few data on such effect of repeated short-fallow cycles, if such negative effects are considered explicitly, real decreasing trend would be worse than the simulations in Fig. 5.

Overall, the model-based assessment of ecosystem carbon stock was reasonable compared to the above-ground carbon in mature tropical forests under

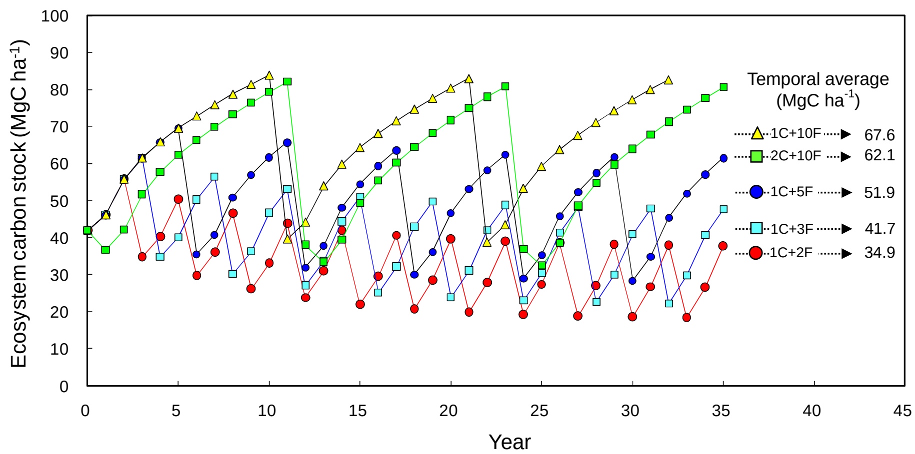


Fig. 5. Chrono-sequential changes in ecosystem carbon stock under some typical land-use patterns as assessed by a coupled model of carbon in the soil and fallow vegetation. “C” and “F” denote cropping and fallow, respectively, so that “1C+10F”, e.g., means 1-yr cropping and 10-yr fallow pattern. The arrow and number attached to each line indicate the temporal average of carbon stock.

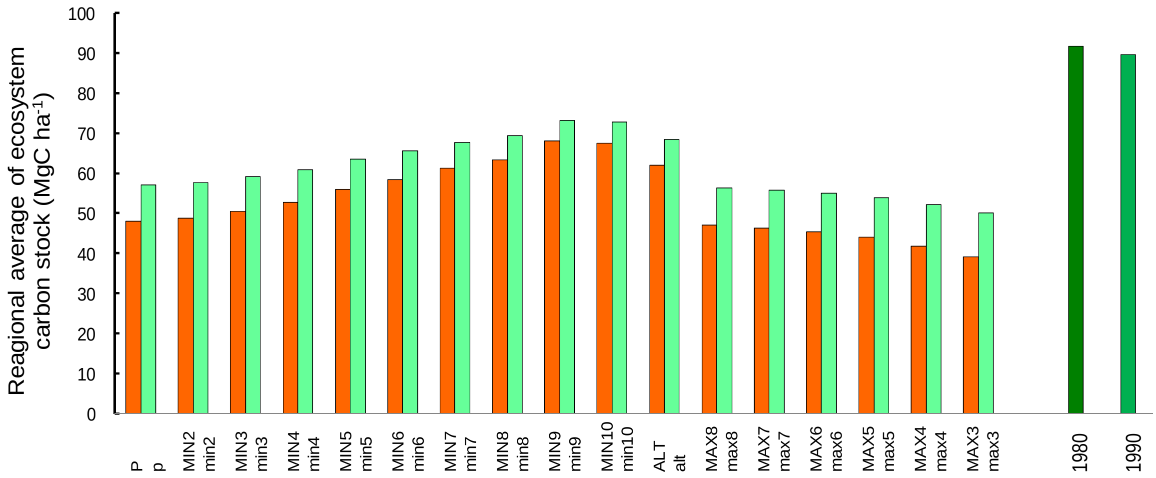


Fig. 6. Comparison of regional average of ecosystem carbon stock in some typical land-use scenarios.

similar climatic conditions [24]. In this relative comparison, some part of uncertainty due to limitations in the availability of *in situ* data and simplifications in modeling procedures may be cancelled. Results may be useful to infer the impact of land use on the ecosystem carbon stock and the potential of carbon sequestration by changing land-use and ecosystem management practices.

4) Comparison of regional carbon stock under various land-use scenarios

Since a region consists of various land-use patches at a range of stages in C+F cycles, we compared the regional average of ecosystem carbon stock under various combinations of major C+F patterns. The graph in Fig. 6 depicts the regional average of ecosystem carbon stock under 36 different scenarios.

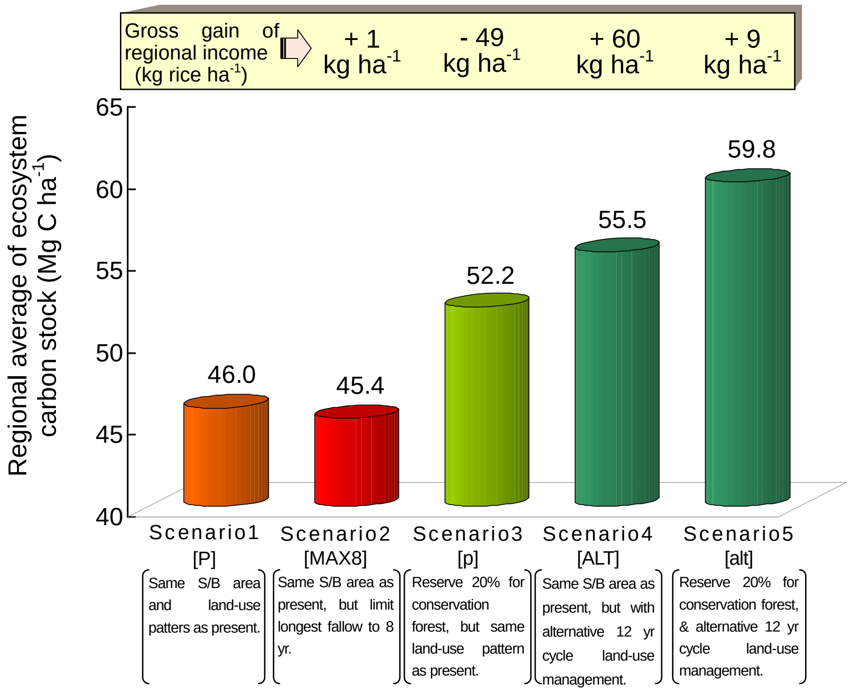
It is obvious that the regional average of carbon stock increases by elongating the minimum fallow length as in scenarios MIN2 - MIN10 compared to the present status (P). On the other hand, regional carbon stock decreases by reducing the longer fallow periods as in scenarios MAX8 - MAX3; however, the change is rather small partly because the areas with long-fallow patterns have already been reduced considerably at the present situation, and because the growth rate of fallow vegetation is lower for higher community age. The regional level of carbon stock will increase by 7.1 MgC ha^{-1} if the 1C+5F pattern and those with shorter fallow are all replaced with 1C+6F (MIN6), whereas it will decrease by 5.9 MgC ha^{-1} if longer fallow are diminished leaving 1C+3F or shorter fallow patterns (MAX3). The exclusion of 20 % area from S/B land use to conservation forest (scenarios p, min#, max#, and alt) is also effective to increase the regional carbon stock since the area is never used again for S/B in the future. The difference between P and p was 6.2 MgC ha^{-1}.

Land-use scenarios in 1980 and 1990 are also included for reference assuming the area (Fig. 2) and most probable S/B patterns inferred from interview during the reconnaissance and previous studies [7,8]. The difference of carbon stock in 1980 and 1990 scenarios was small as presumed from the slow rate of area change in Fig. 2, but the differential from 1990 to the recent status (P: 2003/2004) was as large as 28 MgC ha^{-1} for the whole region. This change is caused partly by the increase in S/B area and by the shortened fallow periods; the former effect is quantified in Fig. 2, and the latter effect is quantified in Fig. 6. This value may be a hypothetic basis to infer the amount of carbon released from the ecosystems in the tropical mountain to the atmosphere during the period. There are no similar data for the region to be compared; however, Houghton and Hackler [25] and Flint and Richards [26] have reported that the change in average forest biomass in tropical Asia between 1880 and 1980 was 23 MgC ha^{-1} and 43 MgC ha^{-1}, respectively. Although these estimates are for the 100 year period, our estimates may be comparable with these values because the major change in the study area has occurred after late 1980s as indicated in Fig. 2, and because our estimate is an average on the whole-region basis whereas their estimates are on the forest-area basis.

5) Implications of land-use scenarios to livelihood

The major focuses in this study are regional land use and ecosystem carbon stock, as well as the possible influence of land-use scenarios on regional carbon stock. Nevertheless, food and resource security (sustainability of forest, NTFP, drinking water, biodiversity) is of the highest priority for livelihood in the region [6, 9]. There are some evidences showing that shorter fallow period is associated, more or less, with some negative effects on crop yield, non-timber forest products, and labour productivity [7, 8, 22, 23, 27, 28]. Due to decreasing land and labour productivities, villagers are forced to expand the S/B area illegally to the long-fallow or conservation areas. During the field reconnaissance in 2006-2007, S/B practices at long-fallow or conservation forest areas (community age > 15 yr) have been sometimes observed. The conflict between forest conservation and the livelihoods of poor people seemed serious. Therefore, alternative land-use scenarios are strongly required for higher food and resource security as well as for higher carbon stock. The balancing between food production and environmental remediation is of increasing importance in ecosystem management and policy making, especially in developing countries [10, 29, 30].

Against this background, alternative cropping systems for higher rice productivity and/or improved incomes have been investigated in the study area concurrently with the present study [21, 22, 28]. High yielding rice cultivars, green manure plants and cash crops have been screened to evaluate their performance under S/B conditions. These studies suggested that the cropping system based on the combination of high yielding rice cultivars, green manure plants (e.g. *Stylosanthes guianensis*) and cash crop (e.g. paper mulberry) is most promising, and that the system would allow 2C+10F pattern [20]. Hence, we included the ALT scenario, i.e. 2C+10F land-use pattern using this new cropping system. The simulation in Fig. 6 showed that ALT and alt allow some moderate increase in regional carbon stock (9.5 and 13.8 MgC ha^{-1}, respectively).



Summary of simulated results of gross gain of regional income.

Balance (in kg rice ha^{-1})	Senario1	Senario2	Senario3	Senario4	Senario5
Rice production					
Indigenous cultivars	261.8	262.8	157.1	-	-
Improved cultivars	-	-	-	286.1	228.8
Cash crop (paper mulberry)	0.0	0.0	0.0	112.2	89.7
Technical cost					
Seed: indigenous culti.	-11.5	-11.6	-6.9	-	-
Seed; improved culti.	-	-	-	-19.6	-15.7
Technology transfer	0.0	0.0	0.0	-75.0	-75.0
Income from surplus labor	0.0	0.0	51.4	6.8	31.1
Total	250.2	251.2	201.5	310.4	259.0

Note: Gross regional income was derived as the sum for all land-use patterns in S/B areas, and indicated as the differentials from the that in the present conditions (Scenario1).

Fig. 7. Comparison of regional carbon stock and gross regional income under a few selected land use and ecosystem management scenarios based on simulation for 35 years.

On the basis of these background and investigations, the gross regional income was compared for some selected scenarios (P, MAX8, p, ALT, and alt) based on preliminary simulation. The summary of the preliminary calculations is shown in Fig. 7. The gross gain of regional income in MAX8 is estimated to be comparable with P, while the regional level of carbon is lowered by 0.6 Mg ha^{-1}. In the p-scenario, relatively large increase of carbon level is expected, but the income is seriously reduced. If the possible crop-yield reduction due to repeated short fallow cycles was included, results may be worse in reality under such short fallow scenarios (e.g. P, MAX8, and p). The ALT scenario allows the highest gain in gross income as well as relatively high carbon level, but the area of S/B is not reduced. In the alt-scenario, the increase in carbon level is highest, while the gross income is also improved to some extent. Hence, some scenarios between ALT- and alt-scenarios may be reasonable options for balancing food security and carbon sequestration. These simulations are based on the most probable data and information at the moment, but should be affected by many conditions such market price of products. Nevertheless, results may help designing the regional land-use and ecosystem management scenarios taking account of both gross regional benefit and level of carbon stock. In this simulation, we assumed a simple alternative land-use such as ALT, but further agronomic studies in the site will add a wider range of cropping options for new alternative scenarios. Carbon trading issue was not included in this preliminary investigation, but it may add a positive incentive towards improved ecosystem management.

4. Summary of the case study

This study was conducted to provide some quantitative bases to better understand and manage the land use and ecosystem carbon stock in the slash-and-burn region of tropical mountains in Laos.

The cropping area by S/B practice in each year increased rapidly from around 5 % in 1970's to 12 % in 2000s; especially, the increase during 1990s was remarkable, while it was still small before mid-1980s. Overall, the annual increasing rate of S/B cropping area during the decade after 1990 was estimated to be 3-5 % in northern part of Laos. In 2003, the total potential area for S/B land use was estimated up to 60-70 % of the whole area. On average, 75 % of S/B area in each year was newly slashed patches, whereas nearly the same area (76%) was abandoned after a single year of cropping. Long S/B consecutive use (>4 yr) was very minor. Approximately 37 % of the whole area was with the community age of 1-5 years, whereas 10 % for 6-10 years. The most common fallow length was 3 yr (20% of cropped area by S/B) followed by 2 yr (17.5 %). The ratio of short fallow (1-3 yr) was up to 45 %, while the ratio of 5-11 yr fallow was 27 %. It was also found that long-fallow areas (>11 yr) were slashed and burnt for cropping (9 %).

These data played a crucial role in the regional assessment of ecosystem carbon stock through the combination with semi-empirical model derived from *in situ* measurements. A large variability was found in the temporal average of carbon stock under various C+F patterns; e.g. 33 MgC ha^{-1} between 1C+2F and 1C+10F cycles. Simulation results on the average ecosystem carbon stock in the potential S/B area under various land-use scenarios suggested the strong effects of land-use and ecosystem management on regional carbon stock. Under the land-use situation in recent years (2003-2004), the average carbon stock would increase by 7.1 MgC ha^{-1} if the 1C+5F pattern and those with shorter fallow were all replaced with 1C+6F, whereas it would decrease by 5.9 MgC ha^{-1} if longer fallow periods were diminished leaving 1C+3F or shorter fallow patterns. The differential from 1990 to the recent status was inferred to be 28 MgC ha^{-1}. This large change was caused by the increased S/B area and by the shortened fallow periods.

Poverty is a serious problem in the region and food security is the highest priority for villagers, while livelihood depends largely on the S/B land use. Considering the recent situation observed during reconnaissance, people are forced to expand the S/B area illegally into the long-fallow or conservation areas due to decreasing land- and labour-productivities. Therefore, alternative land-use scenarios should be beneficial to regional livelihood. Preliminary accounting suggested that alternative scenarios with prolonged fallow periods (such as 2C+10F) in support of new cropping systems may contribute both higher food security and carbon sequestration. Carbon trading issue was not included in the preliminary accounting, but it could add a positive incentive for pushing the domestic and international efforts towards poverty reduction through alteration of regional land-use and ecosystem management [31].

Results would be useful to design more productive and sustainable land-use and ecosystem management scenarios taking account of the carbon sequestration capacity and benefit to regional livelihood. Further research is needed to overcome the limitations in data availability and accessibility to the region in order to improve the accuracy in *in situ* measurements, image processing and modeling. The results and their applicability to wider regions should be examined in various sites based on the combination of *in situ* measurements and geoinformation as attempted in this study.

5. Ecosystem informatics for agro-ecosystem intelligence

The case study clearly indicates that remote sensing and GIS play an important role in food and environmental intelligence which is the activity for monitoring, analyzing, and predicting the dynamics of agro-ecosystems, i.e., biological and environmental resources. The use of time-series satellite images proved crucial to derive not only the chrono-sequential change of land use, but also the relative areas for consecutive S/B use and community age at a regional scale.

In general, diagnostics of plant growth, health, and yield is the basis for higher productivity, quality and sustainability in plant production [32]. Understanding, predicting, and efficiently managing the ecophysiological processes involved in plant production require a wide range of information. So-called "precision agriculture" is one of the promising strategies to realize the efficient yet environmentally protective crop production.

Agricultural production is strongly affected by the global climate change, so that monitoring and prediction of crop conditions and meteorological disasters are important for preventive crop management and strategies for food security. On the other hand, local crop production is closely linked to regional and global environments via carbon and nitrogen cycles as well as air and water pollution (e.g., green-house gases, nitrates, and other agro-chemicals). The behavior of the non-point source pollutants may have significant influences on regional and global environment. Since agro-ecosystems are highly heterogeneous and changing dynamically, these interactions among agricultural land use, crop management practices and productivity as well as their environmental impacts have to be understood at local, regional or global scales.

Therefore, it is essential to obtain the spatio-temporal variability of agricultural fields, crop growth and yield, stress conditions, and environmental resources for local, national and international purposes. Spectral remote sensing has a number of advantages in such applications. Useful information can be acquired remotely on wide-area, non-destructive and real-time bases. Sensor technologies allow detecting the invisible signatures over near-infrared and microwave wavelengths from a distance. Spectral signatures such as reflectance, brightness temperature, and backscattering coefficient in various wavelengths carry a range of useful information from plant and agro-ecosystems [32].

The GIS is a powerful tool for integrating, managing, and simulating the spatial data in agro-ecosystem applications. NIAES has already developed a powerful GIS platform (GSAS) for agro-ecosystems applications in Japan (Fig. 8). The GSAS is designed to integrate a wide range of both static and dynamic landscape data, soil and

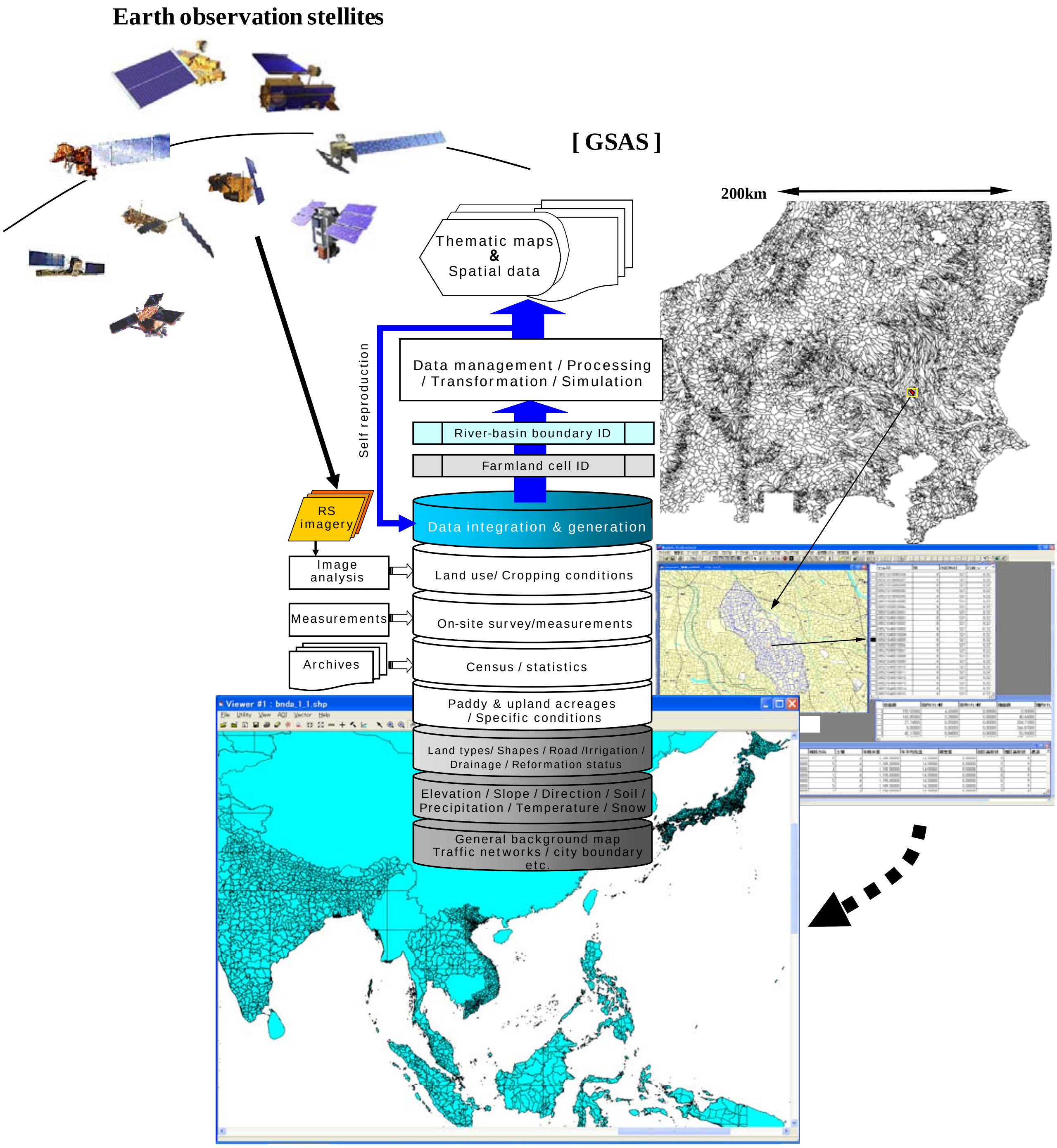


Fig. 8. A generic geoinformation platform scheme for agro-ecosystems intelligence. The Geo-spatial Agro-ecosystem Simulator (GSAS) was designed for data integration, analysis, and simulation of agro-ecosystem behavior. Each parcel unit is approximately a few hectares in size and each farmland parcel has a unique ID number throughout the entire farmland in Japan. A wide range of satellite images can be integrated and analyzed with various geoinformation at high resolution. Expansion of such geoinformation systems to monsoon Asia based on international collaboration networks may be useful for food and environmental strategies.

meteorological data, and administrative data covering all agricultural lands throughout Japan. Entire farmlands in Japan are expressed as polygons of a few hectares [33]. The computerized modeling of biophysical and biogeochemical processes is essential to generalize the underlying mechanisms from observed phenomena, and to predict the dynamic change of plant and agro-ecosystems [15, 34].

Thus, so called ecosystem informatics based in remote sensing, GIS, and process-based modeling plays crucial roles in spatial and dynamic assessment of plant and agro-ecosystems. Timely, regional, and systematic information is essential for agro-ecosystems intelligence, i.e., to analyze, understand, and predict the dynamics of agro-ecosystem resources, and to assist the strategies for both domestic and international food and environmental security.

Already, a number of satellites are observing the earth surface (Fig. 8), and quite a few satellites with advanced sensors will soon be lunched from various countries including those of MARCO partners. We anticipate the construction of global collaboration network for monitoring, analyzing, and predicting the ecosystem resources worldwide using remote sensing and geo-spatial information systems. As a first step, it is necessary to foster a collaboration scheme in Asian countries for agro-ecosystems intelligence based on satellite sensor networks. Constructing the extended version of geoinformation system like the GSAS in monsoon Asia would be a good start.

Acknowledgement

The major part of the case study is based on the papers from the collaborative research project with my colleagues at Kyoto University (Japan), Forestry and Forest Products Research Institute (Japan), INRA (France), Michigan State University (USA), and National Agricultural and Forest Research Institute (Laos). The author also thanks Dr. Miwa, T. for his useful comments on this paper.

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