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Simulating Land-Cover Change in Montane Mainland Southeast Asia

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Abstract We used the conversion of land use and its effects (CLUE-s) model to simulate scenarios of land-cover change in Montane mainland southeast Asia (MMSEA), a region in the midst of transformation due to rapid intensification of agriculture and expansion of regional trade markets. Simulated changes affected approximately 10 % of the MMSEA landscape between 2001 and 2025 and 16 % between 2001 and 2050. Roughly 9 % of the current vegetation, which consists of native species of trees, shrubs, and grasses, is projected to be replaced by tree plantations, tea, and other evergreen shrubs during the 50 years period. Importantly, 4 % of this transition is expected to be due to the expansion of rubber (*Hevea brasiliensis*), a tree plantation crop that may have important implications for local-to-regional scale hydrology because of its potentially high water consumption in the dry season.

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Introduction

Montane mainland southeast Asia (MMSEA), 300 m elevation and above, is a large, ecologically vital region comprising approximately half of the land area of Cambodia, Laos, Myanmar, Thailand, Vietnam, and China's Yunnan Province (Fig. 1) The region harbors a wealth of natural resources including globally important stocks of forest and biological diversity and the headwaters for several major river systems (Mekong, Chao Praya, Irrawaddy, and Yuan-Hong). Much of MMSEA has reopened to outside influences within the last three decades, bringing profound and widespread changes to both its physical environment and to its local societies. Principal determinants of social and environmental change in the region include a transition to agricultural commodity production and plantation agriculture (Fortunel 2000, 2007; Déry 2000, 2001; de Koninck 2003; Hall and others 2011); large-scale infrastructure development including road-building and hydropower dams (Wyatt and Baird 2007; Sneddon and Fox 2006; Lacombe and others 2010; Milloy and Payne 1997); the awarding of "economic land concessions" and similar state-backed land-development instruments (Kenney-Lazar 2010; UNCOHCHR 2004); legal, semi-legal, and illegal logging (Lang 2001; Le Billon 2002; Barney 2005); mineral exploration and development; and in-migration of new residents occasioned by governmental policy and the pursuit of economic opportunity (Guérin and others 2003; McElwee 2008; High 2008; Baird and others 2009).

Swidden agriculture, or swiddening (also called shifting cultivation), has been the dominant farming system in

Fig. 1 Montane mainland southeast Asia with simulation model domains (*blue boundaries*), Chiang Mai to Kunming highway corridor (*yellow lines*) and east–west corridor (*red line*). Areas shaded in *green* indicate elevation of 300 m and above

MMSEA where it has been practiced for at least a millennium and has greatly influenced land cover throughout the region. A great deal of recent literature suggests that swiddening is rapidly giving way to commercial agriculture driven by domestic demand and by regional trade agreements (Padoch and others 2007; Fox and others 2009; Cramb and others 2009; Ziegler and others 2011). In Xishuangbanna (the most southern prefecture in Yunnan Province), China, both semi-privatized state farms and minority farmers are planting rubber trees (*Hevea brasiliensis*) at rates that threaten to transform the landscape between 300 and 1,000 m elevations into an unbroken carpet of rubber (Xu and others 2005; Xu 2006; Li and others 2007; Ziegler and others 2009a, b; Sturgeon 2010). In northern Thailand, rural people are becoming increasingly divorced from farming, with education and consumerism creating a context where rural people are dis-intensifying, even abandoning their land, in favor of non-farm pursuits (Rigg and Nattapoolwat 2001; Rigg 2006). In Laos and Cambodia, entrepreneurs have contracted farmers to grow corn, bananas, and sugar cane for the Chinese and Vietnamese markets (Thongmanivong and others 2005; Fujita and Phanvilay 2008; Fox and others 2008). In response to soaring prices for natural rubber, highlanders, usually ethnic minorities, are planting rubber trees on family plots. In Laos, they are turning to relatives in China for advice; and in both countries, to merchants for seeds, grafts, and tapping tools (Thongmanivong and others 2005; Fujita and Phanvilay 2008; Phanvilay 2010). In Vietnam, researchers have reported the expansion of tree crops such as rubber, tea, and coffee in the central highlands (Thomas and others 2008) and fast-growing species for pulp and timber in the northern part of the country (Sunderlin and Huynh 2005).

A review of FAO statistics for the period 2000–2010 reveals that rubber is the most rapidly expanding tree crop in the five countries that make up the core of MMSEA (Cambodia, Laos, Myanmar, Thailand, and Vietnam) (FAO 2010). Natural rubber is cheaper and of superior quality to synthetic rubber for high-stress purposes; jet and truck tires are almost entirely natural rubber. A native of the Amazon basin, rubber trees have traditionally been cropped in the equatorial zone between 10° N and 10° S in areas with 12 months of rainfall. Historically, Thailand, Indonesia, and Malaysia have produced the vast majority of the world's rubber supply. In an attempt to free itself from the world market and to promote economic development, China began investing heavily in the 1950s into research on growing rubber in environments perceived to be marginal in terms of cooler temperatures and a distinct dry season. China's success in growing rubber in these 'non-traditional' environments greatly expanded the habitat in which rubber is planted. Hybrids are now grown at elevations exceeding 1,000 m (Qiu 2009) and in areas with distinct dry seasons across most of MMSEA.

Li and Fox (2011) report that over the last several decades more than 1,000,000 ha have been converted to rubber in non-traditional rubber growing areas of the region. Some scholars suggest that the transitions from ecologically important secondary forests and traditionally managed swidden fields to widely spread rubber plantations may affect local energy, water, and carbon fluxes (Hu and others 2008; Guardiola-Claramonte and others 2008, 2010; Ziegler and others 2009a, b, 2011). At the regional level, prior research by Sen and others (2004) found that deforestation in the lowlands of mainland southeast Asia increased rainfall downstream of the deforested area and reduced it at higher latitudes over eastern China. Little assessment has been made on how projections of future land-cover change in MMSEA could affect regional climate. The degree of influence will surely depend on the extent and locations of major land-cover changes.

In this study, we used the conversion of land use and its effects (CLUE-s) model to simulate landcover change in MMSEA (with a focus on rubber) to provide a basis for further analyses of probable impacts on hydrology in the region (Guardiola-Claramonte and others 2008, 2010; (Sen and others 2011a). To achieve this goal, we developed a regional database of land cover and other environmental, infrastructural, and population variables in MMSEA; obtained expert opinions on land change processes, drivers, and future trajectories of change in the region; and simulated land-cover change in MMSEA annually to 2025 and 2050. This paper describes the CLUE-s modeling exercise and its results in terms of probable land covers and their proportions and the spatial distribution of conversions by 2025 and 2050.

Methods

The CLUE-s model (Verburg and others 1999a, 2002; Verburg 2006) and its predecessor, CLUE, have been used in land change investigations across a wide range of scales of analysis and in several regions worldwide, including Asia (Verburg and others 1999b), central America (Wassenaar and others 2007), and Europe (Verburg and others 2006). In southeast Asia alone, CLUE-s has been applied at the sub-national level in northern Vietnam (Castella and Verburg 2007; Willemen 2002) and Malaysia (Engelsman 2002; Verburg and others 2002) and the national and sub-national levels in the Philippines (Verburg and Veldkamp 2004; Soepboer 2001). Based on the model's success in these many diverse applications, we selected the CLUE-s framework for exploring and simulating land-cover change in MMSEA. MMSEA extends into six countries each possessing unique social, political, and economic histories, and therefore, potentially unique land-cover change trajectories. Hence, we developed a specific CLUE-s model for the portion of each country that intersects MMSEA, hereafter referred to as country domain. This approach allowed for independent model parameterization and simulations of land-cover change by country domain.

Baseline Land-Cover Classification

We developed a 2001 land-cover map to serve as the simulation model baseline. To do so, we first acquired a 1 km resolution global land-cover dataset from the USGS Land Processes Distributed Active Archive Center that was generated from 2000 to 2001 MODIS/Terra observations (Friedl and others 2002) and made available in the 17-class International Geosphere–Biosphere Programme (IGBP) global vegetation classification scheme. We subset the data to the extent of the MMSEA model domain and reclassified the map to the 20-class biosphere–atmosphere transfer scheme (BATS) (Dickinson and others 1993) to support regional climate modeling in a related work (Sen and others 2011b). The resulting MMSEA map excluded four BATS categories (tundra, ice caps and glaciers, water and land mixtures, and ocean categories) as they were not present in the study landscape. Since BATS does not recognize urban\built-up nor sparsely vegetated categories, we retained those IGBP classes in the reclassified map. The final baseline map for initiating land cover simulations included 16 land-cover types (Fig. 2).

CLUE-s Model

CLUE-s employs an iterative spatial allocation procedure for generating simulation maps at regular time intervals. The model requires parameterization of the following components: land-cover demands, location suitability, conversion characteristics, and location restrictions.

Land-Cover Demands

Demand refers to the aggregate area occupied by each land-cover type at each simulation time step. We estimated annual land-cover demands based on interviews with

Fig. 2 Baseline (2001), 16-class land-cover map for the MMSEA simulation region

experts familiar with land change in each country domain and by referencing country economic profiles (Economic Intelligence Unit 2004a, b, 2005a, b, c, d). Expert interviews consisted of in-depth discussion of each domain's land change history and opinions regarding potential land change trajectories in the region. We presented experts with 2001 land-cover maps of MMSEA and their specific region of expertise, and then asked each to estimate the expected % change in each land cover by 2025 and 2050. By coupling expert estimates with the country profiles, we determined domain- and cover-specific demands for target years and all intervening annual time steps. Table 1 summarizes for each country domain the observed baseline land covers and expected land-cover demands (expressed as % of total country domain area) for target simulation years 2025 and 2050.

Location Suitability

Land-cover conversions, particularly in deterministic models, typically occur at locations with the highest suitability for a particular cover type at a particular point in time. Determining the relative suitability of a location for each cover type requires (1) consideration of the biophysical, geographic, and socio-economic factors and processes hypothesized to be driving different land-cover conversions, (2) identifying a parsimonious set of factors influencing the locations of observed land covers and conversions and quantifying their relative influences by statistical analysis, and (3) combining factor location values (e.g., elevation, distance to road) and relative influences in a function that empirically quantifies the probability of occurrence of each cover type at each location in the landscape.

CLUE-s uses a logit model to define a function that, for each modeled cover type, calculates a total probability (i.e., suitability) that the given land cover will occur at a location based on a combination of factor (driver) values and their relative influences (the model coefficients). Based upon drivers of change suggested by regional experts, we developed a spatial database of potential predictor variables, or location suitability factors, at 1 km resolution (Table 2). We obtained source data corresponding to (or

Table 1 Baseline land cover proportions and land-cover demands (expressed as % of country domain) as estimated from expert knowledge

	Cambodia				Laos				Myanmar			
	59,579 km^2				283,363 km^2				462,495 km^2			
Land cover type	2001	2025	2050	%ch	2001	2025	2050	%ch	2001	2025	2050	%ch
Crops, mixed farming	1.4	4.5	7.5	6.1	1.3	2.0	3.0	1.7	2.7	4.0	5.0	2.3
Short grass	0.9	1.0	1.0	0.1	1.7	3.0	3.0	1.3	2.1	3.0	3.0	0.9
Evergreen needleleaf trees	0.1	0.1	0.1	0.0	0.2	0.0	0.0	−0.2	0.2	0.2	0.2	0.0
Deciduous needleleaf trees	na[a]	na[a]	na[a]		na[a]	na[a]	na[a]		0.0	0.0	0.0	0.0
Deciduous broadleaf trees[b]	9.1	8.5	6.0	−3.1	13.5	16.0	18.0	4.5	15.5	18.0	20.0	4.5
Evergreen broadleaf trees	44.5	41.0	37.0	−7.5	63.3	55.5	51.0	−12.3	34.4	31.5	29.5	−4.9
Tall grass	7.0	6.0	5.0	−2.0	5.6	6.0	6.0	0.4	3.8	3.8	3.8	0.0
Urban/built-up	0.1	1.0	2.0	1.9	0.1	1.0	1.5	1.4	0.4	1.0	2.0	1.6
Irrigated crops	3.9	6.0	11.0	7.1	2.2	2.3	2.5	0.3	12.6	13.0	13.0	0.4
Sparse vegetation	0.3	0.3	0.3	0.0	0.2	0.2	0.2	0.0	1.1	1.1	1.1	0.0
Bogs and marshes	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0
Inland water	1.5	1.5	1.5	0.0	0.6	0.6	0.6	0.0	0.8	0.8	0.8	0.0
Evergreen shrubs[c]	0.1	0.1	0.1	0.0	0.2	0.5	1.0	0.8	0.3	0.3	0.3	0.0
Deciduous shrubs	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.3	0.3	0.3	0.0
Mixed forest	0.8	3.5	6.0	5.2	0.9	0.9	0.9	0.0	2.4	3.0	3.0	0.6
Forest/field mosaic	30.3	26.0	22.0	−8.3	10.1	12.0	12.0	1.9	23.3	20.0	18.0	−5.3
	Thailand				Vietnam				Yunnan (China)			
	303,093 km^2				28,5271 km^2				337,532 km^2			
	2001	2025	2050	%ch	2001	2025	2050	%ch	2001	2025	2050	%ch
Crops, mixed farming	5.1	7.0	5.0	−0.1	6.7	10.0	11.0	4.3	4.5	8.0	7.0	2.5
Short grass	3.4	4.0	5.0	1.6	1.5	2.5	2.0	0.5	5.2	2.5	4.5	−0.7
Evergreen needleleaf trees	0.1	0.1	0.1	0.0	0.7	1.0	1.5	0.8	0.5	1.0	0.0	−0.5
Deciduous needleleaf trees	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Deciduous broadleaf trees[b]	9.7	13.0	15.5	5.8	8.9	8.0	7.0	−1.9	10.6	15.0	15.0	4.4
Evergreen broadleaf trees	22.7	25.0	27.0	4.3	42.2	38.0	35.0	−7.2	19.7	21.0	25.0	5.3
Tall grass	7.3	7.3	7.3	0.0	5.2	7.0	8.0	2.8	7.2	4.0	2.5	−4.7
Urban/built-up	0.6	1.0	2.0	1.4	0.5	1.0	2.0	1.5	0.6	2.0	4.0	3.4
Irrigated crops	27.2	24.0	22.0	−5.2	8.7	10.0	11.0	2.3	2.0	1.0	1.0	−1.0
Sparse vegetation	0.5	0.5	0.5	0.0	0.8	0.8	0.8	0.0	0.9	0.9	0.9	0.0
Bogs and marshes	0.1	0.1	0.1	0.0	0.2	0.2	0.2	0.0	0.1	0.1	0.1	0.0
Inland water	0.9	0.9	0.9	0.0	0.4	0.4	0.4	0.0	0.3	0.3	0.3	0.0
Evergreen shrubs[c]	0.7	1.0	1.5	0.8	0.8	2.0	3.5	2.7	9.1	13.0	14.5	5.4
Deciduous shrubs	0.2	0.2	0.2	0.0	0.6	1.0	1.0	0.4	2.0	2.0	2.0	0.0
Mixed forest	0.5	1.0	1.0	0.5	3.9	3.0	2.5	−1.4	17.9	14.0	11.0	−6.9
Forest/field mosaic	21.0	15.0	12.0	−9.0	18.9	15.0	14.0	−4.9	19.2	15.0	12.0	−7.2

Percent change shown for the 2001–2050 time period

[a] Indicates absence of land-cover type in model domain

[b] Includes rubber

[c] Includes tea

near as possible to) the date of the baseline land cover (2001), however, the availability and scale of the source data varied by country domain. While it was assumed that many location factors would remain unchanged over the simulation period, we treated distance to roads and population density as dynamic variables that we updated annually in the model runs. We assumed annual decreases in distance from each location to nearest road as the region becomes more connected via new and improved road infrastructure. To represent changing population densities

Table 2 Data used to derive location factors

Variable	Data source	Baseline Year	Scale or Resolution	Static or Dynamic
Land cover—land use	LPDAAC at USGS[a] (MODIS/terra land cover) (http://lpdaac.usgs.gov/)	2001	1 km	Dynamic
Population density	SEDAC–CIESIN[b] (http://sedac.ciesin.org/gpw/)	2000	1 km	Dynamic
Distance to populated place	Derived from populated places UNEP-RRCAP[c] (http://www.rrcap.unep.org/)	2001	1:100–1:250 k	Static
Distance to domestic city (nearest domestic market)	Derived from cities GIS layer UNEP-RRCAP	2001	1:100–1:250 k	Static
Distance to foreign city (nearest foreign market)	Derived from cities GIS layer UNEP-RRCAP	2001	1:100–1:250 k	Static
Distance to major road	Derived from roads GIS layer UNEP-RRCAP	2001	1:100–1:250 k	Dynamic
Distance to road	Derived from roads GIS layer UNEP-RRCAP	2001	1:100–1:250 k	Dynamic
Distance to major river	Derived from major river GIS layer UNEP-RRCAP	2001	1:100–1:250 k	Static
Distance to river	Derived from rivers GIS layer UNEP-RRCAP	2001	1:100–1:250 k	Static
Parks and protected areas	WDPA[d] (http://www.unep-wcmc.org/wdpa/)	2005	National–Global	Static
Elevation	SRTM at USGS[e] (http://srtm.usgs.gov/)	2000	1 km	Static
Slope	Derived from SRTM	2000	1 km	Static
Major landform	ISRIC[f] (http://www.isric.org/)	1997	1:5 M	Static
Human-induced soil degradation (major type and intensity)	ISRIC (http://www.isric.org/)	1997	1:5 M	Static

[a] Land Processes Distributed Active Archive, US Geological Survey

[b] Socioeconomic Data and Applications Center, Center for International Earth Science Information Network

[c] United Nations Environment Programme, Regional Resource Center for Asia and the Pacific Region

[d] World Database on Protected Areas

[e] Shuttle Radar Topography Mission, US Geological Survey

[f] International Soil Reference and Information Centre

in the simulations, we obtained annual (2001–2050) projected growth rates from the US Census Bureau's International Data Base (IDB) and applied them to the baseline 2000 population density grid for each country domain.

We used SPSS software for statistical analysis of land cover presence/absence and location factors. For each country domain, we applied binary stepwise logistic regression to identify a parsimonious set of the most significant, explanatory factors associated with occurrence of each cover type. The probability of occurrence of some cover types can also be partially explained by presence of certain other land covers in the surrounding area. Urban\built-up areas are a prime example where these neighborhood interactions are important (Verburg and others 2003; Veldkamp and Fresco 1996, 1997a, b), with new urban growth typically developing at the edges of extant urban areas. Using CLUE-s, we derived an "enrichment factor" to describe the neighborhoods of urban areas and to enhance the probability of simulated urban growth in the adjacent landscape.

Conversion Characteristics and Restrictions

Conversion characteristics and restrictions describe the temporal transition behaviors for each cover type. In CLUE-s, these behaviors are defined in a transition matrix of possible 'from-to' land-cover conversions. For each country domain, we specified permitted and restricted land-cover conversions. We also assigned an "elasticity" parameter which further defines how resistant or amenable each cover type is to change (Verburg and others 1999b) with values ranging from 0 (easy conversion to other allowable types) to 1 (completely resistant, irreversible change). Values of 0 allow conversion without consideration of the current land cover or adjacent land cover. We assigned values of 1 to cover types that are too difficult or costly to convert or that are unidirectional (e.g., once urban/built-up, always urban/built-up). We completely restricted land conversions in each of our country domains in any area designated as national park or protected area based on the World Database on Protected Areas (WDPA) 2005 dataset (UNEP-WCMC 2005).

Land-Cover Allocation

Land-cover spatial allocation is the automated, iterative process in CLUE-s that generates landscape patterns that best satisfy the demands for a given simulation year. Since demand is non-spatial, simulated emergent patterns are driven by a combination of location suitability, allowable land-cover transitions and elasticities, and the conversion restrictions as described above. Up to 20,000 iterations of the allocation process are allowed per time step in order to reach a satisfactory model solution. Provided a solution is reached, the resulting pattern is retained and input to the subsequent simulation year. We performed multiple, 50 years simulations per country domain, testing sensitivity of input parameters, and evaluated resulting patterns and cover proportions against country domain demands. We selected simulation outputs with overall patterns that most accurately reflected the plausible scenarios envisioned by regional experts.

Results

Simulated change in years 2025 and 2050 generally reflects the role of small-scale diversified farming, monocropping (by both large operators and small holders), and establishment and enforcement of protected areas (national parks, state forests, and protected watersheds) in each country domain (Table 3). Across MMSEA, the following land covers are estimated to increase by 2050: diversified farming of crops and other mixed farming activities (2.45 %, approximately 42,500 km^2); rubber and other deciduous broadleaf trees (2.46 %, approximately 42,500 km^2); tea and other evergreen shrubs (1.63 %, or approximately 28,300 km^2); urban and other built-up areas, such as those associated with peri-urbanization (1.62 %, or approximately 28,300 km^2). These simulated increases take place largely at the expense of the following land-cover groups: (1) evergreen broadleaf trees, which are the most suitable habitat for rubber; and (2) mixed forests, forest/field mosaics, and tall grass—land covers that are historically associated with swidden cultivation. The overall decline in these four land-cover categories is about 9 % (approximately 155,300 km^2). The forecast decline in native tree cover is somewhat offset by a 4 % increase in deciduous broadleaf trees (i.e., rubber), tree crops, tea, and other evergreen shrubs. Figure 3 highlights areas in the MMSEA region where projected changes occur during the 2001–2025 and 2001–2050 simulation periods. These results only include conversions between the modeled land-cover classes used in the study; other conversions that are not represented in the land cover classification (e.g., among crop types or between residential and industrial areas) are not accounted for here.

Among the six countries in MMSEA, Cambodia has the least amount of land within the region (59,579 km^2) and Myanmar the greatest amount (462,495 km^2). Laos, Thailand, and Vietnam have roughly the same amount of land in the region (283,363–303,093 km^2) (Table 4). Model results suggest that Myanmar will undergo the least amount of change throughout the 50 years period (<10 %). This is evident in the map of change/no change for the 2001–2050 time period in Fig. 3. In Laos, Thailand, and Vietnam, the model suggests that land-cover changes will range from 9.38 to 11.9 % during the first 25 years period, and

Table 3 Baseline land cover (expressed as % of region) and simulation results aggregated to MMSEA region showing overall % change for 2001–2025 and 2001–2050 time periods

	MMSEA (1,731,333 km^2)		
Land-cover type	2001	2025	2050
Crops, mixed farming	3.69	+2.29	+2.45
Short grass	2.99	−0.06	+0.42
Evergreen needleleaf trees	0.31	+0.12	+0.01
Deciduous needleleaf trees	0.00	0.00	0.00
Deciduous broadleaf trees[a]	12.82	+1.41	+2.46
Evergreen broadleaf trees	36.58	−2.96	−3.73
Tall grass	5.70	−0.27	−0.44
Urban/built-up	0.69	+0.51	+1.62
Irrigated crops	9.53	+0.56	+0.58
Sparse vegetation	1.00	0.00	0.00
Bogs and marshes	0.11	0.00	0.00
Inland water	0.64	0.00	0.00
Evergreen shrub[b]	2.30	+0.92	+1.63
Deciduous shrubs	0.6	+0.07	+0.07
Mixed Forest	5.13	−0.66	−1.24
Forest/field mosaic	17.9	−1.67	−3.56

[a] Includes rubber

[b] Includes tea

14.46–19.17 % of the landscape during the 50 years period. These results suggest land-cover experts in these countries see relatively similar futures. In Cambodia and Yunnan, the model suggests that land-cover change will affect approximately one-quarter of the upland landscape over the 50 years period. Overall, the model simulated change across the entire region of approximately 10 % of the landscape over the first 25 years period and 16 % over the 50 years period.

Validation

We used the CLUE-s model to simulate patterns of land-cover change that may emerge in MMSEA in 2025 and 2050 based upon an amalgam of (1) expert knowledge of historical land change; (2) expert knowledge of current trends and narratives of future trajectories of change that considered agricultural intensification, road development, and market growth in the region; and (3) economic forecasts. Land change projections are at best future explorations for which true validation is not possible (Wassenaar and others 2007). We can evaluate projected simulation results, however, in terms of (1) historical rates of change, (2) rates of change forecast by independent experts not surveyed in this research, and (3) by comparing emergent patterns of change produced by the model with expert opinion of where change is likely to occur.

An evaluation of the rate of change is an assessment of the 'expert knowledge' used in this research—i.e., how close to historical and predicted rates of change were the rates of change forecast by the experts we surveyed? Our results suggest that between 2001 and 2050 rubber and other deciduous broadleaf trees will increase in non-traditional rubber growing areas of MMSEA by approximately 42,500 km^2; this represents a rate of 3.37 % per year. FAO statistics report that in the 10 years period between 2000 and 2010, rubber in the five countries of mainland southeast Asia (Cambodia, Laos, Myanmar, Thailand, and Vietnam) increased at a rate of 3.39 % per year (this statistic is for the whole country and is not limited to the non-traditional rubber growing areas we modeled) (FAO 2010). Dr. Prachaya Jumpasut of the Rubber Economist Quarterly Reports predicts that between 2008 and 2018 the global production of natural rubber will expand at an annual rate of 3.7 % annually (Prachaya 2009). Hence, our projected rate of change represents both recent historical and future forecasts of change quite accurately.

Assessing the spatial accuracy of the simulation maps is more difficult. Visual inspection revealed some localized anomalies in the location of individual grid cells of particular land-cover types. However, when we combined output from the six country domains, the resulting land-cover patterns for MMSEA were consistent along and across borders between domains with no artificial or unexpected, abrupt changes in land-cover patterns at country borders. Zhe and Fox (2011) report that even with high-resolution imagery, efforts to map the distribution of rubber trees face significant difficulties. They used MODIS Terra 16-day composite 250 m Normalized Difference Vegetation (NDVI) images from 2008 and 2009 and statistical data to map rubber in non-traditional rubber growing areas of mainland southeast Asia. Here, we used a 1 km resolution global land-cover map as our baseline, which did not include 'rubber' as a category. We used change in 'deciduous broadleaf' trees as a proxy for rubber tree expansion. Hence, at best our results are only rough estimates of change. We compared areas simulated by CLUE-s as 'deciduous broadleaf forests' (i.e., potentially rubber) in 2010 with the 2008/2009 map of rubber produced by Zhe and Fox (2011) and found a 20 % agreement. Two additional simulated land-cover categories that had high overlap with the 2008/2009 rubber map were evergreen broadleaf trees (33 %) and forest/field mosaic (22 %). As previously noted, these are precisely the two land-cover categories we suggest will be replaced by rubber expansion in the region. Hence, we conclude that the simulated distribution of rubber expansion in the region is reasonably accurate given the course resolution of the baseline data used in the analysis.

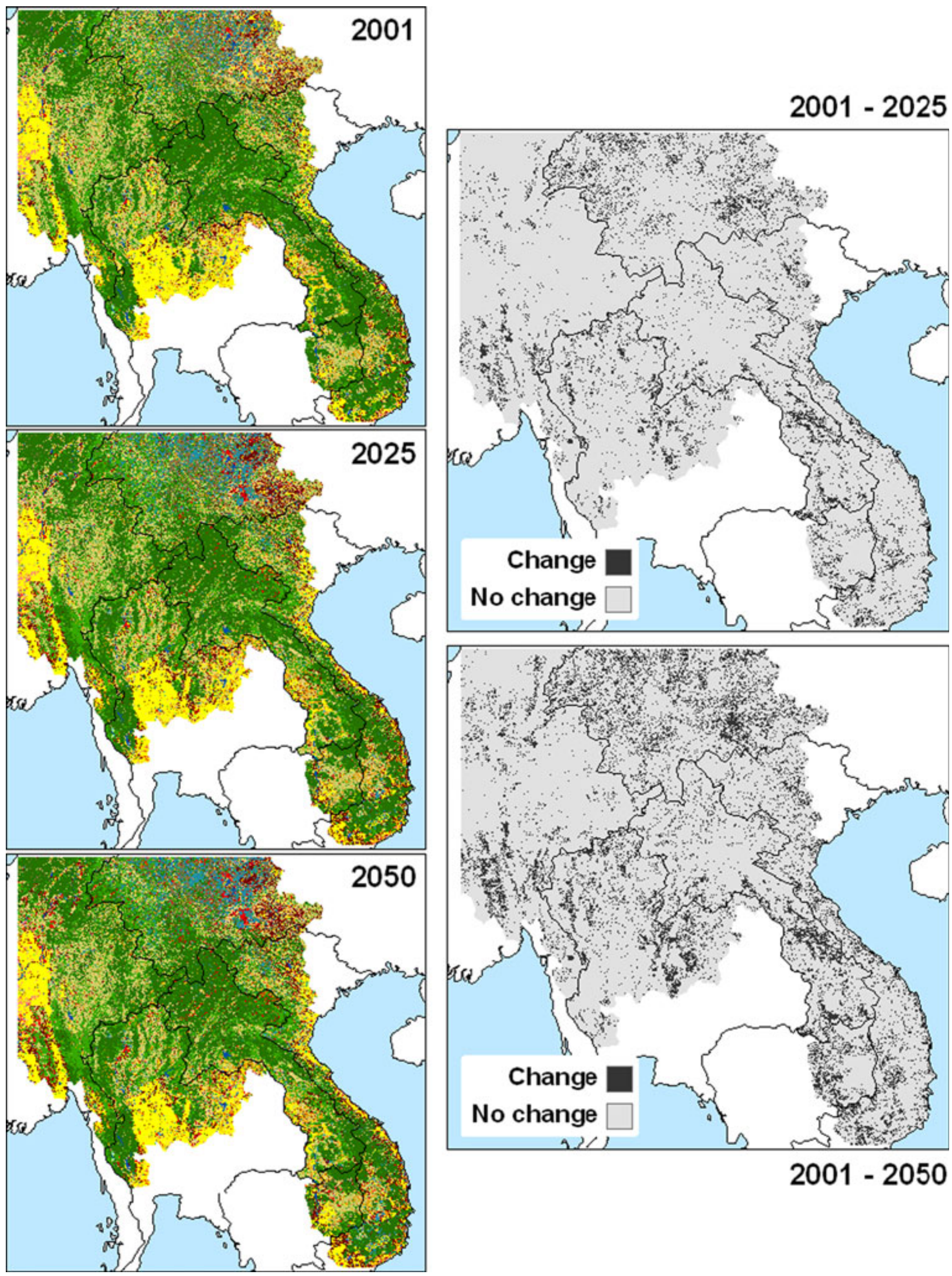

Fig. 3 Baseline land-cover map (2001), simulation output maps for years 2025 and 2050, and maps highlighting areas of change/no change for 2001–2025 and 2001–2050 simulation periods

We attribute our satisfactory results to (1) identifying and modeling the important drivers of change based on regional expert knowledge, (2) using highly plausible land-cover demands garnered from expert knowledge of historical, current, and future trajectories of change in MMSEA, and (3) the ability of the CLUE-s model to combine these data to simulate realistic, complex, non-linear land-cover patterns. The ability of experts to forecast change, however, is based on the important assumption that historical change can inform future events. This assumption breaks down if a paradigm shift occurs and future rates of change are no longer related to historical rates. This could happen in MMSEA if rubber, which is no longer perceived to be restricted to the humid tropics, is replaced by another high value crop which is restricted to the humid tropics, such as oil palm. If this happens, the rate of expansion into non-traditional rubber growing areas could be much greater than estimated here.

Discussion and Conclusion

Upland peoples in MMSEA have participated in trade for centuries, but in recent decades patterns of land use have

Table 4 Cumulative change for the six country domains and the MMSEA region in terms of area (km^2) and % of total area summed over 5 years increments for the 25 and 50 year periods

Country	Total upland area (km^2)	2001–2025		2001–2050	
		Cumulative area change (km^2)	Cumulative % change	Cumulative area change (km^2)	Cumulative % change
Cambodia	59,579	6,142	10.31	14,963	25.11
Laos	283,363	26,589	9.38	40,982	14.46
Myanmar	462,495	27,096	5.86	44,819	9.69
Thailand	303,093	28,583	9.43	50,032	16.51
Vietnam	285,271	33,954	11.90	54,694	19.17
Yunnan	337,532	49,189	14.57	78,560	23.27
MMSEA	1,731,333	171,553	9.91	284,050	16.41

changed rapidly in response to development projects, markets, and state policies. A number of factors are driving these changes including the transition to agricultural commodity production and plantation agriculture; large-scale infrastructure development including road-building, irrigation, and hydropower dams; the awarding of "economic land concessions" and similar state-backed land-development instruments; legal, semi-legal, and illegal logging; mineral exploration and development; and in-migration of new residents occasioned by governmental policy and the pursuit of economic opportunity. It is beyond the scope of this paper to review and investigate all of these driving factors or the plethora of changes they may engender. Rather, we sought to simulate changes in land cover (particularly tree cover types) in the region in order to begin assessing their implications for water processes and carbon sequestration.

Our estimates of cumulative land-cover change in the six countries of MMSEA simulation region ranged from 5.86 (Myanmar) to 14.57 (Yunnan) % during the first 25 years period, and from 9.69 (Myanmar) to 25.11 (Cambodia) % during the 50 years period from 2001 to 2050 (Table 4; Fig. 3). These changes are 2–3 times greater than the 5–8 % simulated change projected to occur in Europe between 2000 and 2030 (Verburg and others 2006). The results suggest that MMSEA may lose as much as 9 % of current native cover (secondary trees, shrub, and grass) by 2050. This loss will, however, be somewhat offset by the increase in rubber and other tree crops as well as tea and other evergreen shrubs (about 4 % in total).

At the regional scale, climate change predictions using our simulated changes in land cover suggest little influence on regional precipitation patterns, compared with the influence of global warming (Sen and others 2011b). Nevertheless, the potential threat of rubber expansion on water resources at other scales should not be overlooked. For example, in Xishuangbanna prefecture, China, dry season water extraction in the sub-soil layers beneath rubber increased sharply, coinciding with the annual leaf shedding and new leaf-flushing period (Guardiola-Claramonte and others 2008, 2010). This pattern of root-water uptake contrasts with that observed for secondary forest, shrub, and tea, which declined throughout the dry season. If these plot-scale observations manifest at larger scales, less catchment-wide water may be available at the peak of the dry season for rubber versus native tree covers. Our ability to quantify the effect of potentially high, dry season water demand on catchment and regional hydrology is hindered, however, because the underlying processes cannot be parameterized in conventional land–atmosphere models. Clearly, more work is needed both in terms of field observations and model advances.

Much of the uncertainty regarding the hydrological impacts of land-cover conversion stems from a failure to develop and use reasonable land-cover projections in climate simulations (Giambelluca and others 1996). Herein, we attempted to provide plausible land-cover projections for MMSEA using a land change modeling approach driven in part by expert knowledge. Although these simulated land-cover changes—which exhibit a continued trend of rapid expansion of rubber at the expense of other native land covers—did not produce substantial changes in predicted rainfall in subsequent climate simulations (Sen and others 2011a), the results are important. Because while conversion of vast landscapes from native cover to rubber may have a small footprint in terms of altering regional rainfall patterns, at the local level, the impacts may be profound, for example, if increased dry season water consumption leads to seasonal stream desiccation. Furthermore, the potential loss of biodiversity associated with whole-sale conversions to monoculture plantations, for which oil palm elsewhere in the region is a parallel, should not be overlooked (Rerkasem and others 2009; Ziegler and others 2011).

References

Bruun TB, De Neergaard A, Lawrence D, Ziegler AD (2009) Environmental consequences of the demise in swidden agriculture in SE Asia: soil nutrients and carbon stocks. Hum Ecol 37:375–388

Castella J, Verburg PH (2007) Combination of process-oriented and pattern-oriented models of land-use change in a mountain area of Vietnam. Ecol Model 202:410–420
Dickinson RE, Henderson-Sellers A, Kennedy JP (1993) Biosphere-atmosphere transfer scheme (bats) version 1e as coupled to the NCAR community climate model. In: Technical report, National Center for Atmospheric Research, Boulder
Economic Intelligence Unit (2004a) Country profile 2004: Myanmar (Burma). The Economic Intelligence Unit Limited, London
Economic Intelligence Unit (2004b) Country profile 2004: Vietnam. The Economic Intelligence Unit Limited, London
Economic Intelligence Unit (2005a) Country profile 2005: Cambodia. The Economic Intelligence Unit Limited, London
Economic Intelligence Unit (2005b) Country profile 2005: China. The Economic Intelligence Unit Limited, London
Economic Intelligence Unit (2005c) Country profile 2005: Laos. The Economic Intelligence Unit Limited, London
Economic Intelligence Unit (2005d) Country profile 2005: Thailand. The Economic Intelligence Unit Limited, London
Engelsman W (2002) Simulating land-use changes in an urbanizing area in Malaysia: an application of the CLUE-s model in the Selangor river basin. Research thesis paper. Department of Environmental Sciences, Wageningen University, Wageningen
Fox J, Vogler J (2005) Land-use and land-cover change in Montane mainland southeast Asia. Environ Manage 36(3):394–403
Fox J, McMahon D, Poffenberger M, Vogler J (2008) Land use and tenure change in Ratanakiri: 1989–2007. Community Forestry International, Phnom Penh
Friedl MA, McIver DK, Hodges JCF, Zhang XY, Muchoney D, Strahler AH, Woodcock CE, Gopal S, Schneider A, Cooper A, Baccini A, Gao F, Schaaf C (2002) Global land cover mapping from MODIS: algorithms and early results. Remote Sens Environ 83(1–2): 287–302
Fujita Y, Phanvilay K (2008) Land and forest allocation in Lao people's democratic republic: comparison of case studies from community-based natural resource management research. Soc Nat Res 21(2):120–133
Giambelluca TW, Tran LT, Ziegler AD, Menard TP, Nullet MA (1996) Soil-vegetation-atmosphere processes: simulation and field measurement for deforested sites in northern Thailand. J Geophys Res 101:25867–25885
Guardiola-Claramonte M, Troch PA, Ziegler AD, Giambelluca TW, Vogler JB, Nullet MA (2008) Local hydrologic effects of introducing non-native vegetation in a tropical catchment. Ecohydrology 1:13–22. doi:10.1002/eco.3
Guardiola-Claramonte M, Troch PA, Ziegler AD, Giambelluca TW, Durcik M, Vogler JB, Nullet MA (2010) Modeling basin-scale hydrologic effects of rubber (*Hevea brasiliensis*) in a tropical catchment. Ecohydrology 3(3):306–314
Guo H, Padoch C, Coffey K, Aiguo C, Yongneng F (2002) Economic development, land use and biodiversity change in the tropical mountains of Xishuangbanna, Yunnan, southwest China. Environ Sci Policy 5:471–479
Li HM, Aide TM, Ma YX, Liu XJ, Cao M (2007) Demand for rubber is causing the loss of high diversity rainforest in SW China. Biodivers Conserv 16:1731–1745
Maekawa T (2002) Road link makes dream possible. ADB Rev 9–10
Padoch C, Coffey K, Mertz O, Leisz S, Fox J, Wadley R (2007) The demise of swidden in southeast Asia? Local realities and regional ambiguities. Dan J Geogr 107(1):29–42
Rerkasem K, Lawrence D, Padoch C, Schmidt-Vogt D, Ziegler AD (2009) Consequences of swidden transitions for crop and fallow biodiversity. Hum Ecol 37:347–360
Rigg J (2006) Land, farming, livelihoods and poverty: rethinking the links in the rural south. World Dev 34(1):180–202
Rigg J, Nattapoolwat S (2001) Embracing the global in Thailand: activism and pragmatism in an era of de-agrarianisation. World Dev 29(6):945–960
Schneider RR (1994) Government and the economy on the Amazon frontier. In: Latin America and the Caribbean technical department. World Bank, Washington D.C
Sen OL, Bozkurt D, Fox J, Vogler JB, Giambelluca TW, Ziegler AD (2011a) Projected impacts of global warming on regional climate in southeast Asia. Clim Dyn (in review)
Sen OL, Vogler JB, Ziegler AD, Fox J, Giambelluca TW (2011b) Climatic effects of anthropogenic changes in Montane mainland southeast Asia: land cover / land use change simulations. Clim Chang (in review)
Sen OL, Wang L, Wang B (2004) Impact of Indochina deforestation on the East-Asian summer monsoon. J Climate 17:1366–1380
Soepboer W (2001) CLUE-s: an application for Sibuyan island, the Philippines. Research thesis paper. Department of Environmental Sciences, Wageningen University, Wageningen
Sturgeon JC (2010) Governing minorities and development in Xishuangbanna, China: Akha and Dai rubbers farmers as entrepreneurs. Geoforum 42(2):318–328
Sunderlin W, Huynh TB (2005) Poverty alleviation and forests in Vietnam. CIFOR, Jakarta
Thant M, Nair O (2002) Linking nations coast to coast. ADB Rev 14–16
Thomas D, Ekasingh B, Ekasingh M, Lebel L, Ha HM, Ediger L, Thongmanivong S, Xu J, Sangchyoswat C, Nyberg Y (2008) Comparative assessment of resource and market access of the poor in upland zones of the greater Mekong region. World Agroforestry Center, Chiang Mai
Thongmanivong S, Fujita Y, Fox J (2005) Resource use dynamics and land-cover change in Ang Nhai village and Phou Phanang national reserve forest, Lao PDR. Environ Manag 36(3):382–393
UNEP-WCMC (2005) World database on protected areas. http://www.wdpa.org/
Veldkamp A, Fresco L (1996) CLUE-CR: an integrated multi-scale model to simulate land use change scenarios in Costa Rica. Ecol Model 91:231–248
Veldkamp A, Fresco L (1997a) Exploring land use scenarios: an alternative approach based on actual land use. Agric Syst 55:1–17
Veldkamp A, Fresco L (1997b) Reconstructing land use drivers and their spatial scale dependence for Costa Rica (1973 and 1984). Agric Syst 55:19–43
Verburg PH (2006) Conversion of land use and its effects (CLUE) model. In: Geist H (ed) Our earth's changing land: an encyclopedia of land-use and land-cover change, vol 1(A–K). Greenwood Press, Westport, pp 144–146
Verburg PH, Veldkamp A (2004) Projecting land use transitions at forest fringes in the Philippines at two spatial scales. Landsc Ecol 19:77–98
Verburg PH, de Koning GHJ, Kok K, Veldkamp TA, Bouma J (1999a) A spatial allocation procedure for the modeling the pattern of land use change based upon actual land use. Ecol Model 116:45–61
Verburg PH, Veldkamp A, Fresco LO (1999b) Simulation of changes in the spatial pattern of land use in China. Appl Geogr 19: 211–233
Verburg PH, Soepboer W, Veldkamp A, Limpiada R, Espaldon V, Mastura SSA (2002) Modeling the spatial dynamics of regional land use: the CLUE-s model. Environ Manag 30(3):391–405
Verburg PH, de Groot WT, Veldkamp A (2003) Methodology for multi-scale land-use change modelling: concepts and challenges. In: Dolman AJ, Verhagen A, Rovers CA (eds) Global environmental change and land use. Kluwer Academic Publishers, Dordrecht/Boston/London, pp 17–51

Verburg PH, Schulp CJE, Witte N, Veldkamp A (2006) Downscaling of land use change scenarios to assess the dynamics of European landscapes. Agric Ecosyst Environ 114:39–56

Wassenaar T, Gerber P, Verburg PH, Rosales M, Ibrahim M, Steinfeld H (2007) Projecting land use changes in the neotropics: the geography of pasture forest expansion. Glob Environ Change 17:86–104

Willemen L (2002) Modelling of land-cover changes with CLUE-s in Bac Kan province, Vietnam. Research thesis paper. Department of Environmental Sciences, Wageningen University, Wageningen

Xu J (2006) The political, social and ecological transformation of a landscape: the case of rubber in Xishuangbanna, China. Mt Res Dev 26(3):254–262

Xu J, Fox J, Zhang P, Fu Y, Yang L, Qian J, Leisz S, Vogler J (2005) Land-use/land-cover change and farmer vulnerability in Xishuangbanna. Environ Manag 36(3):404–413

Ziegler AD, Bruun TB, Guardiola-Claramonte M, Giambelluca TW, Lawrence D, Lam Nguyen Thanh (2009a) Environmental consequences of the demise in swidden agriculture in SE Asia: hydrology and geomorphology. Hum Ecol 37:361–373

Ziegler AD, Fox JM, Xu J (2009b) The rubber juggernaut. Science 324:1024–1025

Ziegler AD, Fox JM, Webb EL, Padoch C, Leisz S, Cramb RA, Mertz O, Bruun TT, Vien TD (2011) Rapid land use changes and the role of swiddening in SE Asia. Conserv Biol 25:846–848