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# Projecting Land-Use Change and Its Consequences for Biodiversity in Northern Thailand

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**Abstract** Rapid deforestation has occurred in northern Thailand over the last few decades and it is expected to continue. The government has implemented conservation policies aimed at maintaining forest cover of 50% or more and promoting agribusiness, forestry, and tourism development in the region. The goal of this paper was to analyze the likely effects of various directions of development on the region. Specific objectives were (1) to forecast land-use change and land-use patterns across the region based on three scenarios, (2) to analyze the consequences for biodiversity, and (3) to identify areas most susceptible to future deforestation and high biodiversity loss. The study combined a dynamic land-use change model (Dyna-CLUE) with a model for biodiversity assessment (GLOBIO3). The Dyna-CLUE model was used to determine the spatial patterns of land-use change for the three scenarios. The methodology developed for the Global Biodiversity Assessment Model framework (GLOBIO 3) was used to estimate biodiversity intactness expressed as the remaining relative mean species abundance (MSA) of the original species relative to their abundance in the primary vegetation. The results revealed that forest cover in 2050 would mainly persist in the west and upper north of the region, which is rugged and not easily accessible. In contrast, the highest deforestation was expected to occur in the lower north. MSA values decreased from 0.52 in 2002 to 0.45, 0.46, and 0.48, respectively, for the three scenarios in 2050. In addition, the estimated area with a high threat to biodiversity (an MSA decrease >0.5) derived from the simulated land-use maps in 2050 was approximately 2.8% of the region for the trend scenario. In contrast, the high-threat areas covered 1.6 and 0.3% of the region for the integrated-management and conservation-oriented scenarios, respectively. Based on the model outcomes, conservation measures were recommended to minimize the impacts of deforestation on biodiversity. The model results indicated that only establishing a fixed percentage of forest was not efficient in conserving biodiversity. Measures aimed at the conservation of locations with high biodiversity values, limited fragmentation, and careful consideration of road expansion in pristine forest areas may be more efficient to achieve biodiversity conservation.

**Keywords** Deforestation · Land-use modeling · Landscape · GIS · Northern Thailand

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Deforestation and land-use change are critical threats to biodiversity in Southeast Asia (Fox and Vogler 2005). The Food and Agriculture Organization of the United Nations (2005) estimated that tropical regions lost 15.2 million ha of forest per year during the 1990s and Southeast Asia experienced the highest rate of net cover change (0.71% per year) compared with other continents. Forest loss in Thailand was ranked the highest of all countries in the Greater Mekong subregion and as fourth in the "Top 10" of tropical countries in terms of annual rate of loss in 1995

(CFAN 2005). According to Charuphat (2000), forest cover in Thailand declined from 53% of the country's area in 1961 to approximately 25% in 1998. The total loss of forest area during this 37-year period was 14.4 million ha, and the average annual loss was 400,000 ha, or 2.0%.

Deforestation in Thailand is mainly caused by commercial logging of primary forest, agribusiness, and urban development, driven by ongoing population growth (Panayotou and Sungsuwan 1989) and the national development strategy (Delang 2002) to gain foreign income. Cropper and others (1996) indicated that road development and population growth explain about 70% of the deforestation that occurred in Thailand between 1976 and 1989. During this period, about 1.2 million new agricultural households and about 17,000 km of roads was added in northern and northeast Thailand. In addition, land-use change is also driven synergistically by a combination of scarce resources leading to an increase in production pressures on resources, changing opportunities created by markets, outside policy intervention, loss of adaptive capacity, and changes in social organization and attitudes (Lambin and others 2003).

Deforestation is causing concerns for policymakers; it has been listed as the most important environmental issue in the Kingdom of Thailand in the last 10 years (Office of Natural Resources, Environmental Policy and Planning 2006). In 1989, the Thai government declared the closure of commercial logging concessions as part of its change in strategy for national development. In addition, the Royal Thai Government (RTG) has implemented two measures to avoid further deforestation and increase forest cover, namely, the establishment of a protected areas network and reforestation, respectively (Trisurat 2007). Nevertheless, the latest assessments based on new and improved methods of measuring and classifying forest cover show that the remaining forest cover decreased between 2000 and 2005 from 33.1 to 31.4% of the total land area (Royal Forest Department 2007).

The impacts of deforestation are well known and observed. Of primary concern are impacts on biodiversity (Redford and Richter 1999) and the ability of biological systems to support human needs (Lambin and others 2003). Not only does deforestation cause habitat loss, but also it results in habitat fragmentation, diminishing patch size and core area, and isolation of suitable habitats (MacDonald 2003). In addition, fragmentation provides opportunities for pioneer (light-demanding) species to invade natural habitat along the forest edge (Forman 1995; McGarigal and Marks 1995). Pattanavibool and others (2004) found that the fragmented forest in the Mae Tuen Wildlife Sanctuary in northern Thailand contained lower densities of large mammals (e.g., Asian elephant, gaur) and hornbills compared to the relatively intact Om Koi Wildlife Sanctuary. In addition, recovery of degraded ecosystems to their original state is extremely difficult and time-consuming. Fukushima and others (2008) investigated the recovery of tree species composition in secondary forests in northern Thailand that had been abandoned after swidden cultivation for more than 20 years. The results indicated that native species in recently abandoned poppy fields were mostly absent and that it would take more than 50 years to reach climax species composition. In addition, Oberhauser (1997) also indicated that a high number of vascular species were observed and increasing numbers of animal species became established in the older plantations.

Models of land-use change can address two separate issues: where land-use changes are likely to take place (location of change) and at what rates changes are likely to progress (quantity of change). The first issue requires the identification of the natural and cultural landscape attributes that are the spatial determinants of change. The rate or quantity of change is driven by demands for land-based commodities and these demands are often described using economic models accounting for demand–supply relations and international trade (Verburg and others 2008). Land-use change models range from simple system representations including a few driving forces to simulation systems based on a profound understanding of situation-specific interactions among a large number of factors at different spatial and temporal scales, as well as environmental policies. Reviews of different land-use models have been provided by Verburg and others (2004), Matthews and others (2007), and Priess and Schaldach (2008).

The current research focused on the northern region of Thailand, which contains the highest percentage of remaining forest cover and protected areas compared with other regions. Due to ongoing human population growth (e.g., 3.9% for Chiang Mai province and 1.4% for Mae Hong Son province [Department of Local Administration 2007]), expansion of agriculture (1.4% per annum [Land Development Department 2003]), and infrastructure development in the region, continuing deforestation and decreasing biodiversity can be expected. This paper assesses the potential consequences of ongoing deforestation for biodiversity. Two spatial models were combined, namely, the Dyna-CLUE (Conversion of Land Use and its Effects) model (Verburg and others 2002; Overmars and others 2007) and the Global Biodiversity Model framework (GLOBIO3 [Alkemade and others 2009]). The research aim was to analyze the likely effects on biodiversity of various conservation policy options in the region, with the combined use of these models. Specific objectives were (1) to forecast land-use change and land-use patterns across the region based on three scenarios, (2) to analyze the consequences for biodiversity, and (3) to identify areas most susceptible to future deforestation and high biodiversity loss.

## Materials and Methods

### Study Area

Northern Thailand is situated between the northern latitudes of 14°56′17″ and 20°27′5″ and the eastern longitudes of 97°20′38″ and 101°47′31″, covering 17 provinces and encompassing an area of 172,277 km$^2$, or one-third of the country's land area (Fig. 1). The dominant topography is mountainous, with a north–south orientation. The average annual temperature ranges from 20 to 34°C; the average annual rainfall ranges between 600 and 1000 mm in low areas to more than 1000 mm in mountainous areas. The rainy season is from May to October. The total population has been almost stable at 11 million over the last 10 years but the population is relatively different among provinces (Department of Local Administration 2007).The growing population is leading to additional pressure on a limited land resource for the purposes of agricultural production and food self-sufficiency (Cropper and others 1996).

Northern Thailand was originally covered by dense forest. Dominant vegetation included dry dipterocarp and mixed deciduous forests at low and moderate altitudes, while pine forest, hill evergreen forest, and tropical montane cloud forest dominated areas at high altitudes (Santisuk 1988). The Land Development Department (2003) indicated that forest cover in this region declined from 68 to 57% during 1961 to 2002. Except in protected areas, the lowland forests have been removed due to extensive logging in the past and the expansion of agricultural land. These areas are now extensively managed for agriculture, with rice on irrigated land and vegetables and fruit trees (e.g., longan, lychee) elsewhere. Agriculture currently covers approximately 32% of the region. Secondary forest in mountainous northern Thailand has been the result mainly of swidden cultivation (Fukushima and others 2008). In addition, some swidden cultivation has been shortened in its cycle or changed to monoculture cash crops over the last 50 years (Schmidt-Vogt 1999; Fox and Vogler 2005). According to the Office of Agricultural Economics (OAE), approximately 50,000 ha of rubber was planted in this region during 2004 to 2006 (Office of Agricultural Economics 2007). The continuing increase in the rubber price in the last decade has stimulated a huge land demand for rubber plantations.

### Land-Use Modeling and Scenario Definition

The Dyna-CLUE model (Verburg and others 2002; Overmars and others 2007) was used to project land-use transitions for different scenarios during the period 2002–2050. It has been used and validated in multiple case studies and has proven to be capable of simulating land-use dynamics in Southeast Asian mountain regions (Castella and Verburg 2007; Pontius and others 2008; Verburg and Veldkamp 2004). The model requires four inputs that

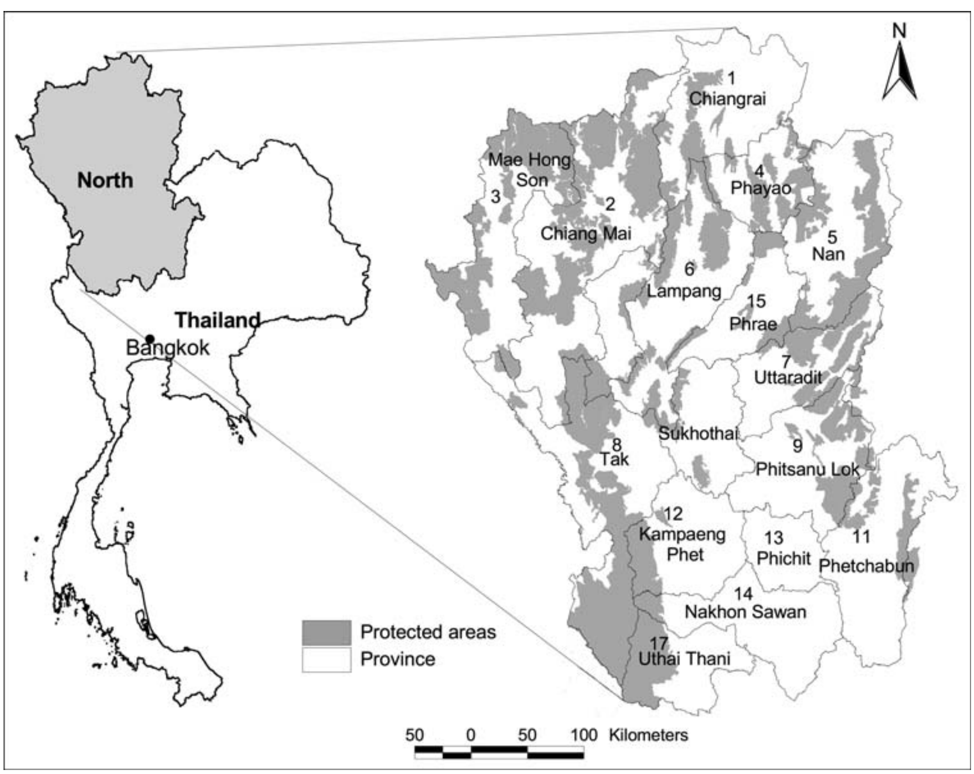


**Fig. 1** Location of protected areas and provinces in northern Thailand

together create a set of conditions and possibilities for which the model calculates the best solution by an iterative procedure: (1) land-use requirements (demand), (2) location characteristics, (3) spatial policies and restrictions, and (4) land-use type-specific conversion settings. Land-use requirements and spatial policies are scenario specific, whereas the location characteristics and conversion settings are assumed equal for all scenarios.

*Land-Use Requirements (Demand)*

These were calculated at the aggregate level as part of a specific scenario. Three land-demand scenarios for northern Thailand in 2050 were developed: (1) trend scenario, (2) integrated management scenario, and (3) conservation-oriented scenario. The trend scenario was based on a continuation of the land-use change of recent years (1998–2003 [Office of Agricultural Economics 2007]). The integrated scenario was derived from the long-term environmental policy (Office of Environmental Policy and Planning 1997) and aimed to maintain 50% forest cover at the national level. The conservation-oriented land use scenario aimed to maintain 55% of the region as forest cover and rehabilitate the degraded head watershed. The characteristics of the three scenarios are reported in Table 1.

*Location Characteristics*

The Dyna-CLUE model quantifies the location preferences of the different land uses based on logistic regression models. The logit models indicate the preference for a specific type of land use based on the relation between the occurrence of a land-use type and the physical and socio-economic conditions of a specific location (location factors):

$$\begin{aligned}\text{Logit}(p_i) &= \ln(p_i)/(1-p_i)\\ &= \beta0 + \beta_1X_1 + \beta_2X_2 + \cdots + \beta_nX_n \qquad (1)\end{aligned}$$

where $p_i$ is the probability of a grid cell for the occurrence of the considered land-use type and the $X$ parameters are the driving factors, which include physical and socioeconomic factors. The coefficients ($\beta$) are estimated through logistic regression using the occurrence of the land uses in 2002 as the dependent variable.

The goodness-of-fit of a logistic regression model is evaluated using the receiver operating characteristic (ROC [Swets 1986]). The value of the area under the curve ranges between 0.5 (completely random) and 1.0 (perfect fit).

The original land-use classes derived from the 1:50,000 land-use map for 2002 (Land Development Department 2003) were aggregated into nine classes to facilitate land-use simulations: (1) intact forest, (2) disturbed forest, (3) forest plantation, (4) paddy, (5) upland crop, (6) tree crop, (7) miscellaneous area (e.g., old clearing, wetland, rock outcrop), (8) built-up area, and (9) water body. In the current study, models were developed for seven land-use classes, as the 'intact forest' was a function of other changes and 'water body' was assumed to remain unchanged during the simulation period.

The physical factors included topographic variables, annual precipitation, distance to available water, and soil texture. Some topographic factors (altitude, slope, and aspect) represented limiting factors for agriculture. Altitude, aspect, slope, distance to main roads, and distance to streams and rivers were extracted and/or interpolated from 1:50,000 topographic maps (Royal Thai Survey Department 2002). A surface representing the spatial variation in annual precipitation was interpolated from rainfall data recorded at meteorological stations across northern Thailand, using universal kriging techniques (Theobald 2005).

**Table 1** Characteristics of land demand scenarios for northern Thailand in 2050

| | Scenario 1: Trend | Scenario 2: Integrated management | Scenario 3: Conservation oriented |
|---|---|---|---|
| Forest cover target | 45% (annual loss follows trend of 0.6% annual loss) | 50% | 55% |
| Other land-use claims | Based on trends: plantation (0.2% increase annually), paddy (0.8%), upland crop (0.2%), tree crop (1.6%), miscellaneous (−0.7%), and built-up (1.1%) | Rubber plantation: 480,000 ha other land uses: paddy (0.7% increase annually), upland crop (−0.2%), tree crop (0.8%), miscellaneous (−1.0%) and built-up (1.1%) | Rubber plantation: 300,000 ha other land uses: paddy (0.3% increase annually), upland crop (−0.1%), tree crop (0.5%), miscellaneous (−1.0%) and built-up (1.1%) |
| Resulting total agricultural Area | Agriculture: 44% | Agriculture: 41% | Agriculture: 36% |
| Spatial policies | No spatial policies implemented | • Restriction (no land change) within national parks and wildlife sanctuaries<br>• Establishment of forest plantations: 230,400 ha (~4800 ha/yr) | • Restriction (no land change) within national parks and wildlife sanctuaries<br>• Reforestation in degraded Class 1 watershed (230,400 ha) |

Soil types were derived from the 1:100,000 soil map (Land Development Department 2001).

The socioeconomic factors influencing deforestation included distance to village, distance to city, distance to main road, and population density. Distance to village and population density were proxy indicators for local consumption, while the distance to road and distance to city parameters were important proxies for the costs of transporting agricultural commodities to market. Current population data were obtained from the Local Administration Department. Protected area coverage was digitized from the National Gazette map. All spatial analyses were carried out using ArcGIS software with a spatial resolution of 500 × 500 m.

### *Spatial Policies and Restrictions*

These indicate areas where land-use changes are restricted through strict protection measures, such as protected areas. In the trend scenario, no spatial policies were implemented, thus forest encroachment could occur in protected areas if the location characteristics were favorable. In contrast, land-use policies were imposed for the integrated management and conservation-oriented scenarios. Under the latter scenarios, existing national parks and wildlife sanctuaries, which cover approximately 53,200 $km^2$, or 30% of the region (Royal Forest Department 2007), were designated *restricted areas*, so that no further encroachment was allowed in these areas and natural succession was possible.

### *Land-Use Type-Specific Conversion Settings*

These influence the temporal dynamics of the simulations. Two sets of parameters are essential to characterize each land-use type: conversion elasticities and land-use transition settings. The elasticities were estimated based on capital investment, time, and energy costs and expert judgment, ranging from 0 (easy conversion) to 1 (irreversible change) (Verburg and others 2002). High values for this parameter were assigned to the primary forest, paddy, built-up area, and water body classes, because these land-use types are not likely to be displaced because they involve a high commitment to investment or a large amount of time in the case of establishing primary forest. Medium values were given to disturbed forest and fruit trees. On the other hand, upland crop and miscellaneous areas are highly dynamic land uses, thus low values were assigned to them. In the land-use transition settings a minimum of 30 years was specified as a requirement for the natural succession of reforestation to primary forest and 20 years was specified for succession from disturbed forest back to primary forest, based on the work of Oberhauser (1997).

The Dyna-CLUE model uses all inputs to calculate the total probability for each grid cell of each land-use type based on the local suitability of the location derived from the logit model, the conversion elasticity, and the competitive strength of the land-use type (Verburg and Overmars 2009). Where no constraints to a specific conversion were specified, the location was allocated to the land use with the highest total suitability. Using an iterative process, the competitive strength of the different land-use types was adapted until the total allocated area of each land use equaled the total land requirements specified in the scenario.

The resulting land-use patterns were analyzed in terms of mean patch size, number of patches, and largest patch size with the help of the FRAGSTATS 3.0 software (McGarigal and Marks 1995) to assess landscape structure change and fragmentation because of the land-use changes.

## Calculation of Remaining Mean Species Abundance

The Global Biodiversity Model framework (GLOBIO3) was used to assess the consequences of different land-use scenarios for biodiversity (Alkemade and others 2009). The model was built on the simple cause-effect relationships between human-induced drivers and biodiversity impacts in the past, present, and future, and it can be used at various scales. The relationships were derived from an extensive literature review and meta analyses and are described in Alkemade and others (2009). The mean species abundance (MSA) relative to their abundance in undisturbed ecosystems is used as the proxy indicator for biodiversity, similar to a naturalness or intactness index (see also Scholes and Biggs 2005). The driving factors in the original GLOBIO3 model included land use and land-use intensity, infrastructure development, fragmentation, atmospheric nitrogen deposition, and climate change. In the current study, the last two factors were not included, because these are implemented in the software by coarse-scale, global algorithms not applicable to the local scale. Similar to the Dyna-CLUE model, all spatial analyses were calculated with a spatial resolution of 500 × 500 m.

The overall MSA value of a grid cell $i$ ($MSA_i$) was obtained by multiplying the values for each driving factor in each grid cell according to

$$\mathrm{MSA}_{xi} = \mathrm{MSA}_{LUi} * \mathrm{MSA}_{Ii} * \mathrm{MSA}_{Fi} \quad (2)$$

where $\mathrm{MSA}_{xi}$ is defined as the mean species abundance as a function of LU (land use/land intensity), I (infrastructural development), and F (fragmentation), respectively.

The MSA values range between 1.0 in an undisturbed or primary ecosystem and 0.0 in a completely destroyed ecosystem. MSA values can be categorized into five classes: low (0.0–0.2), relatively low (0.2–0.4), medium (0.4–

0.6), relatively high (0.6–0.8), and high (0.8–1.0). The original $MSA_{LU}$ values as estimated by Alkemade and others (2009) were adapted slightly to suit the local situation, using input obtained from national biodiversity experts (Utis Kutintara and Nipon Tangtham, personal communication) and a literature review (Santisuk 1988). The values used for intact forest, disturbed forest, forest plantation, secondary forest (miscellaneous), intensive agriculture (paddy), extensive agriculture (upland crop), perennial trees, and built-up area were 1.0, 0.7, 0.4, 0.45, 0.1, 0.3, 0.2, and 0.05, respectively.

To estimate the effect of infrastructure, impact zones were calculated along road networks. Roads were buffered by different widths. The width of an impact zone depended on the land-use type, because the direct and indirect effects of roads on the neighboring plants and wildlife differ among ecosystems (United Nations Environmental Programme 2001).

Depending on the land cover type, four sensitivity classes were assigned to the different zones: high impact ($MSA_I = 0.50$), medium impact ($MSA_I = 0.75$), low impact ($MSA_I = 0.900$), and no impact ($MSA_I = 1.00$) at distances of more than 5–10 km.

The GLOBIO3 model estimates of the minimum area requirement of species were used to derive $MSA_F$ values. $MSA_F$ values were ranked from 0.55 for a patch size of 1–10 $km^2$ to 1.00 for a patch size >10,000 $km^2$. More detailed documentation on these relationships is provided by Alkemade and others (2009).

### Assessment of Future Deforestation and Threats to MSA

To determine the extent of the projected deforestation within the protected area network, the current and predicted land-use maps for 2050 were overlaid with a protected-area map. In addition, hotspots of threats to biodiversity were determined by selecting areas where MSA was expected to decrease by more than 0.5 between the current and the simulated 2050 conditions. These areas were determined both inside and outside the protected-area network.

## Results

### Land-Use/Land-Cover Changes

The significant factors and coefficients derived from the logistic regression analysis that determined the location suitability of the seven land-use types are reported in Table 2 From this table, it can be seen that not all location factors were included in the regression models and each factor contributed differently depending on the land-use type. High altitude, lateritic soil, and distance to available water were positively correlated with disturbed forest. These areas contained many limiting factors for agriculture, so further reclamation to agriculture was limited. In contrast, areas close to the stream network, situated in densely populated forested areas, accessible from main

**Table 2** $\beta$ values of significant location factors for regression results related to each land-use location

| Variable | Disturbed forest | Plantation | Paddy | Upland crop | Tree crop | Misc. | Built-up |
|---|---|---|---|---|---|---|---|
| Altitude | 0.00048 | 0.00130 | −0.00376 | −0.00072 | n.s. | 0.00075 | 0.00048 |
| Slope | n.s. | −0.00397 | −0.08228 | −0.01893 | −0.01689 | −0.00239 | − 0.02459 |
| Soil texture[a] | | | | | | | |
| Loam | −1.37044 | −1.76317 | 0.95018 | 0.55511 | 1.07089 | n.s. | n.s. |
| Sand | n.s. | −1.81328 | −0.43501 | n.s. | 1.22317 | n.s. | n.s. |
| Laterite | 0.41532 | −1.10662 | n.s. | n.s. | 0.92850 | 1.00739 | −0.50489 |
| Slope complex | n.s. | n.s. | −0.59339 | −1.29505 | n.s. | 0.93170 | −1.34931 |
| Clay | −0.96675 | n.s. | 1.74109 | n.s. | 0.63130 | | n.s. |
| Wetland | n.s. | −1.51121 | 0.65003 | −1.91855 | n.s. | 1.46027 | n.s. |
| Distance to stream | 0.00011 | −0.00013 | −0.00011 | 0.00038 | 0.00018 | −0.00021 | −0.00016 |
| Distance to village | n.s. | n.s. | −0.00015 | −0.00003 | 0.00021 | −0.00018 | n.s. |
| Distance to main road | −0.00010 | −0.00015 | n.s. | −0.00026 | −0.00024 | n.s. | −0.00026 |
| Distance to city | −0.00001 | −0.00001 | −0.00004 | 0.00003 | −0.00004 | 0.0001 | −0.00006 |
| Population density | −0.00287 | −0.00443 | n.s. | −0.00587 | n.s. | −0.00190 | 0.00025 |
| Constant | 0.47230 | 6.10071 | 1.35047 | −2.82129 | 3.71065 | −0.49785 | 1.90341 |
| ROC | 0.68 | 0.71 | 0.93 | 0.83 | 0.80 | 0.66 | 0.88 |

*Note*: n.s., not significant at 0.05 level

[a] Category variable

roads, at low altitude, and on fertile soil (clay and loam) were identified as at risk of encroachment, because they are prime targets for agriculture. In addition, rugged terrain, poor soil, and remoteness were limiting factors to future encroachment. The spatial distributions of the seven land-use types were explained moderately to well by the selected location factors, as indicated by the ROC values that measure the goodness-of-fit of the logistic regression models (Table 2). High ROC values were found for paddy (0.93) and built-up area (0.88). Relatively high-to-moderate values were found for upland crops (0.83), tree crops (0.80), and forest plantation (0.71). Low values were observed for disturbed forest (0.68) and miscellaneous land use (0.66). These differences in goodness-of-fit occurred because paddy requires specific land characteristics (e.g. poor drainage, clay texture), similar to a built-up area that forms in high population areas, close to roads and cities, and at low altitude. Sand and lateritic soil are not systematic choices for upland crops. Disturbed forest and miscellaneous land use (including abandoned swidden cultivation) can be found in all altitude zones, often on soils vulnerable to soil erosion (Land Development Department 2001; Thanapakpawin and others 2006). In addition, because these classes represented a wide range of different activities, lower ROC values were found.

Land-use/land-cover maps for 2002 and simulation results for 2050 for the three scenarios are shown in Fig. 2. The results of the trend scenario without spatial policies and restrictions show that the highest rate of deforestation and a low percentage of forest cover was found in the four lower-north provinces of Phitsanulok, Sukhothai, Khamphaeng Phet, and Nakhon Sawan (Fig. 2). The dominant topography in these provinces is flat to gently sloping terrain with alluvial deposits, which are highly suitable for agriculture and development. Forest areas have been converted to agriculture for several decades. In contrast, trends of deforestation in Chiang Mai, Phayao, Lampang, Lampun, and Phetchabun provinces were expected to reverse. The annual deforestation rate would be <1% (previously 1.1–1.9%). The highest percentages of remaining forest cover in 2050 were found in the western provinces, such as Mae Hong Son (84%), followed by Chiang Mai (70%). Mae Hong Son province also showed the lowest deforestation rate (0.1% per annum), followed by Nan (0.2% per annum). These provinces have mostly shallow, erosive soils with low fertility and are located in sloping terrain, with very difficult access, so opportunities for agriculture are very restricted by natural barriers. Consequently, the population in Mae Hong Son was less than 300,000 and it had the lowest density (20 people/km$^2$) in Thailand. Although the population in Nakhon Sawan was 1.1 million, the population density was 126 people/km$^2$ or 6–7 times that of Mae Hong Son province.

The integrated-management scenario, with protected areas and a slower rate of agricultural expansion, showed different land-use patterns. This scenario assumed less demand for agriculture and rubber plantations, leading to higher remaining forest cover and tree crops. Forest cover was expected to increase from the west to the upper north and along the eastern national border. Mae Hong Son and Chiang Mai would have more than 75% forest cover in 2050 (Fig. 3), while Nan would have approximately 65%, which is similar to the conditions in 2002. Under this scenario, substantial increases in forest cover were also predicted for Chiang Rai, Nan, Tak, and Phitsanulok provinces. For instance, Nan would gain approximately 2% of forest cover in the next 48 years, due to the restriction of further encroachment into the reserves and the regrowth of natural vegetation in abandoned agricultural areas (5700 ha).

The results of the conservation-oriented scenario showed that the extent and distribution pattern of the remaining forest in 2050 were relatively similar to the conditions in 2002. Similar to other scenarios, high deforestation was found in Pichit, Sukhothai, Phetchabun, Kamphaeng Phet, and Nakhon Sawan provinces. Mae Hong Son, Chiang Mai, Lampang, Tak, and Phrae provinces still encompassed more than 70% forest cover (Fig. 3). In addition, Nan province would gain approximately 5.6% forest cover, mainly converted from secondary forest and abandoned swidden cultivation at high elevation through reforestation.

The results of the Dyna-CLUE model revealed that the number of remaining forest patches increased in all scenarios over the 48 years of simulation. The number of patches increased from 1250 in 2002 to values of 1783 for the trend scenario, 1515 for the integrated-management scenario, and 1321 patches for the conservation-oriented scenario in 2050. This index corresponds to mean patch size index, which revealed that the mean patch size of forests decreased from 7930 ha in 2002 to 4373, 5681, and 7214 ha for the trend, integrated-management, and conservation-oriented scenarios, respectively. In addition, the largest patch of forest cover substantially declined from 54% of the remaining forest cover in 2002 to 39% for the trend scenario, 44% for the integrated scenario, and 50% for the conservation-oriented scenario due to fragmentation. Small, fragmented forest patches surrounded by agricultural land uses can be considered as disturbed forest or sink habitat (Forman 1995), since the whole patch corresponds to a border area.

### Remaining MSA

The overall MSA for northern Thailand in 2002 was approximately 0.52, which was a decrease of 0.48 since human intervention first occurred (Table 3). The decrease

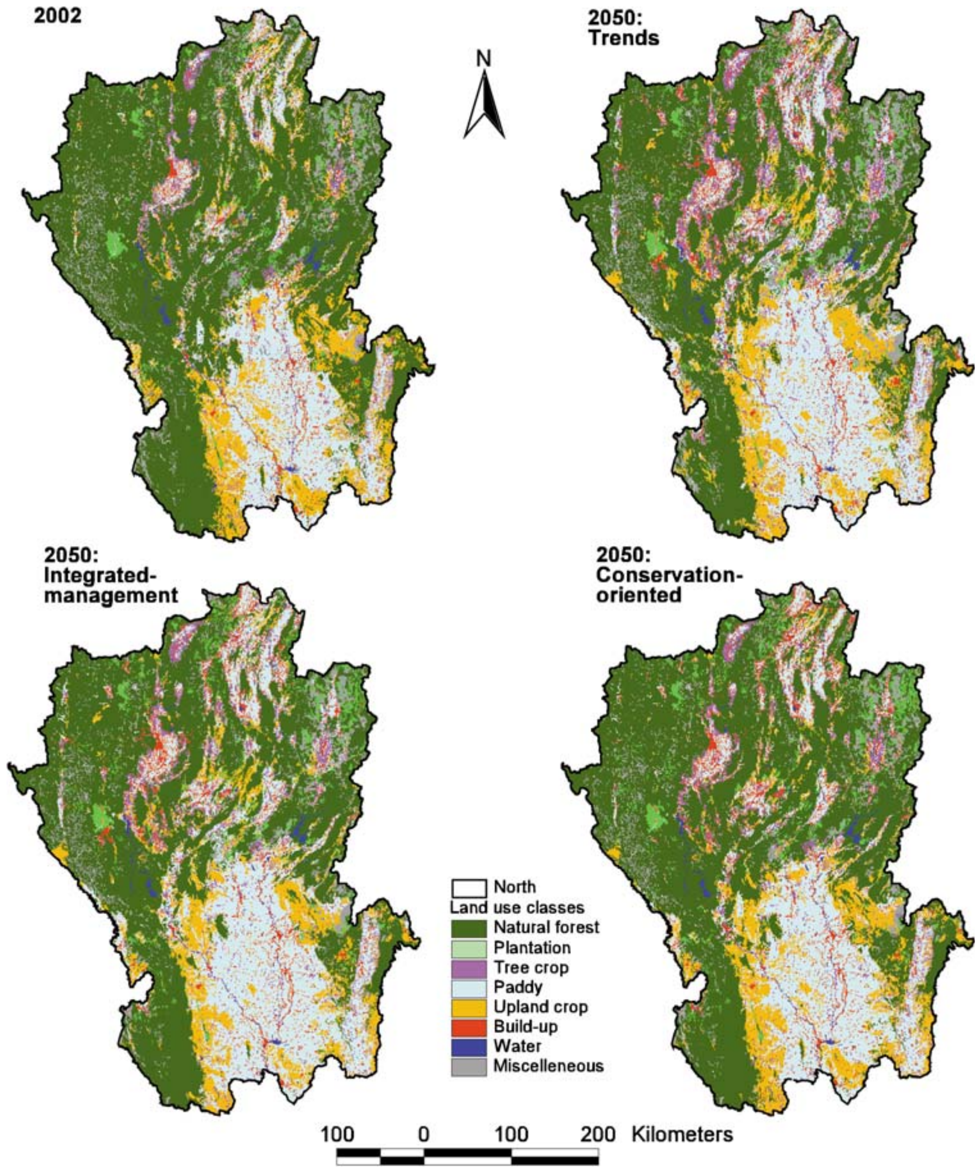


**Fig. 2** Land-use patterns in 2050 simulated by the Dyna-CLUE model for northern Thailand

was mainly caused by land-use change, especially agriculture (34%). The projected MSA value for the trend, integrated-management, and conservation-oriented scenarios for 2050 was estimated as 0.45, 0.46, and 0.48, respectively (Table 3). The expansion of agriculture contributed to a future MSA loss of between 35.1 and 42.2%. The second highest impact factor was infrastructure development (road expansion), followed by fragmentation. The large effect of infrastructure development was a consequence of the assumption for all scenarios that the current unpaved roads would be developed to hard-surface standard within the next 48 years and would facilitate human access to remaining intact forest areas, thus leading to a reduction in MSA.

The highest MSA values were associated with high altitude and inaccessible areas in the west (Fig. 3). Such areas received de facto natural protection except where communities had settled and were practicing agriculture. In addition, patchy areas of high MSA were scattered in remnant protected areas across the landscape. Thus, the persistence of forest cover and MSA in the future would be very likely to occur only in protected areas and on high slopes as indicated by Fox and Vogler (2005). Figure 3 also shows that the remaining MSA in the northwest (Chiang Mai province) would decline due to infrastructure development (road construction) and fragmentation.

## Threats to MSA

Based on the analysis, the estimated area where MSA was seriously threatened (a decrease of 0.5 or more during the

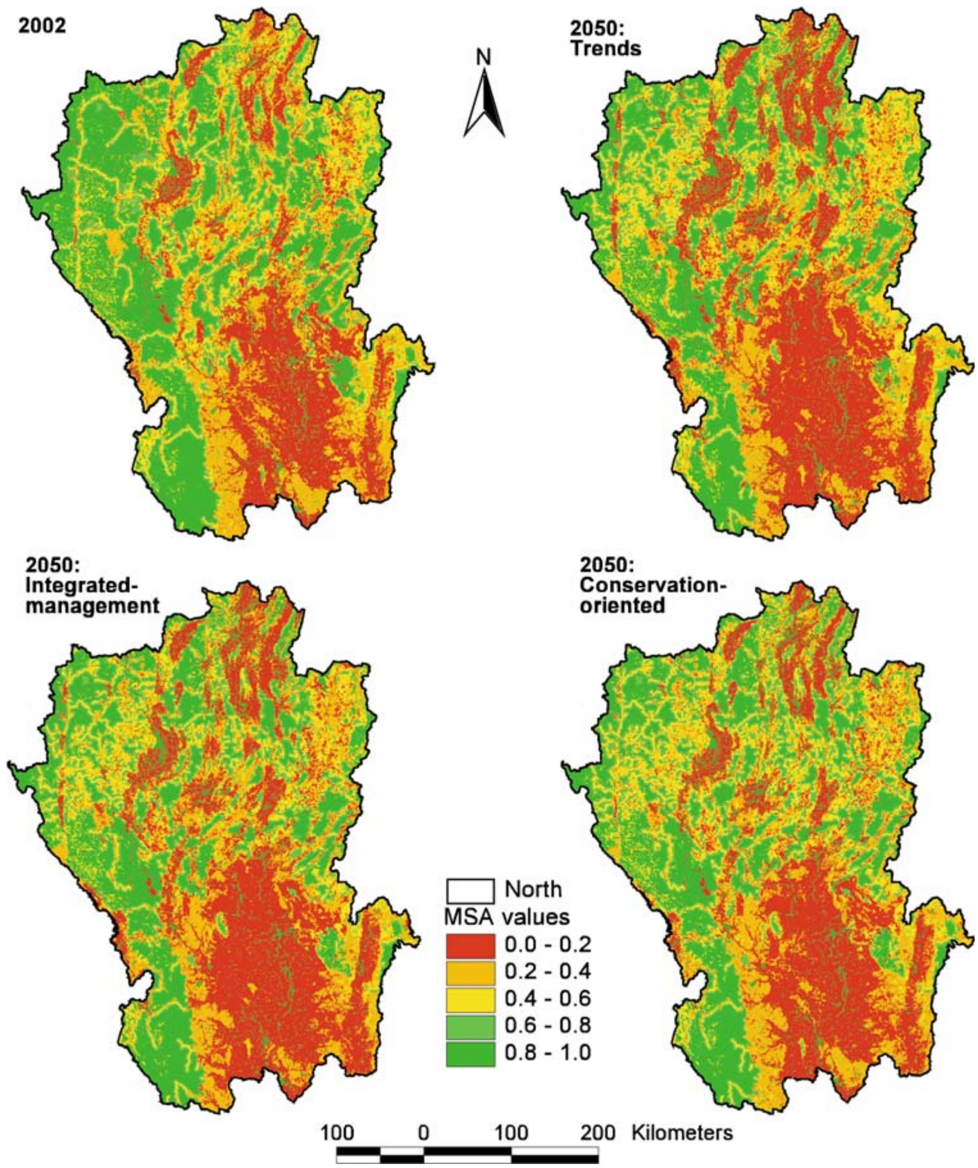


**Fig. 3** Remaining species abundance for northern Thailand under different land-use scenarios in 2050

2002–2050 period) was approximately 4910 km$^2$, or 2.8% of the region under the trend scenario. The total number of forest patches threatened was 2350 and most of these were distributed across the center of the northern region (Fig. 4). Forest patches were unlikely to stay preserved in the lower north of the region, due to the low forest area remaining in this part of the region (Fig. 2). The average patch size was 208 ha. In contrast to these results, the areas threatened under the integrated-management and conservation-oriented scenarios were 2719 km$^2$ (1627 patches) and 556 km$^2$ (337 patches), respectively, while the average remaining patch sizes were 167 and 165 ha, respectively.

Some of the currently protected areas were unlikely to be effective in preventing MSA loss due to deforestation if restrictions were not enforced. The results indicated that the remaining forest cover inside the protected area network would decline from 86% of the reserve areas in 2002 to 76% in 2050 under the trend scenario. Large areas of intact forest cover were likely to be diminished both inside and outside protected areas. On the other hand, the expected forest cover in protected areas would be approximately 87% under the integrated management and conservation-oriented scenarios. Using GLOBIO3, the average MSA value derived in protected areas in 2002 was 0.72 and estimated to be 0.66, 0.69, and 0.70 in 2050 under the trend, integrated management, and conservation-oriented scenarios, respectively (Figs. 3 and 4). The expected extent of threats to MSA under the integrated management and conservation-oriented scenarios was much lower than for the trend scenario, due to the assumption that restrictions to deforestation in protected areas would be successful (Fig. 4).

**Table 3** Landscape indices of remaining forest area and relative contribution of different pressure indicators to the reduced MSA in northern Thailand during 2002–2050 (%)

| | 2002 | Scenario 1: Trend | Scenario 2: Integrated management | Scenario 3: Conservation oriented |
|---|---|---|---|---|
| Total forested area (%) | 57.0 | 45.0 | 50.0 | 55.0 |
| Remaining intact forest (%) | 49.2 | 37.2 | 41.6 | 47.0 |
| No. of patches | 1,254 | 1,783 | 1,515 | 1,312 |
| Average mean patch size (ha) | 7,930 | 4,370 | 5,680 | 7,210 |
| Largest patch index | 53.7 | 38.9 | 43.7 | 49.7 |
| Total core area ($km^2$) | 60,069 | 4,241 | 52,926 | 60,213 |
| Mean core area ($km^2$) | 48 | 24 | 35 | 45 |
| Remaining MSA | 0.52 | 0.45 | 0.46 | 0.48 |
| Reduction (%) by | | | | |
| Land-use change | 33.9 | 42.2 | 40.0 | 35.1 |
| Agriculture | 26.2 | 34.7 | 33.0 | 28.2 |
| Forestry | 3.9 | 3.6 | 4.1 | 4.0 |
| Urban | 0.2 | 0.4 | 0.4 | 0.4 |
| Others | 3.6 | 3.5 | 2.5 | 2.5 |
| Infrastructure development | 10.7 | 10.2 | 11.5 | 13.5 |
| Forest fragmentation | 3.2 | 3.0 | 3.0 | 3.3 |

## Discussion

### Model Performance

Earlier studies implemented various land-use models in Thailand addressing various questions and had either focused on a specific case study or addressed one specific land-use sector (Barnaud and others 2006; Rajan and Shibasaki 1997; Trisurat 1999; Watcharakitti 1976). The modeling approach presented in this paper was chosen for the current study based on the available data, the large spatial extent of the region, and the complexity of the processes. In addition, a pixel size of 25 ha was used, which was considered to be an appropriate resolution for regional-scale assessments and realistic in terms of the spatial scale of the different data used and the computational requirements of the modeling.

Alternative models, such as the Markov chain model, use previous land-use trends to envisage what will happen in the future, without considering the role of changes in the controlling natural, political, and sociological factors, unlike the Dyna-CLUE model, which explicitly addresses the dynamics of the different competing land uses. A dynamic approach that can account for competition between land uses is needed, where there are changing preferences for different land uses that have different environmental and geographic requirements. Therefore, Markov chain models would not be capable of addressing the different scenarios presented in this paper.

Multiagent models have high data requirements and so they are not often applied at a large regional scale, as was the case in the current study (Matthews and others 2007). In addition, logistic regression approaches in deforestation studies often focus on the identification of forest versus nonforest land use only, which is insufficient given the diverging characteristics of nonforest land uses.

The estimated MSA values were different from the biodiversity assessments based on the species-area relationship (SAR) concept, which estimates that 80–90% of the original species will remain if 30–40% of the area of any given terrestrial community or ecosystem can be conserved (Dobson 1996). This is due to the SAR approach ignoring the variation of habitat quality and fragmentation effects and not including the species abundance (Gotelli 2001). In addition, the SAR approach may underestimate the potential losses of MSA, especially when the remaining habitat is highly fragmented. For instance, Lomolino (1982) found that not only the patch size, but also the distance between patches was a significant factor for terrestrial mammals. In addition, Delin and Andren (2004) revealed that neither fragment size nor the degree of isolation was significant for the distribution of Eurasian red squirrels (*Sciurus vulgaris*). The only factor that significantly influenced a density index was the proportion of spruce within a habitat fragment. Similar results were observed for terrestrial birds on British islands, where there was no significant relationship between the average number of visiting birds and the island area or island distance,

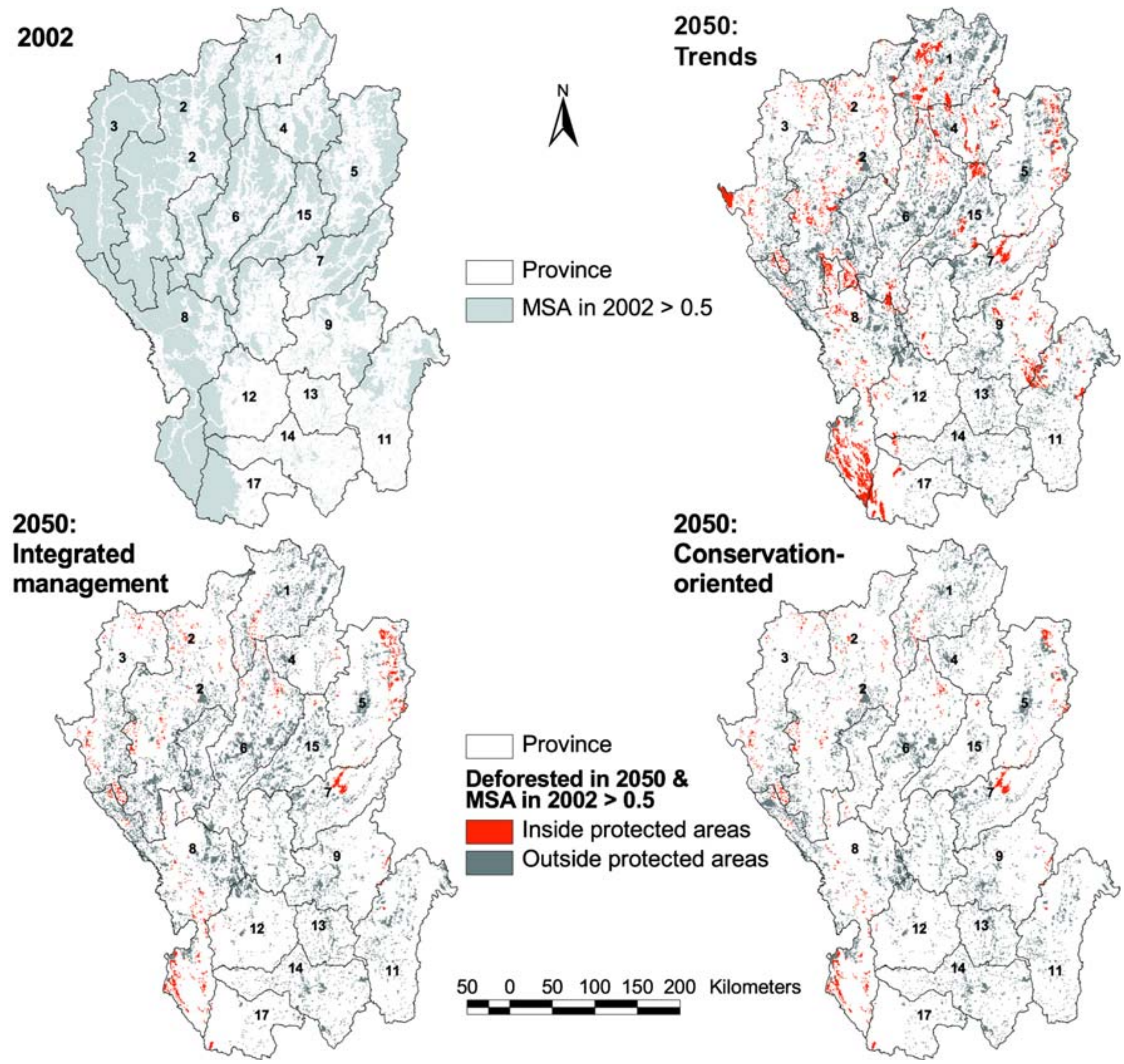


**Fig. 4** Location of areas with a high threat to biodiversity under different land-use scenarios in 2050. Indices: 1, Chiang Rai; 2, Chiang Mai; 3, Mae Hong Son; 4, Phayao; 5, Nan; 6, Lampang; 7, Uttaradit; 8, Tak; 9, Phitsanoluk; 10, Sukhothai; 11, Phetchabun; 12, Kampaeng Phet; 13, Pichit; 14, Nakhon Sawan; 15, Phrae; 16, Lampun; 17, Uthai Thani

but island property was significant (Stracey and Pimm 2009). The GLOBIO3 model incorporated habitat fragmentation and other human pressure factors making it an appropriate method for scenario analysis. Thus, it was an appropriate tool to assess biodiversity integrity in human-induced landscape and heterogeneous habitats.

## Predicted Forest Cover and MSA Values

The predicted forest cover in 2050 showed a similar pattern of forest distribution. High percentages of remaining forest cover in 2050 were predicted in the west and in the upper north provinces, since these regions have more protected areas compared to the lower north provinces (Fig. 1). In addition, all scenarios indicated that agriculture was the largest contributor to biodiversity loss. The dominance of agriculture is not surprising, since agriculture covers vast areas in northern Thailand and will continue to increase substantially in the future, due to high demand for rubber and food. The result was in line with several reports (Office of Environmental Policy and Planning 1997; Panayotou and Sungsuwan 1989), indicating that expansion of agriculture had reduced significantly the amount of forest cover and biological resources over the last four decades.

Even though the predicted forest cover in 2050 was quite different among the three scenarios (45–55%), the overall MSA values showed less distinct differences. There are two reasons to explain this. First, the extent of forest cover was composed of intact forest, disturbed forest, and forest plantation. The estimated reforestation area under

either the integrated-management scenario or conservation-oriented scenario was approximately 684,000 ha, or 4.0% of the region, compared with 499,000 ha, or 2.9%, under the trend scenario (Table 1). Based on calculations by Thai national experts, the $MSA_{LU}$ value for plantation is 0.4 relative to undisturbed ecosystems, because forestry officials usually plant a single species, mainly indigenous *Pinus merkusi* or *P. kesiya* or the exotic *Eucalyptus camaldulensis*. Therefore, the increment of MSA is not proportional to the increase in forest cover given the change in forest types.

Second, the GLOBIO3 model calculated $MSA_F$ and $MSA_I$ values only for natural areas, resulting in a lower contribution to forest fragmentation and infrastructure development to MSA in the trend scenario than in the integrated-management and the conservation-oriented scenarios, because of the smaller forest area and higher forest encroachment along road networks (Table 3). Road construction in densely forested areas in the northwest of the study area would facilitate human access to intact forest for agriculture, hunting and extraction of forest products, and, in the end, would lead to a reduction in biodiversity. Cropper and others (1996) indicated that road development had caused significant loss of forest cover in the north of Thailand from 1976 to 1989. In addition, roads created forest edges that allowed increased light and wind penetration into core areas, forcing some species to move deeper into the forest, and in addition, roads formed physical barriers restricting wildlife movement (Allen and others 2001). The research findings could motivate policymakers to increase the existing 50% forest cover and strengthen land allocation policies (Office of Environmental Policy and Planning 1997) by paying attention not only to the quantity of forest cover, but also to the configuration of the remaining forest and carefully monitoring tourism infrastructure development in pristine ecosystems.

In addition, this research also identified hotspots of threats to biodiversity, where MSA was expected to decrease by 0.5 or more during 2002 to 2050. This value was chosen because it is normally used as a cutoff point for binary classification in statistic analysis. An MSA value $\geq 0.5$ was defined as high biodiversity and a value $<0.5$ was defined as low biodiversity.

### Future Research

Despite the fact that the GLOBIO3 model provided a useful approximation of MSA and the relative contribution of pressure indicators on MSA, the existing model could be improved for more effective implementation at regional and local levels. Improvements could include the addition of other driving factors and validation. First, only three pressure factors of the five available in GLOBIO3 were used, because N deposition and climate change are implemented in the model for global-level analysis using a specification not suitable for regional-to-local applications. Implementing these factors for northern Thailand using local data and predictions may improve the MSA estimates. Additional potential drivers should be investigated in future research, including poverty and forest fire. In Thailand, at least 5 million forest dwellers live in reserve forests and depend on biological resources (Fox and Vogler 2005; Royal Forest Department 2007); most are living below the poverty line.

Second, validation of the accuracy of a prediction model is always important, in order to convince stakeholders and decision makers to accept the results. In this study, it was not possible to validate the predicted land-use map because land-use data beyond 2002 were not available. An absence of appropriate data for validation is a common problem in land-use modeling; only a few models and model applications are properly validated (Pontius and others 2008). The Land Development Department produces a new land-use map when budget funding is available, which would provide validation of this application of the model. For GLOBIO3, one promising method for validation in the future would be to use actual species occurrences and species indices (e.g., species richness or species diversity) derived from long-term forest monitoring plots to test model accuracy.

Nevertheless, the combination of the Dyna-CLUE and GLOBIO3 models was very useful, not only to simulate land-use allocation, but also to visualize forest patterns in the landscape. In addition, the models identified 'hot zones' of deforestation and important areas for biodiversity conservation.

## Conclusion

According to exiting trends, forest cover loss in northern Thailand will continue, unless strict protection measures are undertaken. The results of this study are as follows.

1. The trend scenario was developed based on a continuation of the trends of land-use conversion of recent years. The existing forest cover of 57% of the region in 2002 was expected to decrease to 45% by 2050. However, forest loss was likely to be strongly variable across the region. The remaining forest cover would be found mainly in the upper north and in the west where altitude is high and accessibility is low. The lowest loss and highest percentage of forest cover would be found in the northwest. In contrast, forest cover in the lower north provinces would be <20% by 2050. The

estimated MSA value would decline from ∼0.52 in 2002 to 0.45 in 2050. High threats to MSA would occur in areas covering ∼4910 $km^2$, mainly widespread in the center of the region. Intensive and regular patrolling to minimize deforestation in protected areas is highly recommended because a lot of deforestation is predicted within the reserves.

2. The integrated-management scenario was directed by policies that aimed to maintain 50% forest cover. Under this scenario, much forested land in rugged terrain and protected areas remained intact due to the land not being suitable for agriculture and a restriction policy being undertaken in the existing protected area network, despite there being a high demand for rubber plantations. The estimated MSA value derived from the simulated land-use map in 2050 was 0.46. High threat areas covered ∼2719 $km^2$. Three conservation measures are recommended based on the results of this scenario: minimize future deforestation in protected areas and threats to MSA areas in the buffer zones, raise conservation awareness among local people, and maintain ecosystem connectivity of fragmented protected areas.
3. The conservation-oriented scenario aimed to maintain 55% of the region under forest cover. The results of model simulation showed that the extent and pattern of remaining forest cover in 2050 were relatively similar to those of the forest area in 2002, except in the lower north, which would have less forest cover. Nan province would gain substantial forest cover from secondary forest regeneration and abandoned swidden cultivation at high elevations. The estimated MSA value for this scenario was 0.48 of the original state. Threats to MSA covered an area of 556 $km^2$. Besides protection and conservation awareness, it is recommended that forestry officials use many native species to rehabilitate degraded ecosystems inside protected areas, which will most likely improve MSA values.

The results of this research indicated that the '50–55% forest cover' policies for 2050 might not be the most efficient to promote biodiversity conservation, and these ambitious targets might create significant confrontations over land demands between conservationists and landless farmers. The results suggest that it is more effective for authorized agencies to protect biodiversity by maintaining forest cover with high biodiversity (corresponding with high MSA) values. There is also a need to recognize that infrastructure development in dense forest may have a negative impact on biodiversity and the agencies may need to allocate resources to prevent future deforestation in risk areas.

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