Modeling and Simulating Land-Use Change on Sumatra, Indonesia

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I. Land use change modeling theory

Assume an infinitely lived landowner (or more simply, land users) or a succession of landusers on the same parcel who behave similarly. Index the parcel and its user(s) with *i*. We assume *i* will use their parcel such that the stream of utility they generate from its use is maximized.

$$\max_{x_{ijt\in j=1,\ldots,J}} \sum_{t=0}^{\infty} \rho^t U_i(x_{ijt}, x_{ikt-1}, s_{ijt}) \tag{1}$$

subject to $s_{ijt+1} = f(x_{ijt}, s_{ijt})$ where the discrete variable x_{ijt} indicates whether or not land use *j* exists on parcel *i* at time *t*, the discrete variable x_{ikt} indicates whether or not land use *k* existed on parcel *i* at time *t*, and s_{ijt} is the stock of productive assets in the parcel at time *t* (soil quality, stock of mature trees, access to markets, etc.). The stock of productive assets on *i* evolves over time according to $f(x_{ijt}, s_{ijt})$. Here we assume that utility from a land use choice is a separable function of net monetary return generated by choice *j* less any land use transition costs plus the idiosyncratic preferences of the landowner (measured in a money metric; e.g., Lewis et al. 2010). Therefore, land user *i*'s utility at time t is given by,

$$U_i(x_{ijt}, s_{ijt}) = g(s_{ijt}, x_{ijt}, \mathbf{p}) - c(x_{ijt}, x_{ikt-1}) + \varepsilon_i(x_{ijt}) \tag{2}$$

In equation (2) $g_{ijt} = g(s_{ijt}, x_{ijt}, \mathbf{p})$ is the net return function (revenue less the opportunity cost of all variable inputs to production) and is explained by land use choice at time *t*, the stock of productive assets on the land at time *t*, and the recent market prices of commodities that can be produced on the parcel and productive inputs at time *t*. Further, $c_{ijkt} = c(x_{ijt}, x_{ijt-1})$ is the cost of transitioning to land use *j* at time *t* from land use *k* at time *t* – 1 where *k* = *j* means $c_{ijjt} = 0$. Finally, $\varepsilon_{ijt} = \varepsilon_i(x_{ijt})$ represents *i*'s idiosyncratic value from choosing land use j at time *t*.

Using the dynamic Bellman's equation and the maximum principle, the solution to (1) satisfies,

$$V_i(s_{ijt}) = \max_{x_{ijt\in j=1,\ldots,J}} \{U_i(x_{ijt}, s_{ijt}) + \rho V(s_{ijt+1})\} \quad \forall t \tag{3}$$

subject to $s_{ijt+1} = f(x_{ijt}, s_{ijt})$. Plantinga (1996) proves that myopically choosing the land use *j* at each time step that maximizes $g_{ijt} - c_{ijkt} + \varepsilon_{ijt}$ solves (1) (i.e., satisfies (3)) assuming landowners base their expectations of future net returns on current and historic realizations of g_{ij} and c_{ijk}. In other words, at each time step *t*, the utility-maximizing user of parcel *i* will choose the land use *j* from all possible land use choices *l* ≠ *j* that satisfies the following,

$$\arg\max jt : g_{ijt} - c_{ijkt} + \varepsilon_{ijt} \geq g_{ilt} - c_{ilkt} + \varepsilon_{ilt} \tag{4}$$

where g_{ijt} and c_{ijkt} are given by some combination of *t* – 1, *t* – 2, etc. observations of net returns to the *j* = 1,…,*J* land uses and *k* to *j* transition costs.

II. Estimating Land-Use Change in Indonesia with a Multinomial Logit Model

To adapt decision rule (4) to a framework that facilitates econometric estimation let $U_i(x_{ijt}, s_{ijt})$ be represented by $V_{ijt}(s_{ijt}, \mathbf{p}) + \varepsilon_{ijt}$ where $V_{ijt}(s_{ijt}, \mathbf{p})$ includes all the observable parcel-level characteristics that help explain recent net returns to land use choices (g_{ijt}) and land use transition costs (c_{ijkt}). We do not observe ε_{ijt}. Instead we use a probabilistic function to describe its distribution over *j* for parcel owner *i* at time *t*. Therefore, the land user utility comparisons of equation (4) become probabilistic as well. Now we are looking to calculate P_{ijt},

$$P_{ijt} = Prob\big(U_i(x_{ijt}, s_{ijt}) > U_i(x_{ilt}, s_{ilt}) \ \ \forall l \neq j\big) \tag{5}$$

or after some basic algebra,

$$P_{ijt} = Prob\big(\varepsilon_{ilt} < \varepsilon_{ijt} + V_{ijt}(s_{ijt}, \mathbf{p}) - V_{ilt}(s_{ilt}, \mathbf{p}) \ \ \forall l \neq j\big) \tag{6}$$

Equation (6) is known as a random utility model or RUM for short (Train 2009). If we assume ε_{ijt} are i.i.d. extreme value for all *j* then the P_{ijt}'s for all *i, j, t* combinations are known as logit choice probabilities and (6) is transformed into,

$$P_{ijt} = \frac{e^{V_{ijt}}}{\sum_{n=1}^{N} e^{V_{int}}} \tag{7}$$

where *n* alternatively indexes all land use choices *j* = 1,…,*J*.

We apply this probabilistic model of land use change to the Indonesian island of Sumatra. For each 1-km^2 parcel on the landscape we know 2006 and 2009 land use, expected 2006 to 2009 annualized revenues from each land use possibility, soil quality, distance to the nearest major city, and several other relevant parcel-level measures. We use a multinomial logit estimator to define a version of $V_{jt}\ \forall j$ that makes is as likely as possible that parcels with land use *j* as of 2009 have $U_i(x_{ijt}, s_{ijt}) > U_i(x_{ilt}, s_{ilt}) \ \ \forall l \neq j$. The multinomial logit estimator we use decomposes $V_{ijt}(s_{ijt}, \mathbf{p})$ into a function of 3 types of independent variables,

$$V_{ijt} = \alpha_j + \boldsymbol{\beta}\boldsymbol{y}_{ijt} + \boldsymbol{\gamma}_j\boldsymbol{z}_{it} + \boldsymbol{\delta}_j\boldsymbol{w}_{ijt} \tag{8}$$

where *t* refers to the year 2009 (and the time subscript will now be dropped for simplicity); α_j is a choice-specific intercept; $\boldsymbol{y}_{ij}$, $\boldsymbol{z}_i$, and $\boldsymbol{w}_{ij}$ are vectors of parcel level variables observed over the 2006 to 2009 period; and $\boldsymbol{\beta}$, $\boldsymbol{\gamma}_j$, and $\boldsymbol{\delta}_j$ are vectors of associated model coefficients (Train 2009, Croissant 2012).[1] The z_i variables are parcel-level variables that do not vary according to land use choice but potentially have different impacts on utilities generated by the various land-use choices. For example, soil quality on *i* is likely to have a much larger impact on agriculture-derived utility than development-derived utility. Distance from parcel *i* to a major

[1] The multinomial logit routine mlogit for R uses maximum likelihood estimation to find the parameter values that best fit the observed land use-choice data.

city is another parcel-level variable that should have a different impact on landowner utility conditional on the land use choice in 2009. For example, producers of goods that are export-orientated will generate better returns, all else equal, being closer to ports while the returns to producers of locally-consumed goods may be less affected by the location of marketing centers on the landscape (Comitz and Gray 1996). Or consider 2006 land use on parcel *i*. For example, transitioning from small-scale agriculture to rice agriculture will be less costly (and therefore, reduce utility less, all else equal) than moving from secondary forest cover to rice agriculture given the relatively high cost of tree and tree stump removal.

The variables y_{ij} and w_{ij} are parcel-level characteristics that are sensitive to land use choice. For example, the expected annual revenue on parcel *i* is a function of *i*'s land use choice *j* as well as i's productive assets such as soil quality and access to water. Whether such a variable is classified as y_{ij} and w_{ij} depends on whether or not the utility impact of the variable is the same across all choices. For example, if the impact of an additional dollar of revenue from forestry can have a different impact on parcel owner utility than an additional dollar of revenue from agriculture then the choice specific parameter δ_j is appropriate. However, if the impact of an additional dollar of revenue on utility is the same no matter the land use that earned the dollar then a choice-insensitive coefficient β is appropriate.

Once the multinomial logit model is estimated the predicted probability that parcel *i* is in land use *j* in 2009 is given by,

$$\hat{P}_{ij} = \frac{e^{\hat{\alpha}_j + \hat{\beta} y_{ij} + \hat{\gamma}_j z_i + \hat{\delta}_j w_{ij}}}{\sum_{n=1}^{N} e^{\hat{\alpha}_n + \hat{\beta} y_{in} + \hat{\gamma}_n z_i + \hat{\delta}_n w_{in}}} \tag{9}$$

where the 'hats' indicate model estimates. As can be seen in equation (6), when estimating land use choice probabilities with the multinomial procedure, differences in V_{ijt} are the relevant statistical values, not the absolute levels of V_{ijt}. We set land use choice *j* = 1 as the comparative land use. Therefore $\hat{\alpha}_1$ = 0 and $\hat{\gamma}_1 = 0$ for each z_i variable and all other $\hat{\alpha}_j$ and $\hat{\gamma}_j$ will be defined relative to the numeraire.

III. Data used in our model

III.a. z_i variables in our model

Let x_{iu} equal one if parcel *i* was in land use *u* in 2006 and 0 otherwise. There are 7 land use choice types in our model; therefore *j*, *n*, *u* = 1,…,7. ("Urban" and "other" land uses, although present on the 2006 and 2009 land use maps, are ignored in our land use change model.) See the supplementary information (SI) for more information on the 7 land uses in our model. We do not have data on land use transition costs. Therefore, these dummies and their choice specific estimated coefficients, $\hat{\gamma}_{x_1 1}$,…, $\hat{\gamma}_{x_u 1}$,…, $\hat{\gamma}_{x_7 1}$,…, $\hat{\gamma}_{x_1 j}$,…, $\hat{\gamma}_{x_u j}$,…, $\hat{\gamma}_{x_7 j}$,…, $\hat{\gamma}_{x_1 7}$,…, $\hat{\gamma}_{x_u 7}$,…, $\hat{\gamma}_{x_7 7}$ will serve as proxies for the relative cost of transitioning from *u* to *j*. A similar technique was used by Lubowski et al. (2006). All else equal, transitions that are more costly should occur less frequently on the landscape and the estimated $\hat{\gamma}_{x_u}$ should scale accordingly vis-à-vis the numeraire land use.

There are eight parcel-level soil variables in our database. The seven from the World Harmonized Soil Database (Fisher et al. 2008) use a categorical scale to describe the quality of a grid cell's soil on seven dimensions. The eighth soil variable indicates whether parcel *i* is comprised of peat soil or not. For parsimony we use just one soil variable in the model, nutrient availability on parcel *i* (soil quality measure one in the Harmonized database). Let s_{i1} equal one if parcel *i*'s lies in a World Harmonized Soil Database grid cell with a soil score of 1 on nutrient availability and equals 0 otherwise. Let s_{i2} equal one if parcel *i*'s soil score is 2 on nutrient availability and equals 0 otherwise. Let s_{i3} equal one if parcel *i*'s soil score on nutrient availability is greater than 2 or is equal to 0 and equals zero otherwise. Lower scores (not counting 0) indicate better nutrient availability. Because soil nutrient availability is more important to the productivity of some land uses than others, we treat each soil quality dummy as a parcel-specific variable with land use choice specific coefficients. For example, we hypothesize $\hat{\gamma}_{S_1,j}$ will be greater for agricultural land uses *j* then $\hat{\gamma}_{S_1,j}$ is for non-agricultural land uses *j*. See Table 1 for a summary of parcel-level soil quality scores on Sumatra where lower scores indicate better quality on the given measure.

Table 1: Average nutrient availability and retention scores across all Sumatra parcels by 2009 land use

2009 land use (*j*)	**Average nutrient availability score** (the measure we use in our model)	**Average nutrient retention score** (an alternative measure)
Forest on mineral soils	2.03	1.70
Forest on peat soils	2.94	2.05
Degraded land on peat	2.66	2.07
Degraded land on mineral soils	2.50	1.97
Plantation	2.94	2.14
Agriculture	2.60	2.04
Clearing (Plantation)	2.90	2.11

Notes: Lower values mean greater nutrient availability and retention. According to the World Harmonized Soil Database nutrient availability "…is decisive for successful low level input farming and to some extent also for intermediate input levels. Diagnostics related to nutrient availability are manifold. Important soil characteristics of the topsoil (0-30 cm) are: Texture/Structure, Organic Carbon (OC), pH and Total Exchangeable Bases (TEB). For the subsoil (30-100 cm), the most important characteristics considered are: Texture/Structure, pH and TEB." Further, "[n]utrient retention capacity is of particular importance for the effectiveness of fertilizer applications and is therefore of special relevance for intermediate and high input level cropping conditions. Nutrient retention capacity refers to the capacity of the soil to retain added nutrients against losses caused by leaching."

In some cases parcel users may find it difficult to choose the utility-maximizing land use because of a parcel's zoning restrictions or the land concession associated with the parcel. Let z_{im} for $m = 1,…,5$ be a series of dummy variables that indicates the zoning / concession type associated with parcel *i*. Let z_{i1} equal one if parcel *i* has no zoning or concession attached to it and equals zero otherwise. Let z_{i2} equal one if parcel *i* has an industrial forest plantation concession attached to it and equals zero otherwise. Let z_{i3} equal one if parcel *i* has a sawn logs concession attached to it and equals zero otherwise. Let z_{i4} equal one if parcel *i* has a non-timber tree plantation (e.g., palm oil plantation) concession attached to it and equals zero otherwise. Finally, let z_{i5} equal one if parcel *i* is in a protected area and equals zero otherwise. Again, the effect of zoning regulations and concessions on landowner utility will be a function of land use choice. For example, a land user that attempts to log a forest that is protected could generate lower utility for themselves, all else equal, given the associated risk of being caught and punished for illegal use of land whereas this zoning should have little to no effect on the returns associated with unmanaged primary and secondary forest. Let $\hat{\gamma}_{Z_m j}$ indicate the estimated (relative) impact of the zoning / concession category *m* on the probability of land use *j* as of 2009.

Beginning with Von Thunen's work on city and suburban land use patterns in the 18th and 19th centuries, economists have been keenly aware of the impact that proximity to market centers and transportation networks can have on a parcel's net returns and optimal land use choice. Generally, land uses that derive more utility from being closer to cities and transportation networks (e.g., producers of highly perishable food, producers of export-oriented products) will replace other land uses on the rural-urban fringe (Chomitz and Gray 1996). To control for the impact of proximity to market and trade centers on a land user's utility from land use choice, we include the Euclidean distance from parcel *i* to the closet major city ($City_i$) and the nearest coastal point ($Coast_i$). Both of these distance measures are exogenous to landowner decision making as they tend to be immutable, at least in the time span we will cover in our land-use change simulation analysis (see below). The effect of $City_i$ and $Coast_i$ on landowner utility is a function of land use choice in our model. While all commodity production is more valuable if it is near or can easily access major market areas, we assume net returns to some commodities are particularly sensitive to market access. Let $\hat{\gamma}_{City,j}$ and $\hat{\gamma}_{Coast,j}$ indicate the estimated (relative) impact of distance to a major city and the coast on the probability that a parcel is in land use *j*.

Another potentially important marketing variable is the landscape's road network. Presumably parcel's closer to road networks will find it easier and cheaper to get their products to the appropriate markets and to bring productive inputs to their land. However, while land use is certainly affected by road presence and development, road development is also influenced by land-use choice (Chomitz and Gray 1996). For example, if a large area on the landscape is converted to oil palm plantation the government may respond by immediately running a road out to the area in order to improve the expected economic returns from the development. Therefore, the inclusion of distance to road from each parcel as an explanatory variable could introduce bias to our results given that causal relationship between land use choice and roads can run both ways. Chomitz and Gray (1996) use several exogenous instruments to control for road endogeneity in their analysis on the effect of road placement on deforestation in Belize. They find that the inclusion of soil quality variables is sufficient to eliminate most model bias generated by including roads in the model. Given that we have a soil quality measure in our model as well we plan to include distance to road in future versions of this model. For now, however, we assume the exogenous variables $City_i$ and $Coast_i$ help explain the presence of roads on land-use decision making as road coverage on the landscape is denser near major cities (distance to road and distance to major city have a 0.19 correlation coefficient in our dataset) and interior areas on the island are more dense with roads (distance to road and distance to coast have a -0.17 correlation coefficient in our dataset). Otherwise, if $City_i$ and $Coast_i$ are not very effective at also generally explaining access to roads then our model is likely to be affected by omitted variable bias and spatial autocorrelation (a possibility when omitted explanatory variables, such as road network, are correlated over space). See Table 2 for the average parcel-level distance to closest major city, closest coastal point, and closest major road by 2009 land use.

Table 2: Average parcel distance to various landscape features by 2009 land use

2009 land use (*j*)	**Avg. distance to major city (km)**	**Avg. distance to coast (km)**	**Avg. distance to road (km)**
Forest on mineral soils	66.4	56.6	7.0
Forest on peat soils	58.4	25.2	4.9
Degraded land on peat soils	109.2	47.5	5.4
Degraded land on mineral soils	73.4	57.1	3.3
Plantation	59.4	66.4	1.3
Agriculture	59.6	63.9	2.2
Clearing (Plantation)	60.2	53.2	2.4

III.b. w_{ij} variables in our model

We hypothesize that expected annual net returns less any transition costs across the 7 land use choices will be the primary driver in parcel-level land use decisions. Recall Plantinga (1996)'s dynamic optimization proof, and therefore our RUM, is dependent on expected annual net returns. In our case we only have expected annual revenues on each parcel for each possible land use (based on 2004 to 2006 average annual revenues, see the SI text). However, we have already included some proxies for relative production costs, including soil quality and distance to output and input markets. We also implicitly proxy for production costs by making annual revenue a w_{ij}-type variable. To see this, assume that we had classified annualized revenue as a x_{ij}-type variable instead. If we had done this we would be claiming, for example, that a dollar of revenue from logging affects land user utility the same as a dollar of revenue from agriculture. This hypothesis would be credible if production costs on *i* were equal across all land uses *j*. However, assuming they are not, we cannot claim that a dollar of revenue from logging affects utility similarly to a dollar of revenue from agriculture. For example, suppose for every dollar of logging revenues generated on parcel *i* production costs are 75 cents. Further, suppose the parcel owner would only realize a cost of 50 cents for every dollar of revenue he generated from rice production on his land. Obviously the owner of parcel *i* would get more utility out of the dollar of revenue from rice agriculture than the dollar of revenue from logging, all else equal. Therefore, by treating annual revenue as a w_{ij}-type variable ($Revenue_{ij}$) instead, each additional unit of revenue from each *j* can have a unique effect on landowner utility (see the appendix for details on how $Revenue_{ij}$ was calculated for each *i,j*). And when we find that some land uses are more probable given a one dollar increase in expected annual revenue than others, all else equal, we can surmise that the more likely land-uses have lower production costs per dollar of marginal revenue than some of the less likely land-uses. Let $\hat{\delta}_j$ indicate the estimated impact of expected annual revenue form land use *j* on the probability that a parcel is in land use *j*.

IV. Model estimation

We estimate multinomial model (7)-(8) twice: once with a random sample of Sumatra parcels ("random sample"; N = 7,556) and another time with equidistant grid of parcels where each selected parcel is 10 km from each of its nearest 4 neighbors ("block sample"; N = 4,309). The model is estimated with 'mlogit' package for R (Croissant, 2012). (Contact the author Nelson for a copy of the R code.) See the appendix for details on the variable calculation. The block sample estimate should be less affected by spatial autocorrelation as the minimum 10 km distance between each parcel reduces the probability that unexplained landscape processes jointly affect land use decision making on multiple parcels.

Select estimated coefficients and standard errors are given in the series of tables below (see the appendix for all results). In a few cases the estimated coefficients' standard errors are exceedingly large. And while some estimated coefficients are also very large, choice-related estimated coefficients (e.g., the collection of land use choice specific coefficients associated with the non-timber tree plantation concession dummy variable) are relatively different in intuitive ways. The presence of very large estimated coefficient standard errors is a sign that some of the land classes appear too infrequently in the data given the model structure we have chosen. The McFadden R^2 is 0.73 with both samples, indicating both estimated models explain observed 2006 to 2009 land use choices well.

Table 3: The estimated land use choice model

3A. Land use choice specific intercepts

	Random Sample				Block Sample			
	Est.	**St. Err.**	**t-value**		**Est.**	**St. Err.**	**t-value**	
Forest on mineral soils	0.00				0.00			
Forest on peat soils	-2.27	1.45	-1.57		-3.04	1.90	-1.60	
Degraded land on peat soils	-3.61	1.34	-2.69	***	-21.55	4368	0.00	
Degraded land on mineral soils	1.45	0.77	1.87	*	-1.74	1.10	-1.59	
Plantation	-1.79	0.98	-1.82	*	-3.20	1.32	-2.43	**
Agriculture	-1.63	0.90	-1.81	*	-3.15	1.36	-2.32	**
Clearing (Plantation)	-2.20	1.23	-1.79	*	-3.51	1.60	-2.19	**

Notes: '***' means statistically significant at the p = 0.01 level. '**' means statistically significant at the p = 0.05 level. '*' means statistically significant at the p = 0.1 level.

3B. Land use choice specific impact of distance (in hundreds of km) to nearest major city

	Random Sample				Block Sample			
	Est.	**St. Err.**	**t-value**		**Est.**	**St. Err.**	**t-value**	
Forest on mineral soils	0.00				0.00			
Forest on peat soils	1.01	0.40	2.56	**	0.31	0.48	0.64	
Degraded land on peat soils	1.09	0.37	2.93	***	1.43	0.45	3.20	***
Degraded land on mineral soils	0.45	0.27	1.67	*	0.57	0.35	1.63	
Plantation	0.80	0.31	2.62	***	0.51	0.39	1.30	
Agriculture	0.29	0.25	1.14		0.37	0.34	1.09	
Clearing (Plantation)	-0.21	0.38	-0.56		0.33	0.45	0.74	

3C. Land use choice specific impact of distance (in hundreds of km) to nearest coastal point

	Random Sample				Block Sample			
2009 land use (*j*)	**Est.**	**St. Err.**	**t-value**		**Est.**	**St. Err.**	**t-value**	
Forest on mineral soils	0.00				0.00			

	Random Sample				Block Sample			
2009 land use (*j*)	**Est.**	**St. Err.**	**t-value**		**Est.**	**St. Err.**	**t-value**	
Forest on peat soils	-1.37	0.42	-3.27	***	-1.77	0.52	-3.39	***
Degraded land on peat soils	-0.04	0.36	-0.11		-0.46	0.45	-1.02	
Degraded land on mineral soils	-0.18	0.27	-0.66		-0.41	0.35	-1.17	
Plantation	-0.51	0.29	-1.73	*	-0.25	0.36	-0.69	
Agriculture	0.59	0.25	2.31	**	0.37	0.33	1.11	
Clearing (Plantation)	-0.68	0.35	-1.94	*	-0.74	0.42	-1.77	*

3D. Land use choice specific impact of zoning / concession type

	Random Sample				Block Sample			
Zoning / concession type x 2009 land use (*j*)	**Est.**	**St. Err.**	**t-value**		**Est.**	**St. Err.**	**t-value**	
Industrial forest plantation concession								
Forest on mineral soils	0.00				0.00			
Forest on peat soils	-0.89	0.47	-1.92	*	0.11	0.51	0.22	
Degraded land on peat soils	-0.90	0.47	-1.90	*	0.01	0.52	0.01	
Degraded land on mineral soils	0.29	0.33	0.88		1.30	0.41	3.21	***
Plantation	-0.20	0.38	-0.53		0.58	0.43	1.35	
Agriculture	-0.90	0.35	-2.56	**	0.00	0.43	-0.01	
Clearing (Plantation)	-0.78	0.43	-1.82	*	1.15	0.46	2.51	*
Sawn logs concession								
Forest on mineral soils	0.00				0.00			
Forest on peat soils	0.44	0.60	0.73		-0.98	0.67	-1.46	
Degraded land on peat soils	-0.78	0.64	-1.22		-0.88	0.70	-1.26	
Degraded land on mineral soils	-1.20	0.37	-3.21	***	-0.85	0.48	-1.75	
Plantation	-1.44	0.55	-2.60	***	-0.95	0.58	-1.63	
Agriculture	-1.57	0.39	-4.03	***	-2.18	0.50	-4.39	***
Clearing (Plantation)	-2.03	0.84	-2.41	**	-2.02	0.89	-2.27	**
Non-timber tree plantation concession								
Forest on mineral soils	0.00				0.00			
Forest on peat soils	0.31	0.68	0.45		1.38	0.76	1.83	*
Degraded land on peat soils	-0.05	0.68	-0.07		0.46	0.77	0.59	
Degraded land on mineral soils	-0.41	0.62	-0.67		-0.11	0.69	-0.16	
Plantation	0.57	0.59	0.97		1.07	0.63	1.69	
Agriculture	-0.43	0.57	-0.75		0.27	0.64	0.42	
Clearing (Plantation)	-0.26	0.68	-0.39		0.76	0.73	1.04	
Protected status								
Forest on mineral soils	0.00				0.00			
Forest on peat soils	0.79	0.48	1.65	*	0.78	0.58	1.36	
Degraded land on peat soils	-0.85	0.53	-1.61		-0.16	0.64	-0.24	
Degraded land on mineral soils	-1.23	0.29	-4.21	***	-1.00	0.42	-2.37	**
Plantation	-1.85	0.60	-3.10	***	-3.14	0.92	-3.40	***
Agriculture	-1.26	0.28	-4.49	***	-0.90	0.42	-2.12	**
Clearing (Plantation)	-1.07	0.52	-2.05	**	-0.32	0.62	-0.52	

Notes: The category of no restrictions and no concessions (‘unrestricted’) is the dropped dummy variable.

3E. Land use choice specific impact of soil nutrient availability

	Random Sample				Block Sample			
Nutrient availability x 2009 land use (*j*)	**Est.**	**St. Err.**	**t-value**		**Est.**	**St. Err.**	**t-value**	
Excellent								
Forest on mineral soils	0.00				0.00			
Forest on peat soils	-19.88	4247	0.00		-20.09	6840	0.00	
Degraded land on peat soils	-19.21	3992	0.00		-3.10	1.26	-2.45	**
Degraded land on mineral soils	-1.25	0.30	-4.18	***	-0.95	0.43	-2.19	***
Plantation	-3.25	0.57	-5.70	***	-3.04	0.81	-3.75	***
Agriculture	-1.39	0.29	-4.83	***	-1.86	0.42	-4.42	***
Clearing (Plantation)	-2.51	0.61	-4.13	***	-3.28	0.96	-3.41	***
Average								
Forest on mineral soils								
Forest on peat soils	-2.73	0.43	-6.41	***	-2.27	0.50	-4.53	***
Degraded land on peat soils	-2.04	0.35	-5.79	***	-1.51	0.43	-3.53	***
Degraded land on mineral soils	-1.52	0.21	-7.32	***	-1.21	0.29	-4.24	***
Plantation	-2.55	0.28	-9.24	***	-2.27	0.36	-6.24	***
Agriculture	-1.51	0.20	-7.65	***	-1.23	0.28	-4.45	***
Clearing (Plantation)	-2.92	0.39	-7.59	***	-2.89	0.50	-5.82	***

Note: Poor nutrient availability is the dropped dummy variable.

3F. Land use choice specific impact of annual revenue (in units of $10,000)

	Random Sample				Block Sample			
	Est.	**St. Err.**	**t-value**		**Est.**	**St. Err.**	**t-value**	
Forest on mineral soils	11.38	2.15	5.29	***	5.49	3.02	1.82	*
Forest on peat soils	3.05	3.55	0.86		4.55	4.76	0.96	
Degraded land on peat soils	2.33	1.88	1.24		0.93	2.48	0.38	
Degraded land on mineral soils	-1.04	1.20	-0.87		2.25	1.74	1.30	
Plantation	0.23	0.10	2.42	**	0.29	0.14	2.08	**
Agriculture	0.40	0.09	4.59	***	0.28	0.13	2.19	**
Clearing (Plantation)	0.54	0.16	3.41	***	0.37	0.19	1.90	*

The standard errors on the estimated coefficients from the block sample estimate are consistently larger than the standard errors from the random sample estimate. In the random sample we undoubtedly have selected some parcels that are clumped together in space and are similarly affected by unobserved landscape processes (e.g., road access in a neighborhood, microclimate in a neighborhood, etc.). Standard errors estimated in the presence of such spatial autocorrelation tend to underestimate the true standard errors. We suspect that if we controlled for spatial autocorrelation in the model estimated with the random sample we would get larger standard errors, similar to those estimated with the block sample.

V. Marginal effects

Given that the values of the estimated coefficients are relative to the numeraire land use's coefficients a bit more mathematical manipulation is needed before estimated coefficients can be interpreted intuitively. Let $\hat{P}_{ij}$ be the predicted probability (in decimal form) that parcel *i* will be in land use *j* in 2009 where $\sum_{j=1}^{J=7} \hat{P}_{ij} = 1$. We generate a $\hat{P}_{ij}$ value for every {*i*,*j*} combination on Sumatra using estimated coefficients indicated in Table 3 and *i*'s data.

To illustrate how we calculate marginal effects we will assume, without loss of generality, that there are only three land-use choices, *j*, *m*, and *n*, and the model only includes one z_i – type variable and w_{ij} – type variable (our model does not use any x_{ij}-type variables and thus is not included in this exposition). Therefore, with this simpler set-up the predicted probability of parcel *i* being in land use *j* in 2009 is equal to,

$$\hat{P}_{ij} = \frac{e^{\hat{\alpha}_j+\hat{\gamma}_j z_i+\hat{\delta}_j w_{ij}}}{e^{\hat{\alpha}_j+\hat{\gamma}_j z_i+\hat{\delta}_j w_{ij}}+e^{\hat{\alpha}_m+\hat{\gamma}_m z_i+\hat{\delta}_m w_{im}}+e^{\hat{\alpha}_n+\hat{\gamma}_n z_i+\hat{\delta}_n w_{in}}} \quad (10)$$

where the coefficients with "hats" indicate estimated (relative) coefficients as given in Table 3 and z_i and w_{ij} are replaced with the parcel *i*'s values for these variables. Assume that *m* is the numeraire land use choice. Therefore, $\hat{\alpha}_m = 0$ and $\hat{\gamma}_m = 0$.

After some math (see the appendix) we find,

$$\frac{\partial \hat{P}_{ij}}{\partial z_i} = \hat{P}_{ij}\left(\hat{\gamma}_j - \left(\sum_{k=1}^{3}\hat{\gamma}_k\hat{P}_{ik}\right)\right) \quad (11)$$

where *k* indexes all three land use choices. In other words, a one unit increase in z_i (e.g., a 100 km increase in the distance between parcel *i* and the closest major city) increases $\hat{P}_{ij}$ by $\hat{P}_{ij}\left(\hat{\gamma}_j - \left(\sum_{k=1}^{3}\hat{\gamma}_k\hat{P}_{ik}\right)\right)$. To investigate the impact of a small change in z_i on representative parcels we can evaluate (10) at parcel-level averages for continuous variables (e.g, the average of $City_i$, $Coast_i$, and $Revenue_{ij}$ across all parcels in Sumatra) and a set of values for the discrete variables (e.g., excellent nutrient availability, primary forest in 2006, and protected land). Then (11) for a representative parcel becomes,

$$\frac{\partial P_{rj}}{\partial z_i} = \hat{P}_{rj}\left(\hat{\gamma}_j - \left(\sum_{k=1}^{3}\hat{\gamma}_k\hat{P}_{rk}\right)\right) \quad (12)$$

where $\hat{P}_{rj}$ is the solution to (10) where parcel-level averages for continuous variables are used and *r* is defined by the choice of a nutrient availability score, a 2006 land use, and a zoning / concession category (see Appendix Database A for all estimated $\hat{P}_{rj}$ values evaluated at the mean when using the random parcel model estimate).

If we want an elasticity measure for a small change in continuous variable z_i we multiply equation (12) by $z_i/\hat{P}_{rj}$,

$$E_{j,z_i} = \frac{\partial P_{rj}}{\partial z_i}\frac{z_i}{\hat{P}_{rj}} = z_i\left(\hat{\gamma}_j - \left(\sum_{k=1}^{3}\hat{\gamma}_k\hat{P}_{rk}\right)\right) \quad (13)$$

where we interpret E_{j,z_i} as the percentage change in $\hat{P}_{rj}$ given a 1% change in z_i.

In the Table 4 we present the estimated effect of an additional 100 km of distance between a parcel and the nearest major city ($\partial z_i = 1$) on the probability of choosing land use *j* in 2009. In these estimates the continuous variables are set to parcel – level means and the nutrient availability in the parcel is excellent and the parcel has no concessions tied to it. However, we do toggle between unprotected and protected status to investigate the impact of distance to the nearest city on land use choice in unrestricted areas versus protected areas. In this case we only present marginal effects from model estimate derived from the dataset of random parcels (see Appendix Database A for all estimated $\partial P_{rj}/\partial z_i$ values evaluated at the mean as derived from the random parcel model estimate).

Table 4. The increase in P_{rj} for every additional 100 km gap between a parcel and the closest major city where soil quality is excellent

2006 land use	For., MS	For., PS	DL, PS	DL, MS	Plant.	Ag.	Clearing
2009 land use	**Unrestricted area**						
Forest on mineral soils	-0.015	0.000	-0.020	-0.046	-0.021	-0.006	-0.001
Forest on peat soils	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Degraded land on peat soils	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Degraded land on mineral soils	0.008	0.000	0.021	0.056	-0.013	0.004	0.092
Plantation	0.001	0.124	0.028	0.003	0.127	0.002	0.045
Agriculture	0.007	0.049	0.013	-0.011	-0.072	0.000	0.024
Clearing (Plantation)	-0.001	-0.174	-0.043	-0.002	-0.020	-0.001	-0.159
	Protected area						
Forest on mineral soils	-0.031	0.000	-0.011	-0.023	-0.009	-0.003	-0.002
Forest on peat soils	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Degraded land on peat soils	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Degraded land on mineral soils	0.018	0.000	0.018	0.036	-0.016	0.005	0.087
Plantation	0.002	0.160	0.039	0.004	0.106	0.003	0.066
Agriculture	0.013	0.016	-0.013	-0.016	-0.070	-0.004	0.017
Clearing (Plantation)	-0.002	-0.175	-0.033	-0.001	-0.012	-0.001	-0.168

Notes: Mean parcel-level value of *City* is 0.66. Mean parcel-level value of *Coast* is 0.57. Parcel-level means of $Revenue_j$ are 0.345, 0.345, 0.339, 0.339, 6.904, 6.892, and 6.988, respectively.

According to the marginal impacts presented in Table 4, areas with excellent nutrient availability and no restrictions on use or concessions and that are further from cities are more likely to convert to plantation than excellent soil areas closer to cities. On similar areas clearing is less likely to occur by 2009, all else equal. On unrestricted areas with excellent soil, the impact of distance to city is mixed for agriculture. The impact of distance from the closet major city on agricultural and some plantation conversion probabilities is affected by the implementation of protected status. First, distance from city has a larger positive impact on the probabilities of conversion to plantation in protected areas with excellent soil quality than in similar unrestricted areas. Does this mean that land users who establish plantations in protected areas do so further away from bureaucratic centers to reduce the risk of detection? The interactive effect of protected status and distance from city on the establishment of agricultural and clearing is mixed. In some cases, conversion to agriculture and clearing becomes more likely in excellent soil quality areas closer to cities if the land is protected versus having no land use regulations. In other cases, the opposite effect is seen. As to the other continuous z_i variable, distance to nearest coastal point, clearing (logging), and plantation production are more probable by 2009 near the coast and agriculture is more likely in the interior given excellent soil quality (see Appendix Database A). Conversion to plantation on excellent soil quality is driven even closer to the coast when the user is on a protected parcel. Conversion to clearing on excellent soil is driven further to the interior when the user is on a protected parcel.

Many of the z_i variables are dummy variables. When z_i is a dummy variable the change in $\hat{P}_{ij}$ given by z_i being equal to 1 instead of 0 is,

$$\frac{\Delta\hat{P}_{ij}}{\Delta z_i} = \hat{P}_{ij} - \frac{e^{\hat{\alpha}_j+\hat{\delta}_j w_{ij}}}{e^{\hat{\alpha}_j+\hat{\delta}_j w_{ij}}+e^{\hat{\alpha}_m+\hat{\delta}_m w_{im}}+e^{\hat{\alpha}_n+\hat{\delta}_n w_{in}}} \quad (14)$$

Notice that the $\hat{\gamma}_j z_i$ term has been dropped from the exponential terms on the right-hand side of equation (14). Here we interpret $\Delta\hat{P}_{ij}/\Delta z_i$ relative to the omitted dummy variable category. For example, suppose there are two parcel-level values for soil quality, high and low. Further, suppose the z_i variable indicates high quality soil if the variable is equal to one. Thus, the poor soil quality dummy is the omitted dummy category in the model. Therefore, $\Delta\hat{P}_{ij}/\Delta z_i$ measures the change in the likelihood that parcel *i* will be in land use *j* as of 2009 given that the parcel has good soil quality in lieu of poor quality soil.

In the Table 5 we present the estimated effect of a parcel going from poor nutrient availability (our omitted soil quality variable) to high nutrient availability on unrestricted and protected land. Again, we only present marginal effects from the random parcel model estimate and at continuous variable means and the various 2006 land uses (see Appendix Database A for all estimated $\Delta P_{rj}/\Delta z_i$ values evaluated at the mean as derived from the random parcel model estimates).

Table 5. The increase in P_{rj} for a representative parcel with excellent nutrient availability in lieu of poor nutrient availability

2006 land use	For., MS	For., PS	DL, PS	DL, MS	Plant.	Ag.	Clearing
2009 land use	**Unrestricted area**						
Forest on mineral soils	0.158	0.000	0.073	0.089	0.034	0.015	0.017
Forest on peat soils	-0.004	-0.722	-0.040	-0.012	-0.003	-0.002	-0.007
Degraded land on peat soils	-0.002	-0.126	-0.878	-0.013	-0.007	-0.010	0.000
Degraded land on mineral soils	-0.037	0.000	0.113	0.009	0.073	0.004	0.159
Plantation	-0.016	0.125	0.033	-0.045	-0.289	-0.023	-0.099
Agriculture	-0.058	0.287	0.626	-0.020	0.184	0.021	0.066
Clearing (Plantation)	-0.040	0.436	0.073	-0.008	0.007	-0.005	-0.136
	Protected area						
Forest on mineral soils	0.255	0.000	0.032	0.042	0.012	0.007	0.009
Forest on peat soils	-0.002	-0.558	-0.051	-0.004	-0.001	-0.001	-0.003
Degraded land on peat soils	-0.001	-0.053	-0.598	-0.002	-0.001	-0.002	0.000
Degraded land on mineral soils	-0.064	0.000	0.104	0.045	0.063	0.005	0.194
Plantation	-0.041	0.072	-0.038	-0.063	-0.233	-0.033	-0.166
Agriculture	-0.098	0.289	0.532	-0.013	0.153	0.027	0.077
Clearing (Plantation)	-0.050	0.250	0.019	-0.006	0.005	-0.003	-0.111

In unrestricted lands, better soils are much more likely to induce agriculture use, especially on peat soils, than any other use. Clearing and plantation conversion is not related to soil quality in a consistent matter in unrestricted areas. Further, improving soils in forests on mineral soils mean less conversion to other uses. Improvements in soil quality in protected areas do not induce as much conversion to agriculture, plantations, and clearing uses as in unrestricted areas. Of the 3 intensive land use categories, conversion to agriculture due to improvements in soil is the least affected by protection status. Finally, forests on mineral soils are much more likely in protected areas where soil improves versus unrestricted areas where soil improves.

In the Table 6 we present the estimated effect of a parcel having a non-timber tree plantation concession in lieu of no restrictions or concessions on excellent and poor nutrient availability parcels. Again, we only present marginal effects from the random parcel model estimate and at continuous variable means and the various 2006 land uses (see Appendix Database A for all estimated $\Delta P_{rj}/\Delta z_i$ values evaluated at the mean as derived from the random parcel model estimates).

Table 6. The increase in P_{rj} for a representative parcel with non-timber tree plantation concession in lieu of unrestricted area

2006 land use	For., MS	For., PS	DL, PS	DL, MS	Plant.	Ag.	Clearing
2009 land use	**Excellent nutrient availability**						
Forest on mineral soils	0.003	0.000	0.022	-0.017	0.022	0.013	-0.005
Forest on peat soils	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Degraded land on peat soils	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Degraded land on mineral soils	0.006	0.000	0.081	0.091	0.100	0.034	-0.007
Plantation	0.000	-0.103	-0.020	-0.004	-0.140	-0.001	-0.040
Agriculture	-0.011	-0.145	-0.180	-0.072	-0.022	-0.050	-0.064
Clearing	0.003	0.249	0.097	0.001	0.040	0.004	0.116
	Poor nutrient availability						
Forest on mineral soils	0.002	0.000	0.001	-0.004	0.002	0.003	-0.001
Forest on peat soils	-0.001	-0.029	0.014	-0.004	0.001	0.000	-0.003
Degraded land on peat soils	-0.001	-0.042	-0.058	-0.007	0.000	-0.002	0.000
Degraded land on mineral soils	0.017	0.000	0.009	0.119	0.027	0.029	-0.003
Plantation	-0.009	-0.020	-0.002	-0.030	-0.072	-0.005	-0.104
Agriculture	-0.036	-0.003	0.003	-0.079	0.005	-0.039	-0.026
Clearing	0.028	0.095	0.033	0.005	0.037	0.013	0.137

First, note that clearing use is much more likely and agriculture and plantation use is generally less likely on areas with non-timber tree plantation concessions in lieu of no concessions. Further, clearing is even more likely in such areas if the soil quality is high. Finally, mineral and peatland forests are more likely to remain in such cover in non-timber tree plantation concessions when the soil quality is lower, all else equal.

The change in $\hat{P}_{ij}$ assuming a small change in continuous variable w_{ij}, such as annual revenue on parcel *i* from land use *j*, is,

$$\frac{\partial \hat{P}_{ij}}{\partial w_{ij}} = \hat{\delta}_j \hat{P}_{ij}\left(1 - \hat{P}_{ij}\right) \quad (15)$$

Further, the own-choice elasticity is given by,

$$E_{j,w_{ij}} = \frac{\partial \hat{P}_{ij}}{\partial w_{ij}} \frac{w_{ij}}{\hat{P}_{ij}} = \hat{\delta}_j w_{ij}\left(1 - \hat{P}_{ij}\right) \quad (16)$$

where we interpret E_{j,z_i} as the percentage change in $\hat{P}_{ij}$ given a 1% change in w_{ij}.

We can also look at the change in the probability of choosing land use *j* given a change in w_{il} where $l \neq j$. For example, the change in $\hat{P}_{ij}$ given a small change in w_{im} is,

$$\frac{\partial \hat{P}_{ij}}{\partial w_{im}} = \frac{0 \times \left(\sum_{k=1}^{3} e^{V_{ik}}\right) - \hat{\delta}_m e^{V_{im}}\left(e^{V_{ij}}\right)}{\left(\sum_{k=1}^{3} e^{V_{ik}}\right)^2} \tag{17}$$

$$= -\frac{\hat{\delta}_m e^{V_{im}}}{\sum_{k=1}^{3} e^{V_{ik}}} \frac{e^{V_{ij}}}{\sum_{k=1}^{3} e^{V_{ik}}} \tag{18}$$

$$= -\hat{\delta}_m \hat{P}_{im} \hat{P}_{ij} \tag{19}$$

For example, if *j* is non-rice agriculture and m indexes non-timber crop plantation then $\partial \hat{P}_{ij}/\partial w_{im}$ measures the increase in the probability that *i* will adopt non-rice agriculture as of 2009 given a small increase in the annual revenue associated with non-timber crop plantation (of course this probability will be affected by land use in *i* in 2006, its zoning / concession data, and its soil quality). Finally, the other-choice elasticity is given by,

$$E_{j,w_{im}} = \frac{\partial \hat{P}_{ij}}{\partial w_{im}} \frac{w_{im}}{\hat{P}_{ij}} = -\hat{\delta}_m w_{im} \hat{P}_{im} \tag{20}$$

where we interpret $E_{j,w_{im}}$ as the percentage change in $\hat{P}_{ij}$ given a 1% change in w_{im}.

In Table 7 we present the estimated effect of an expected $10,000 annual revenue increase for a land use type on the probability of a representative parcel converting to that land use type ($\partial \hat{P}_{ij}/\partial w_{ij}$, not $\partial \hat{P}_{ij}/\partial w_{im}$ where *m* ≠ *j*). In the table below we assume excellent nutrient availability and unrestricted and protected land use, respectively, in the representative parcels. Again, we only present marginal effects for the probabilities estimated with the random parcel dataset (see Appendix Database A for all estimated $\partial \hat{P}_{rj}/\partial w_{rj}$ values evaluated at the mean as derived from the random parcel model estimates).

Table 7. The increase in mean P_{rj} for every $10,000 increase in expected annual revenue for land use *j* on parcels with excellent nutrient availability

2006 land use	For., MS	For., PS	DL, PS	DL, MS	Plant.	Ag.	Clearing
2009 land use	**Unrestricted land**						
Forest on mineral soils	0.534	0.000	0.777	1.238	0.398	0.218	0.216
Forest on peat soils	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Degraded land on peat soils	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Degraded land on mineral soils	-0.020	0.000	-0.109	-0.208	-0.086	-0.029	-0.193
Plantation	0.000	0.035	0.012	0.002	0.056	0.001	0.014
Agriculture	0.010	0.085	0.090	0.049	0.073	0.021	0.040
Clearing (Plantation)	0.002	0.135	0.044	0.002	0.013	0.001	0.133
	Protected land						
Forest on mineral soils	1.061	0.000	0.376	0.615	0.147	0.099	0.114
Forest on peat soils	0.000	0.000	0.000	0.000	0.000	0.000	0.000

2006 land use	For., MS	For., PS	DL, PS	DL, MS	Plant.	Ag.	Clearing
Degraded land on peat soils	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Degraded land on mineral soils	-0.043	0.000	-0.118	-0.176	-0.074	-0.030	-0.219
Plantation	0.001	0.048	0.017	0.002	0.049	0.001	0.022
Agriculture	0.020	0.089	0.086	0.050	0.063	0.018	0.046
Clearing (Plantation)	0.003	0.129	0.033	0.001	0.007	0.001	0.134

According to Table 7, protection status does little to prevent conversion to plantation, agriculture, and clearing when the annualized gross returns to such uses increase.

Looking more at the data in Appendix Database A we find that a $10,000 increase in the annualized gross revenue from clearing had the biggest impacts on conversion probabilities in parcels with non-timber tree crop plantation concessions, all else equal. The largest impacts of a $10,000 increase in the annualized gross revenue from agriculture and plantation on agriculture and plantation conversion rates, respectively, showed no pattern across land use regulation category. In addition, intensive land use conversion responses to increases in annualized revenues are larger on better soils than they are on less rich soils. We find this by simply summing all estimated $\partial P_{ij}/\partial w_{ij}$ values across the 2009 land uses of plantation, agriculture, and clearing, all 2006 land uses, and all zoning categories for each soil attribute category. See the appendix for more details on the calculations of the marginal effects.

VI. Model estimation and baseline land use transition matrices

Marlier et al. (2014) uses the estimated model to create land use transition matrices for Sumatra. These transition matrices are used by Marlier et al. (2014) to forecast Sumatra land use change and related land use conversion emissions out to 2030 at 3-year time steps. In this section we describe the creation of the set of baseline transition matrices (called the "Stable Prices" transition matrices by Marlier et al. 2014).

First, we use the estimated multinomial logit model coefficients based on the random parcel sample with a dataset of every parcel in the study area to calculate a $\hat{P}_{ij}$ value for each {*i,j*} combination.[2] Second, we group parcel-level probability estimates $\hat{P}_{ij}$ according to each unique {district – 2006 land use – soil category – zoning / concession category} combination. Let N_{dumg} indicate the set of parcels that are part of district *d*, 2006 land use *u*, zoning / concession category *m*, and soil category *g*. Therefore, $\hat{P}_{dujmg}$ – the average probability that a parcel in district *d* with zoning / concession category *m* and soil type *g* in land-use *u* at *t* = 2006 ends up in land use *j* as of 2009 – is given by,

$$\hat{P}_{dujmg} = \frac{1}{s(N_{dumg})} \sum_{i \in N_{dumg}} \hat{P}_{ij} \quad (21)$$

where $s(N_{dumg})$ is the size of set N_{dumg}. We calculate $\hat{P}_{dujmg}$ for each unique {*u*, *j*, *m*, *g*} combination in district *d*.

After this we will have the following 7 x 7 land-use transition matrix for each *d*, *m*, and *g* combination where rows index the initial *u* land uses (land use type at the beginning of a 3 year

[2] Marlier et al. (2014) uses the random sample generated set of $\hat{P}_{ij}$. Given the similarity in model fit with both samples the choice is fairly inconsequential.

time period) and columns index the subsequent *j* land uses (land use type at the end of the 3 year time period),

$$\widehat{\mathbf{P}}_{dmg} = \begin{bmatrix} \hat{P}_{d1,1mg} & \cdots & \hat{P}_{d1,7mg} \\ \vdots & \ddots & \vdots \\ \hat{P}_{d7,1mg} & \cdots & \hat{P}_{d7,7mg} \end{bmatrix} \quad (22)$$

Because there are 5 zoning / concession designations and 3 soil categories each district *d* will normally have 15 complete matrices like (22). However, in some cases a row in matrix (22) will not exist because land use *u* was not observed in the district *d* in 2006. In other cases, a whole 7 x 7 matrix will not exist for a district because a unique {*m*,*g*} combination was never observed in district *d*. In the case of missing rows of matrix (22) we set the missing $\hat{P}_{dujmg}$ values equal to $\hat{P}_{ujmg}$, the average probability of converting from *u* to *j* given *m* and *g* across all of Sumatra. In the case of missing 7 x 7 matrices we set the missing $\hat{P}_{dujmg}$ values equal to $\hat{P}_{ujm}$, the average probability of converting from *u* to *j* given *m* across all of Sumatra.

To illustrate how we can use transition matrix (22) to project land use out to 2030 consider a 1-km^2 parcel of land that is in primary forest in 2006 (*u* = 1). Assume the parcel is in district *d* with zoning / concession category *m* and soil type *g*. Further, suppose that *m* and *g* are fixed until 2030. According to matrix (22), by 2009 the parcel will have $\hat{P}_{d1,1mg}$-km^2 of forest on mineral soils, $\hat{P}_{d1,2mg}$-km^2 of forest on peatland soil, $\hat{P}_{d1,3mg}$-km^2 of degraded land on peat soils, and so on. Then by 2012 the same 1 km^2 parcel will have $\sum_{j=1}^{7} \hat{P}_{d1,jmg}\hat{P}_{dj,1mg}$-km^2 of forest on mineral soils, $\sum_{j=1}^{7} \hat{P}_{d2,jmg}\hat{P}_{dj,2mg}$-km^2 of forest on peatland soil, and so on. Notice that expected land use mix on the 1-km^2 parcel *i* in district *d* with zoning / concession category *m* and soil type *g* as of 2009, 2012, etc. (*t* = 1, *t* = 2, etc) can be calculated with the matrix operation $\mathbf{A}_{i\in dmg} \times \widehat{\mathbf{P}}_{dmg}^{t}$ where $\mathbf{A}_{i\in dmg}$ is a 7 x 7 matrix that indicates parcel *i*'s 2006 land use with a value of 1 in the u^{th} diagonal element and zeros elsewhere.

VII. Land use transition matrices under different scenarios of landscape conditions

Besides the "Stable Prices" or baseline trajectory of land use and related land use conversion emissions out to 2030, Marlier et al. (2014) also estimates alternative trajectories of land use and related land use conversion emissions out to 2030. In this section we describe how we create the transition matrices for these alternative scenarios of change.

VII.a Price changes

The baseline transition matrix $\widehat{\mathbf{P}}_{dmg}$ reveals land user reaction to market and policy conditions that existed on Sumatra between 2006 to 2009 period where market price expectations were based on 2004 to 2006 prices (see the SI). When we use the transition matrix $\widehat{\mathbf{P}}_{dmg}$ to generate land use maps out to 2030 we are assuming that 2006 to 2009 conditions on the landscape and land use reactions to these conditions will not change out to 2030. However, suppose we are interested in creating future land use maps where the relative ratios of expected annual revenues across the 7 land uses are different than the observed 2006 to 2009 relative ratios? For example, suppose at that beginning of 2006 the market price of several plantation commodities, including oil palm, coffee, rubber, cocoa, coconuts, and pepper, increased by 30% relative to all other commodities and maintained that gap until 2030. To model land user reaction to this market price change (assuming all other landscape conditions, including land user motivation to maximize utility, remain at 2006 through 2009 levels) we first increase the annualized revenue values for all land uses that include plantations on all parcels by 30%. Then we use the random sample estimated coefficients from Table 3 with the revenue-manipulated parcel dataset to calculate $\tilde{P}_{ij}$ for each {*i*,*j*} combination where the '~' indicates these are probabilities based on a manipulation of revenue figures in the parcel dataset.

We then repeat the steps from section VI to construct the transition matrix $\widetilde{\mathbf{P}}_{dmg}$

$$\widetilde{\mathbf{P}}_{dmg} = \begin{bmatrix} \tilde{P}_{d1,1mg} & \cdots & \tilde{P}_{d1,7mg} \\ \vdots & \ddots & \vdots \\ \tilde{P}_{d7,1mg} & \cdots & \tilde{P}_{d7,7mg} \end{bmatrix} \tag{23}$$

for each unique *m*, *g*, and *d* combination. Under this alternative scenario expected land use mix in 2009, 2012, etc. on the 1-km^2 parcel *i* in district *d* with zoning / concession category *m* and soil type *g* is given by $\mathbf{A}_{i\in dmg} \times \widetilde{\mathbf{P}}_{dmg}^{t}$ where *t* = 2 for 2012, *t* = 3 for 2015, etc. Therefore, the differences in the expected land use maps generated by the transition matrices $\widehat{\mathbf{P}}_{dmg}$ and $\widetilde{\mathbf{P}}_{dmg}$ from 2006 to 2030 in 3-year time steps represent the impact of the perpetual 30% increase in expected plantation commodity prices on land user decision making from 2006 to 2030 assuming all other 2006 to 2009 conditions on the landscape remain fixed until 2030.

VII.b. The Green Vision scenario

The Green Vision is a World Wildlife Fund-Indonesia led sustainable development plan for Sumatra done in collaboration with the Indonesian government (Roosita et al 2010). The main goal of this vision is to establish Sumatran ecosystem-based spatial plan. The vision adds protected forested areas to the landscape and rearranges concession allocation and management across the island. To estimate how implementation of the Green Vision would affect land use out to 2030 we need to create transitions matrices that incorporate the major implications of the Green Vision. First, we create a new zoning / concession map, called the Green Vision map, based on World Wildlife Fund's zoning and concession plan for Sumatra (see the appendix for crosswalk for zoning categories). This means that for many parcels the values of the dummy variable vector $\{z_1,\ldots,z_5\}$ change compared to 2006 to 2009 observed values. Second, we use the random sample estimated coefficients from Table 3 with the manipulated parcel dataset to calculate $\ddot{P}_{ij}$ for each {*i*,*j*} combination where the '¨' indicates these are probabilities based on a manipulation of the $\{z_1,\ldots,z_5\}$ vectors in the parcel dataset. Third, we use the methodology described in section VI to generate the transition matrices $\ddot{\mathbf{P}}_{dmg}$.

VII.c. The National Spatial Plan scenario

The National Spatial Plan represents the Indonesian government's plan seeks to achieve security, economic viability, and sustainability in the use of land across the archipelagic county; specifically for limited and unrestricted production forests, cultivated areas, urban uses, and conservation areas. The plan is meant to guide development over 20 years. To create the transitions matrices for this scenario we take several steps. First we create a new zoning / concession map, called the National Spatial Plan map, based on the Indonesia government's plan for Sumatra (see the appendix for crosswalk for zoning categories). This means that for many parcels the values of the dummy variable vector $\{z_1,\ldots,z_5\}$ change compared to 2006 to 2009 observed values. Second, we use the estimated coefficients from Table 3 with the manipulated parcel dataset to calculate $\dddot{P}_{ij}$ for each $\{i,j\}$ combination where the '...' indicates these are probabilities based on a manipulation of the $\{z_1,\ldots,z_5\}$ vectors in the parcel dataset. Third, we use the methodology described in section VI to generate the transition matrices $\dddot{\mathbf{P}}_{dmg}$.

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Appendix

I. Land cover/ Land use

We derived land-cover/land-use (LULC) maps from an analysis of two spatial data sets. These LULC maps are produced by the Directorate of Forest Resources Monitoring and Inventory of Indonesia's Ministry of Forestry (MoF) to monitor forest resources every three years since 2000 (data used in this study are from 2006 and 2009; MoF 2011). The maps are based on the visual interpretation of Landsat 7 ETM+, Landsat 5 TM and SPOT 4 images that is projected onto a thematic map, scale 1:250,000, and are distinguished by 25 LULC classes (see Table S1). However, classification of land use types (e.g., agriculture crops) is less detailed than that of the natural land cover types (e.g., primary forests, secondary forests). For instance, 'tree crop plantation' is categorized as a single class, which could result in inaccurate estimates of the economic returns of the land uses. Therefore, we made assumptions on specific land management practices for each LULC type in consultation with MoF staff (see Table S2). We chose to crosswalk or group similar land cover types for simplicity resulting in a total of 9 LULC types used in our analysis (see Table S1).

II. Estimating Gross Returns to LULC

Estimates of province-level annual gross returns per hectare were based on a three-year average from 2004 to 2006 (all monetary figures hereafter are in 2006 US dollars; price values from other years were inflated using the Consumer Price Index [CPI] as the inflation method). Estimates were obtained by multiplying the annual commodity yield by the commodity price for each respective year then averaging across the 3 years (Table S3). Below are our assumptions for each commodity type.

A. Cropland Gross Returns

We used province-level yields and crop area from Indonesia Ministry of Agriculture and Budan Pusat Statistik for five major non-tree crops: rice, corn, soybean, cassava, and sweet potato (http://www.bps.go.id/eng/tnmn_pgn.php?kat=3). Non-rice agriculture returns were based on the province-level area-weighted average of the 4 most common non-rice crops grown in Indonesia: corn, soybean, cassava, and sweet potato (see Table S3 and S6). For price we used the average market price for that agricultural commodity from 2004 to 2006 (http://faostat.fao.org) (Table S6).

B. Non-timber Perennial Plantation Gross Returns

We used province-level yields and plantation area from Indonesia Ministry of Agriculture and Budan Pusat Statistik for 26 major tree crops: oil palm, rubber, coconut, coconut palace, hybrid coconut, areca nut, cocoa, clove, hazelnut, nutmeg, palm sugar, kapuk tree, lemongrass, patchouli, cinnamon, tobacco, pepper, cashew, vanilla, tea, sugar cane, rami, jatropha, ginger, and cardamom. Because we do not know the exact crop composition within this LULC type we estimated returns based on a weighted-average of the top 5 crops for each province (see Table S6). For price we used the average market price for that agricultural commodity from 2004 to 2006 (http://faostat.fao.org). Unlike annual crops perennial tree plantations produce a stream of unequal revenues over time. Using a discount rate of 5% and a 100-yr time frame, we estimated the "annualized" present value based on the stream of expected revenues from each plantation crop taking into account both the time to establish mature producing plants and rotation practices. See Table S4 for management assumptions. See section II.F. for information on our annualization technique.

C. Sawlog and Pulpwood Plantation Gross Returns

We used yield data based on the harvestable volume per hectare of sawlog and pulpwood from timber plantations taken from 5 large company HTI concession projects in Sumatra (Maturana 2005). These estimates consider the differences in timber plantation and forest type by region: north (Inti Indo Rayon), central (Arara Abadi and Riau Andalan), Jambi (Lontar Papyrus), and south (Musi Hutan Persada). Pulp wood yields are adjusted based on a species' survival rate and its wood-to-pulp conversion factor. As with non-timber plantations, we estimated an "annualized" present value based on the stream of expected revenues from each pulp or sawlog plantation type using a discount rate of 5% and a 100-yr time frame that considers both the time to establish and rotation practices. For pulp plantation species we assumed a 3-yr establishment period and a 7-yr rotation. For sawlogs we assumed adoption of the Indonesian Selective Cutting and Replanting System (T PTI – *Tebang Pilih Tanam Indonesia)* (MoF 1997, Sist et al. 1998, Ruslim et al. 1999). In this system, natural forest production is managed based on 35-yr rotation to maintain sustainable yields of tropical forests. We assumed a fixed market price for the pulpwood estimated at \$43/m^3 2006 US\$ based on the estimates of actual prices paid for logs at the mill gate by plantation companies (see Maturana 2005). For sawlogs we assumed a fixed price of \$119.45/m^3 2006 US\$ based on recent Indonesian sales (Ruslandi et al. 2011). See Table S4 for management assumptions. We chose not to include one-time timber returns from forest to non-forest transitions. For example, the gross returns from the one-time clearing of secondary forest to plant an oil palm plantation. Because this return is associated with certain transitions we expect this to be captured by the transition dummy variables.

D. Mixed gardens and agroforestry returns

Returns to mixed gardens and agroforestry (the LULC type "non-rice agriculture with bush/shrub") are based on the assumption that 50% of the area is in non-timber perennial plantation and 50% in non-rice agriculture (see Table S4 and Table S6). Mixed gardens and agroforestry crops are intensive production systems including multi-purpose tree species, shrubs, and food crops.

E. Urban Gross Returns

Returns to urban land uses (e.g., settlements, resettlements) are not considered in this study due to a lack of available data on the economic value these uses. Furthermore, there was a lack of data on the degree to which urbanization is driven by economic returns versus government transmigration policy.

F. Animalization methods

For some land uses, for example, annual crops, revenue is already measured on an annual basis. However, for land uses that produce a stream of unequal revenues over time the data needs to be "annualized." For example, think of an oil palm operation established on scrub land. For the first 3 years after establishment no oil is generated as the palms grow to maturity. If we let R_{jpt} indicate the expected revenue generated by a hectare of land use j in province p in year t of its operation this means $R_{jp0} = R_{jp1} = R_{jp2} = 0$ for j = oil palm plantation. Then, assuming the trees can generate oil for 30 years before the stand needs to be re-established, R_{jp3} through R_{jp32} are equal to the expected annual revenue for a mature oil palm plantation in province p. Then in years t = 33, 34, and 35 revenues fall to 0 again as the tree stand has to be re-established, whereas in years t = 36 through t = 65 the plantation earns the expected annual revenue for a mature oil palm plantation in province p, etc. (for simplicity we assume prices and yields do not change over time). Using a discount rate of r (e.g., 5% or r = 0.05) and a 100 year time frame, the present value of the stream of expected revenues from the plantation is given by R_{jp},

$$R_{jp} = \sum_{t=0}^{99} \frac{R_{jpt}}{(1+r)^t} \tag{S1}$$

For example, suppose $r = 0.05$ and $R_{jp3} = \ldots = R_{jp32} = R_{jp36} = \ldots = R_{jp65} = R_{jp69} = \ldots = R_{jp98} = \$1000$ and all other $R_{jpt} = 0$. Then according to equation (S1) R_{jp} is equal to,

$$R_{jp} = \sum_{t=3}^{32} \frac{1000}{1.05^t} + \sum_{t=36}^{65} \frac{1000}{1.05^t} + \sum_{t=69}^{98} \frac{1000}{1.05^t} \tag{S2}$$

$$= 1000\left(\sum_{t=3}^{32} \frac{1}{1.05^t} + \sum_{t=36}^{65} \frac{1}{1.05^t} + \sum_{t=69}^{98} \frac{1}{1.05^t}\right) \tag{S3}$$

$$= 1000(13.94 + 2.79 + 0.56) \tag{S4}$$

$$= 1000(13.94 + 2.79 + 0.56) = 17{,}287 \tag{S5}$$

To annualize R_{jp} we need to find the annual payment A_{jp} (an annuity) from t = 0 to t = 99 that would generate R_{jp},

$$R_{jp} = \sum_{t=0}^{99} \frac{A_{jp}}{(1+r)^t} \tag{S6}$$

$$= A_{jp} \sum_{t=0}^{99} \frac{1}{(1+r)^t} \tag{S7}$$

$$= A_{jp} \sum_{t=0}^{99} \frac{1}{(1+r)^t} \tag{S8}$$

$$= \frac{(1+r)}{r} A_{jp} \left(1 - \left(\frac{1}{1+r}\right)^{100}\right) \tag{S9}$$

$$A_{jp} = \frac{rR_{jp}}{(1+r)\left(1-\left(\frac{1}{1+r}\right)^{100}\right)} \tag{S10}$$

Given our palm oil example A_{jp} would be,

$$A_{jp} = \frac{0.05\times 17{,}287}{(1.05)\left(1-\left(\frac{1}{1.05}\right)^{100}\right)} = \frac{864.36}{(1.05)(1-0.008)} = \frac{864.36}{1.042} = 829.51 \tag{S11}$$

Let the annual net returns to each land use *j* in parcel *i* be given by $A_{jp(i)}$ where *A* could be an annuity or the annual revenues to a land use with a constant stream of revenues and $p(i)$ indicates that parcel *i* is in province p.

III. Other explanatory variables

Observable site characteristics included soil quality, precipitation, temperature, slope, elevation, aspect, distance to the nearest road, distance to the nearest provincial capital, and cells contained within a national park, other protected areas, logging concessions, timber concessions, or estate crop concessions. For a full list and description of explanatory variables see Table S5.

IV. Estimating marginal effects

Marginal effect of a change in z_i

First we show the post-estimation math necessary to determine the impact of a small change in a continuous z_i – type variable on $\widehat{P}_{ij}$.

$$\frac{\partial P_{ij}}{\partial z_i} = \frac{\left(\hat{\gamma}_j e^{V_{ij}}\right)\left(\sum_{k=1}^{3} e^{V_{ik}}\right) - \left(e^{V_{ij}}\right)\left(\hat{\gamma}_j e^{V_{ij}} + \hat{\gamma}_m e^{V_{im}} + \hat{\gamma}_n e^{V_{in}}\right)}{\left(\sum_{k=1}^{3} e^{V_{ik}}\right)^2} \tag{S12}$$

$$= \frac{e^{V_{ij}}\left(\hat{\gamma}_j \sum_{k=1}^{3} e^{V_{ik}} - \left(\hat{\gamma}_j e^{V_{ij}} + \hat{\gamma}_m e^{V_{im}} + \hat{\gamma}_n e^{V_{in}}\right)\right)}{\left(\sum_{k=1}^{3} e^{V_{ik}}\right)^2} \tag{S13}$$

$$= \frac{e^{V_{ij}}}{\sum_{k=1}^{3} e^{V_{ik}}}\left(\frac{\hat{\gamma}_j \sum_{k=1}^{3} e^{V_{ik}} - \left(\hat{\gamma}_j e^{V_{ij}} + \hat{\gamma}_m e^{V_{im}} + \hat{\gamma}_n e^{V_{in}}\right)}{\sum_{k=1}^{3} e^{V_{ik}}}\right) \tag{S14}$$

$$= \widehat{P}_{ij}\left(\frac{\hat{\gamma}_j \sum_{k=1}^{3} e^{V_{ik}} - \left(\hat{\gamma}_j e^{V_{ij}} + \hat{\gamma}_m e^{V_{im}} + \hat{\gamma}_n e^{V_{in}}\right)}{\sum_{k=1}^{3} e^{V_{ik}}}\right) \tag{S15}$$

$$= \widehat{P}_{ij}\left(\hat{\gamma}_j - \frac{\left(\hat{\gamma}_j e^{V_{ij}} + \hat{\gamma}_m e^{V_{im}} + \hat{\gamma}_n e^{V_{in}}\right)}{\sum_{k=1}^{3} e^{V_{ik}}}\right) \tag{S16}$$

$$= \widehat{P}_{ij}\left(\hat{\gamma}_j - \left(\hat{\gamma}_j \widehat{P}_{ij} + \hat{\gamma}_m \widehat{P}_{im} + \hat{\gamma}_n \widehat{P}_{in}\right)\right) \tag{S17}$$

$$= \widehat{P}_{ij}\left(\hat{\gamma}_j - \left(\sum_{k=1}^{3} \hat{\gamma}_k \widehat{P}_{ik}\right)\right) \tag{S18}$$

where $e^{V_{ij}} = e^{\hat{\alpha}_j + \hat{\beta} x_{ij} + \hat{\gamma}_j z_i + \hat{\delta}_j w_{ij}}$.

Marginal effect of a change in w_{ij}

The change in $\hat{P}_{ij}$ assuming a small change in continuous variable w_{ij} is,

$$\frac{\partial \hat{P}_{ij}}{\partial w_{ij}} = \frac{\hat{\delta}_j e^{V_{ij}} (\sum_{k=1}^{3} e^{V_{ik}}) - \hat{\delta}_j e^{V_{ij}} \left(e^{V_{ij}}\right)}{\left(\sum_{k=1}^{3} e^{V_{ik}}\right)^2} \tag{S19}$$

$$= \frac{\hat{\delta}_j e^{V_{ij}}}{\sum_{k=1}^{3} e^{V_{ik}}} \frac{(\sum_{k=1}^{3} e^{V_{ik}}) - \left(e^{V_{ij}}\right)}{\sum_{k=1}^{3} e^{V_{ik}}} \tag{S20}$$

$$= \frac{\hat{\delta}_j e^{V_{ij}}}{\sum_{k=1}^{3} e^{V_{ik}}} \left(\frac{\sum_{k=1}^{3} e^{V_{ik}}}{\sum_{k=1}^{3} e^{V_{ik}}} - \frac{e^{V_{ij}}}{\sum_{k=1}^{3} e^{V_{ik}}} \right) \tag{S21}$$

$$= \hat{\delta}_j \hat{P}_{ij} \left(1 - \hat{P}_{ij}\right) \tag{S22}$$

V. Zoning assumption for the Green Vision and National Spatial Plan scenarios

We cross walked the zoning categories in the Green Vision and the National Spatial Plan to match the 2006-based zoning categories used in the Baseline scenario: logging concession, timber plantation, and tree crop timber plantation. See Table S10-11 for details.

VI. Land Use Change Model Estimation Results

```
[1] "grid results"

Call:
mlogit(formula = LULC_09 ~ 0 | MC_DIST + COAST_DIST + LULC_06 +
    Zoning + NUTRIENT_AVAILAB | returns, data = LULC.grid, method = "nr",
    print.level = 0)

Frequencies of alternatives:
       1        5        7        9       11       13       17
0.221633 0.074046 0.077837 0.080364 0.161486 0.356583 0.028052

nr method
19 iterations, 0h:0m:13s
g'(-H)^-1g = 4.51E-07
gradient close to zero

Coefficients :
                           Estimate  Std. Error t-value  Pr(>|t|)
5:(intercept)           -3.0415e+00  1.9033e+00 -1.5980 0.1100528
7:(intercept)           -2.1554e+01  4.3677e+03 -0.0049 0.9960626
9:(intercept)           -1.7428e+00  1.0984e+00 -1.5867 0.1125854
11:(intercept)          -3.1975e+00  1.3185e+00 -2.4250 0.0153081 *
13:(intercept)          -3.1527e+00  1.3566e+00 -2.3239 0.0201296 *
17:(intercept)          -3.5084e+00  1.6025e+00 -2.1894 0.0285685 *
5:MC_DIST                3.0826e-01  4.8464e-01  0.6361 0.5247367
7:MC_DIST                1.4304e+00  4.4721e-01  3.1985 0.0013814 **
9:MC_DIST                5.6744e-01  3.4779e-01  1.6315 0.1027755
11:MC_DIST               5.0774e-01  3.9048e-01  1.3003 0.1934967
13:MC_DIST               3.6921e-01  3.3799e-01  1.0924 0.2746624
17:MC_DIST               3.3333e-01  4.5158e-01  0.7381 0.4604254
5:COAST_DIST            -1.7652e+00  5.2021e-01 -3.3933 0.0006906 ***
7:COAST_DIST            -4.5537e-01  4.4715e-01 -1.0184 0.3084989
9:COAST_DIST            -4.1402e-01  3.5444e-01 -1.1681 0.2427646
11:COAST_DIST           -2.4784e-01  3.6004e-01 -0.6884 0.4912226
13:COAST_DIST            3.6521e-01  3.2979e-01  1.1074 0.2681176
```

```
17:COAST_DIST                -7.4494e-01  4.2185e-01 -1.7659 0.0774137 .
5:LULC_0611                   3.3797e+00  1.0036e+00  3.3677 0.0007581 ***
7:LULC_0611                   2.2974e+01  4.3677e+03  0.0053 0.9958032
9:LULC_0611                   3.9378e+00  5.8989e-01  6.6756 2.463e-11 ***
11:LULC_0611                  8.0409e+00  5.6013e-01 14.3554 < 2.2e-16 ***
13:LULC_0611                  5.0688e+00  5.4279e-01  9.3384 < 2.2e-16 ***
17:LULC_0611                  4.5196e+00  6.2812e-01  7.1955 6.224e-13 ***
5:LULC_0613                   2.8194e+00  9.3448e-01  3.0171 0.0025520 **
7:LULC_0613                   2.3075e+01  4.3677e+03  0.0053 0.9957848
9:LULC_0613                   4.0799e+00  3.8628e-01 10.5621 < 2.2e-16 ***
11:LULC_0613                  4.5060e+00  4.6167e-01  9.7604 < 2.2e-16 ***
13:LULC_0613                  7.8332e+00  3.5827e-01 21.8641 < 2.2e-16 ***
17:LULC_0613                  3.6619e+00  5.4004e-01  6.7808 1.195e-11 ***
5:LULC_0617                   4.9081e+00  8.9809e+03  0.0005 0.9995639
7:LULC_0617                   4.1459e+01  6.9598e+03  0.0060 0.9952471
9:LULC_0617                   2.2632e+01  5.4186e+03  0.0042 0.9966674
11:LULC_0617                  2.3288e+01  5.4186e+03  0.0043 0.9965708
13:LULC_0617                  2.2991e+01  5.4186e+03  0.0042 0.9966146
17:LULC_0617                  2.5439e+01  5.4186e+03  0.0047 0.9962542
5:LULC_065                    2.6797e+01  5.0941e+03  0.0053 0.9958029
7:LULC_065                    4.2917e+01  6.7102e+03  0.0064 0.9948969
9:LULC_065                    1.9976e+01  5.0941e+03  0.0039 0.9968712
11:LULC_065                   2.3040e+01  5.0941e+03  0.0045 0.9963912
13:LULC_065                   2.2317e+01  5.0941e+03  0.0044 0.9965045
17:LULC_065                   2.3250e+01  5.0941e+03  0.0046 0.9963584
5:LULC_067                    5.9363e+00  9.5701e-01  6.2030 5.540e-10 ***
7:LULC_067                    2.7510e+01  4.3677e+03  0.0063 0.9949745
9:LULC_067                    3.4553e+00  9.0928e-01  3.8000 0.0001447 ***
11:LULC_067                   4.6547e+00  8.7584e-01  5.3146 1.069e-07 ***
13:LULC_067                   4.7155e+00  8.2368e-01  5.7249 1.035e-08 ***
17:LULC_067                   4.0715e+00  9.4751e-01  4.2971 1.731e-05 ***
5:LULC_069                    3.7279e+00  7.1911e-01  5.1841 2.171e-07 ***
7:LULC_069                    2.1585e+01  4.3677e+03  0.0049 0.9960569
9:LULC_069                    5.9767e+00  3.4212e-01 17.4695 < 2.2e-16 ***
11:LULC_069                   2.6422e+00  6.1195e-01  4.3176 1.577e-05 ***
13:LULC_069                   3.8925e+00  3.9084e-01  9.9594 < 2.2e-16 ***
17:LULC_069                   1.2118e+00  1.0913e+00  1.1104 0.2668309
5:ZoningIndustForestTim       1.1451e-01  5.1171e-01  0.2238 0.8229235
7:ZoningIndustForestTim       7.4288e-03  5.2394e-01  0.0142 0.9886875
9:ZoningIndustForestTim       1.3049e+00  4.0684e-01  3.2074 0.0013396 **
11:ZoningIndustForestTim      5.8389e-01  4.3189e-01  1.3519 0.1763935
13:ZoningIndustForestTim     -3.8029e-03  4.2957e-01 -0.0089 0.9929365
17:ZoningIndustForestTim      1.1469e+00  4.5615e-01  2.5144 0.0119251 *
5:ZoningLoggingConcession    -9.8014e-01  6.6962e-01 -1.4637 0.1432698
7:ZoningLoggingConcession    -8.7709e-01  6.9624e-01 -1.2597 0.2077602
9:ZoningLoggingConcession    -8.4524e-01  4.8305e-01 -1.7498 0.0801511 .
11:ZoningLoggingConcession   -9.4888e-01  5.8130e-01 -1.6323 0.1026058
13:ZoningLoggingConcession   -2.1839e+00  4.9745e-01 -4.3902 1.132e-05 ***
17:ZoningLoggingConcession   -2.0163e+00  8.8724e-01 -2.2725 0.0230561 *
5:ZoningNon-TimberTree        1.3786e+00  7.5502e-01  1.8259 0.0678592 .
7:ZoningNon-TimberTree        4.5664e-01  7.7295e-01  0.5908 0.5546680
9:ZoningNon-TimberTree       -1.0961e-01  6.9296e-01 -0.1582 0.8743205
11:ZoningNon-TimberTree       1.0726e+00  6.3310e-01  1.6942 0.0902203 .
13:ZoningNon-TimberTree       2.6752e-01  6.4229e-01  0.4165 0.6770406
17:ZoningNon-TimberTree       7.5669e-01  7.2800e-01  1.0394 0.2986165
5:ZoningProtectedArea         7.8158e-01  5.7652e-01  1.3557 0.1751985
7:ZoningProtectedArea        -1.5604e-01  6.3934e-01 -0.2441 0.8071815
9:ZoningProtectedArea        -1.0027e+00  4.2329e-01 -2.3688 0.0178473 *
11:ZoningProtectedArea       -3.1429e+00  9.2370e-01 -3.4025 0.0006677 ***
13:ZoningProtectedArea       -9.0072e-01  4.2494e-01 -2.1197 0.0340349 *
17:ZoningProtectedArea       -3.2286e-01  6.1699e-01 -0.5233 0.6007759
5:NUTRIENT_AVAILABexcellent  -2.0085e+01  6.8396e+03 -0.0029 0.9976570
7:NUTRIENT_AVAILABexcellent  -3.0978e+00  1.2630e+00 -2.4528 0.0141754 *
9:NUTRIENT_AVAILABexcellent  -9.4545e-01  4.3083e-01 -2.1945 0.0281989 *
11:NUTRIENT_AVAILABexcellent -3.0434e+00  8.1198e-01 -3.7481 0.0001782 ***
13:NUTRIENT_AVAILABexcellent -1.8609e+00  4.2062e-01 -4.4242 9.681e-06 ***
17:NUTRIENT_AVAILABexcellent -3.2759e+00  9.6014e-01 -3.4119 0.0006452 ***
5:NUTRIENT_AVAILABaverage    -2.2653e+00  5.0034e-01 -4.5276 5.966e-06 ***
7:NUTRIENT_AVAILABaverage    -1.5085e+00  4.2703e-01 -3.5326 0.0004115 ***
9:NUTRIENT_AVAILABaverage    -1.2101e+00  2.8552e-01 -4.2382 2.253e-05 ***
11:NUTRIENT_AVAILABaverage   -2.2694e+00  3.6390e-01 -6.2362 4.484e-10 ***
```

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13:NUTRIENT_AVAILABaverage   -1.2315e+00  2.7646e-01 -4.4548 8.399e-06 ***
17:NUTRIENT_AVAILABaverage   -2.8902e+00  4.9635e-01 -5.8230 5.782e-09 ***
1:returns                     5.4886e+00  3.0237e+00  1.8152 0.0694938 .
5:returns                     4.5467e+00  4.7584e+00  0.9555 0.3393227
7:returns                     9.3354e-01  2.4845e+00  0.3757 0.7071073
9:returns                     2.2541e+00  1.7377e+00  1.2972 0.1945719
11:returns                    2.8504e-01  1.3734e-01  2.0754 0.0379513 *
13:returns                    2.8140e-01  1.2836e-01  2.1923 0.0283579 *
17:returns                    3.6974e-01  1.9448e-01  1.9011 0.0572825 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Log-Likelihood: -1808.9
McFadden R^2:  0.72958
Likelihood ratio test : chisq = 9760.3 (p.value = < 2.22e-16)
[1] "rand results"

Call:
mlogit(formula = LULC_09 ~ 0 | MC_DIST + COAST_DIST + LULC_06 +
    Zoning + NUTRIENT_AVAILAB | returns, data = LULC.rand, method = "nr",
    print.level = 0)

Frequencies of alternatives:
       1        5        7        9       11       13       17
0.253456 0.056598 0.066638 0.074931 0.131238 0.394297 0.022843

nr method
19 iterations, 0h:0m:22s
g'(-H)^-1g = 7.28E-07
gradient close to zero

Coefficients :
                               Estimate  Std. Error t-value  Pr(>|t|)
5:(intercept)                 -2.274850    1.449039 -1.5699 0.1164377
7:(intercept)                 -3.613981    1.344104 -2.6888 0.0071717 **
9:(intercept)                  1.449141    0.774764  1.8704 0.0614242 .
11:(intercept)                -1.788541    0.980920 -1.8233 0.0682535 .
13:(intercept)                -1.630632    0.898928 -1.8140 0.0696817 .
17:(intercept)                -2.203813    1.228150 -1.7944 0.0727465 .
5:MC_DIST                      1.014427    0.396012  2.5616 0.0104189 *
7:MC_DIST                      1.089255    0.371137  2.9349 0.0033364 **
9:MC_DIST                      0.445940    0.267149  1.6693 0.0950666 .
11:MC_DIST                     0.801637    0.305393  2.6249 0.0086666 **
13:MC_DIST                     0.289506    0.254949  1.1355 0.2561464
17:MC_DIST                    -0.211073    0.375151 -0.5626 0.5736837
5:COAST_DIST                  -1.366703    0.417818 -3.2710 0.0010715 **
7:COAST_DIST                  -0.041375    0.361015 -0.1146 0.9087564
9:COAST_DIST                  -0.178452    0.269211 -0.6629 0.5074123
11:COAST_DIST                 -0.507301    0.293604 -1.7278 0.0840165 .
13:COAST_DIST                  0.587243    0.254076  2.3113 0.0208169 *
17:COAST_DIST                 -0.681520    0.350980 -1.9418 0.0521657 .
5:LULC_0611                    5.634082    0.990207  5.6898 1.272e-08 ***
7:LULC_0611                    7.206261    1.215950  5.9264 3.096e-09 ***
9:LULC_0611                    4.811644    0.589898  8.1567 4.441e-16 ***
11:LULC_0611                   9.936237    0.645295 15.3980 < 2.2e-16 ***
13:LULC_0611                   5.531903    0.552114 10.0195 < 2.2e-16 ***
17:LULC_0611                   5.007079    0.640336  7.8195 5.329e-15 ***
5:LULC_0613                    4.512291    0.757911  5.9536 2.623e-09 ***
7:LULC_0613                    6.839893    1.048236  6.5251 6.794e-11 ***
9:LULC_0613                    4.268515    0.285352 14.9588 < 2.2e-16 ***
11:LULC_0613                   5.620370    0.459001 12.2448 < 2.2e-16 ***
13:LULC_0613                   7.526772    0.246841 30.4924 < 2.2e-16 ***
17:LULC_0613                   3.329804    0.436337  7.6313 2.331e-14 ***
5:LULC_0617                    6.539462    1.551414  4.2152 2.496e-05 ***
7:LULC_0617                   -9.368804 4378.746507 -0.0021 0.9982928
9:LULC_0617                    6.432141    1.047372  6.1412 8.189e-10 ***
11:LULC_0617                   8.276261    1.110677  7.4515 9.215e-14 ***
13:LULC_0617                   5.396914    1.090211  4.9503 7.408e-07 ***
17:LULC_0617                   8.755374    1.062208  8.2426 2.220e-16 ***
5:LULC_065                    28.230991 4491.260432  0.0063 0.9949847
7:LULC_065                    27.284577 4491.260505  0.0061 0.9951529
```

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9:LULC_065                       3.201317 6401.153106  0.0005 0.9996010
11:LULC_065                     24.326371 4491.260411  0.0054 0.9956784
13:LULC_065                     21.350024 4491.260428  0.0048 0.9962071
17:LULC_065                     23.621831 4491.260402  0.0053 0.9958035
5:LULC_067                       8.897352    1.203270  7.3943 1.421e-13 ***
7:LULC_067                      12.773336    1.431330  8.9241 < 2.2e-16 ***
9:LULC_067                       4.374336    1.179711  3.7080 0.0002089 ***
11:LULC_067                      6.787216    1.145326  5.9260 3.104e-09 ***
13:LULC_067                      5.845259    1.062619  5.5008 3.781e-08 ***
17:LULC_067                      5.572036    1.154541  4.8262 1.392e-06 ***
5:LULC_069                       4.181051    0.716739  5.8334 5.430e-09 ***
7:LULC_069                       5.056343    1.113368  4.5415 5.586e-06 ***
9:LULC_069                       5.655940    0.245382 23.0495 < 2.2e-16 ***
11:LULC_069                      4.263232    0.492863  8.6499 < 2.2e-16 ***
13:LULC_069                      3.764757    0.260572 14.4481 < 2.2e-16 ***
17:LULC_069                      1.783442    0.665444  2.6801 0.0073605 **
5:ZoningIndustForestTim         -0.892025    0.465095 -1.9179 0.0551187 .
7:ZoningIndustForestTim         -0.898539    0.473339 -1.8983 0.0576570 .
9:ZoningIndustForestTim          0.290433    0.329894  0.8804 0.3786519
11:ZoningIndustForestTim        -0.203069    0.382646 -0.5307 0.5956292
13:ZoningIndustForestTim        -0.904454    0.353622 -2.5577 0.0105370 *
17:ZoningIndustForestTim        -0.782760    0.430877 -1.8167 0.0692681 .
5:ZoningLoggingConcession        0.435727    0.600926  0.7251 0.4683945
7:ZoningLoggingConcession       -0.782087    0.641618 -1.2189 0.2228713
9:ZoningLoggingConcession       -1.199285    0.373383 -3.2119 0.0013184 **
11:ZoningLoggingConcession      -1.437345    0.551872 -2.6045 0.0092012 **
13:ZoningLoggingConcession      -1.566062    0.388229 -4.0339 5.487e-05 ***
17:ZoningLoggingConcession      -2.027414    0.842917 -2.4052 0.0161621 *
5:ZoningNon-TimberTree           0.308129    0.684794  0.4500 0.6527399
7:ZoningNon-TimberTree          -0.045994    0.675337 -0.0681 0.9457022
9:ZoningNon-TimberTree          -0.410133    0.616373 -0.6654 0.5057966
11:ZoningNon-TimberTree          0.571435    0.590420  0.9678 0.3331216
13:ZoningNon-TimberTree         -0.431494    0.574356 -0.7513 0.4524935
17:ZoningNon-TimberTree         -0.263862    0.684889 -0.3853 0.7000432
5:ZoningProtectedArea            0.787390    0.476232  1.6534 0.0982546 .
7:ZoningProtectedArea           -0.852468    0.527995 -1.6145 0.1064104
9:ZoningProtectedArea           -1.232374    0.292758 -4.2095 2.559e-05 ***
11:ZoningProtectedArea          -1.847716    0.596212 -3.0991 0.0019411 **
13:ZoningProtectedArea          -1.256878    0.279753 -4.4928 7.029e-06 ***
17:ZoningProtectedArea          -1.073392    0.522414 -2.0547 0.0399103 *
5:NUTRIENT_AVAILABexcellent    -19.878886 4246.850286 -0.0047 0.9962652
7:NUTRIENT_AVAILABexcellent    -19.211900 3992.293737 -0.0048 0.9961604
9:NUTRIENT_AVAILABexcellent     -1.248569    0.298418 -4.1840 2.865e-05 ***
11:NUTRIENT_AVAILABexcellent    -3.251087    0.570030 -5.7034 1.175e-08 ***
13:NUTRIENT_AVAILABexcellent    -1.391977    0.288419 -4.8262 1.391e-06 ***
17:NUTRIENT_AVAILABexcellent    -2.506877    0.606625 -4.1325 3.588e-05 ***
5:NUTRIENT_AVAILABaverage       -2.732259    0.426178 -6.4111 1.445e-10 ***
7:NUTRIENT_AVAILABaverage       -2.042734    0.353066 -5.7857 7.221e-09 ***
9:NUTRIENT_AVAILABaverage       -1.515833    0.207168 -7.3169 2.538e-13 ***
11:NUTRIENT_AVAILABaverage      -2.551074    0.276015 -9.2425 < 2.2e-16 ***
13:NUTRIENT_AVAILABaverage      -1.507128    0.197064 -7.6479 2.043e-14 ***
17:NUTRIENT_AVAILABaverage      -2.923653    0.385139 -7.5912 3.175e-14 ***
1:returns                       11.384228    2.151047  5.2924 1.207e-07 ***
5:returns                        3.054069    3.551016  0.8601 0.3897587
7:returns                        2.332940    1.878930  1.2416 0.2143722
9:returns                       -1.041640    1.203486 -0.8655 0.3867538
11:returns                       0.234338    0.096671  2.4241 0.0153472 *
13:returns                       0.403723    0.088030  4.5862 4.514e-06 ***
17:returns                       0.541546    0.158902  3.4081 0.0006543 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Log-Likelihood: -3013.8
McFadden R^2:  0.72677
Likelihood ratio test : chisq = 16033 (p.value = < 2.22e-16)
```

Table S1. Crosswalk used to revise original classification of the 2006 and 2009 MoF LULC data.

Original LULC Description (Indonesian)	Original LULC Description	Modified LULC Description	LULC Code	Final Crosswalk LULC Description
Hutan lahan kering primer	Primary dryland forest	Primary dryland forest	1	Forest, mineral soils
Hutan primer	Primary forests	Primary dryland forest	1	Forest, mineral soils
Hutan lahan kering sekunder	Secondary dryland forest	Secondary dryland forest	1	Forest, mineral soils
Hutan sekunder	Secondary Forest	Secondary Dryland Forest	1	Forest, mineral soils
Hutan mangrove primer	Primary mangrove forest	Primary mangrove forest	1	Forest, mineral soils
Hutan mangrove sekunder	Secondary mangrove forest	Secondary mangrove forest	1	Forest, mineral soils
Hutan rawa primer	Primary swamp forest	Primary swamp forest	2	Forest, peat soils
Hutan rawa sekunder	Secondary swamp forest	Secondary swamp forest	2	Forest, peat soils
Rawa	Swamp	Swamp	3	Degraded land, peat soils
Semak belukar/rawa	Shrub / marsh	Scrub /bush / swamp	3	Degraded land, peat soils
Belukar rawa	Shrub / swamp	Scrub / bush / swamp	3	Degraded land, peat soils
Savana	Savanna	Savanna	4	Degraded land, mineral soils
Semak/belukar	Bush / shrub	Bush / scrub	4	Degraded land, mineral soils
Hutan tanaman	Forest plants	Timber Plantation	5	Plantation
Perkebunan	Plantation	Non-timber Crop Plantation	5	Plantation
Pertanian campur semak	Farming Mixed bush	Non-rice agriculture mixed bush	6	Agriculture
Pertanian campuran	Mixed farming	Non-rice agriculture mixed bush	6	Agriculture
Pertanian Lahan Kering and Sema	Dryland Agriculture and mixed bush	Non-rice agriculture mixed bush	6	Agriculture
Pertanian lahan kering	Dryland farming	Non-rice agriculture	6	Agriculture
Sawah	Paddy field	Rice agriculture	6	Agriculture
Transmigrasi	Transmigration	Urban	16	Urban
Pemukiman	Settlement	Urban	16	Urban
Bandara	Airport	Urban	16	Other
Tanah terbuka	Clearing	Clearing	7	Clearing (Plantation)
Tambak	Embankment	Other	20	Other
Tambang	Mine	Other	20	Other

Table S2. Land management assumptions associated with each LULC type (*Personal communication B. Arunarwati, Indonesia Ministry of Forests)*.

LULC Description	LULC Code	Notes
Primary dryland forest	1	5% of area in timber and tree crop plantation
Secondary dryland forest	2	5% of area in timber and tree crop plantation
Primary mangrove forest	3	5% of area in timber and tree crop plantation
Secondary mangrove forest	3	5% of area in timber and tree crop plantation
Primary swamp forest	5	5% of area in timber and tree crop plantation
Secondary swamp forest	6	5% of area in timber and tree crop plantation
Swamp	7	5% of area in tree crop plantation
Swamp	7	5% of area in tree crop plantation
Savanna and bush scrub	9	5% of area in tree crop plantation
Savanna and bush scrub	9	5% of area in tree crop plantation
Timber plantation (monoculture)	11	50% of area in 30-yr rotational logging of saw wood and 50% in timber pulp plantation
Non-timber Crop Plantation (monoculture)	12	Weighted area average of the top 5 tree crops by province
Non-rice agriculture mixed bush (agroforestry)	13	50% of area in non-rice agriculture and 50% in tree crop plantation (agroforestry)
Non-rice agriculture	14	Weighted area average mix of top 5 non-rice crops by province
Rice agriculture	15	Irrigated rice paddy
Urban	16	Excluded from analysis
Clearing	17	50% of area rotational logging and 50% of area in monoculture tree crop plantation
Other	20	Excluded from analysis

Table S3. Final estimated annualized gross returns by LULC and Province.

Province	LULC Description	LULC Code	Average annual gross returns per ha (2006$)
Aceh	Primary dryland forest	1	32.35
Aceh	Secondary dryland forest	2	32.35
Aceh	Primary mangrove forest	3	32.35
Aceh	Secondary mangrove forest	3	32.35
Aceh	Primary swamp forest	5	32.35
Aceh	Secondary swamp forest	6	32.35
Aceh	Swamp	7	29.14
Aceh	Swamp	7	29.14
Aceh	Savanna and bush scrub	9	29.14
Aceh	Savanna and bush scrub	9	29.14
Aceh	Timber plantation	11	711.27
Aceh	Tree crop plantation	12	582.88
Aceh	Non-rice agriculture mixed bush	13	536.10
Aceh	Non-rice agriculture	14	566.68
Aceh	Rice agriculture	15	889.59
Aceh	Urban	16	n/a
Aceh	Clearing	17	647.08
Aceh	Other	20	n/a
Bengkulu	Primary dryland forest	1	29.01
Bengkulu	Secondary dryland forest	2	29.01
Bengkulu	Primary mangrove forest	3	29.01
Bengkulu	Secondary mangrove forest	3	29.01
Bengkulu	Primary swamp forest	5	29.01
Bengkulu	Secondary swamp forest	6	29.01
Bengkulu	Swamp	7	37.13
Bengkulu	Swamp	7	37.13
Bengkulu	Savanna and bush scrub	9	37.13
Bengkulu	Savanna and bush scrub	9	37.13
Bengkulu	Timber plantation	11	417.73
Bengkulu	Tree crop plantation	12	742.68
Bengkulu	Non-rice agriculture mixed bush	13	591.89
Bengkulu	Non-rice agriculture	14	557.63
Bengkulu	Rice agriculture	15	775.16
Bengkulu	Urban	16	n/a
Bengkulu	Clearing	17	580.21
Bengkulu	Other	20	n/a
Jambi	Primary dryland forest	1	34.92
Jambi	Secondary dryland forest	2	34.92
Jambi	Primary mangrove forest	3	34.92
Jambi	Secondary mangrove forest	3	34.92
Jambi	Primary swamp forest	5	34.92
Jambi	Secondary swamp forest	6	34.92
Jambi	Swamp	7	35.61

Province	LULC Description	LULC Code	Average annual gross returns per ha (2006$)
Jambi	Swamp	7	35.61
Jambi	Savanna and bush scrub	9	35.61
Jambi	Savanna and bush scrub	9	35.61
Jambi	Timber plantation	11	684.45
Jambi	Tree crop plantation	12	712.16
Jambi	Non-rice agriculture mixed bush	13	630.72
Jambi	Non-rice agriculture	14	694.92
Jambi	Rice agriculture	15	801.24
Jambi	Urban	16	n/a
Jambi	Clearing	17	697.81
Jambi	Other	20	n/a
Lampung	Primary dryland forest	1	25.02
Lampung	Secondary dryland forest	2	25.02
Lampung	Primary mangrove forest	3	25.02
Lampung	Secondary mangrove forest	3	25.02
Lampung	Primary swamp forest	5	25.02
Lampung	Secondary swamp forest	6	25.02
Lampung	Swamp	7	21.25
Lampung	Swamp	7	32.50
Lampung	Savanna and bush scrub	9	44.55
Lampung	Savanna and bush scrub	9	45.35
Lampung	Timber plantation	11	575.68
Lampung	Tree crop plantation	12	425.09
Lampung	Non-rice agriculture mixed bush	13	650.03
Lampung	Non-rice agriculture	14	890.91
Lampung	Rice agriculture	15	906.93
Lampung	Urban	16	n/a
Lampung	Clearing	17	500.39
Lampung	Other	20	n/a
Riau	Primary dryland forest	1	38.55
Riau	Secondary dryland forest	2	38.55
Riau	Primary mangrove forest	3	38.55
Riau	Secondary mangrove forest	3	38.55
Riau	Primary swamp forest	5	38.55
Riau	Secondary swamp forest	6	38.55
Riau	Swamp	7	34.08
Riau	Swamp	7	34.08
Riau	Savanna and bush scrub	9	34.08
Riau	Savanna and bush scrub	9	34.08
Riau	Timber plantation	11	860.41
Riau	Tree crop plantation	12	681.66
Riau	Non-rice agriculture mixed bush	13	602.32
Riau	Non-rice agriculture	14	605.52
Riau	Rice agriculture	15	667.65

Province	LULC Description	LULC Code	Average annual gross returns per ha (2006$)
Riau	Urban	16	n/a
Riau	Clearing	17	771.04
Riau	Other	20	n/a
Sumbar Barat	Primary dryland forest	1	40.37
Sumbar Barat	Secondary dryland forest	2	40.367
Sumbar Barat	Primary mangrove forest	3	40.37
Sumbar Barat	Secondary mangrove forest	3	40.37
Sumbar Barat	Primary swamp forest	5	40.37
Sumbar Barat	Secondary swamp forest	6	40.37
Sumbar Barat	Swamp	7	35.65
Sumbar Barat	Swamp	7	35.65
Sumbar Barat	Savanna and bush scrub	9	35.65
Sumbar Barat	Savanna and bush scrub	9	35.65
Sumbar Barat	Timber plantation	11	901.79
Sumbar Barat	Tree crop plantation	12	712.98
Sumbar Barat	Non-rice agriculture mixed bush	13	693.67
Sumbar Barat	Non-rice agriculture	14	786.72
Sumbar Barat	Rice agriculture	15	950.37
Sumbar Barat	Urban	16	n/a
Sumbar barat	Clearing	17	807.39
Sumbar Barat	Other	20	n/a
Sumsel Selatan	Primary dryland forest	1	35.76
Sumsel Selatan	Secondary dryland forest	2	35.76
Sumsel Selatan	Primary mangrove forest	3	35.76
Sumsel Selatan	Secondary mangrove forest	3	35.76
Sumsel Selatan	Primary swamp forest	5	35.76
Sumsel Selatan	Secondary swamp forest	6	35.76
Sumsel Selatan	Swamp	7	42.74
Sumsel Selatan	Swamp	7	42.74
Sumsel Selatan	Savanna and bush scrub	9	42.74
Sumsel Selatan	Savanna and bush scrub	9	42.74
Sumsel Selatan	Timber plantation	11	575.60
Sumsel Selatan	Tree crop plantation	12	854.74
Sumsel Selatan	Non-rice agriculture mixed bush	13	659.34
Sumsel Selatan	Non-rice agriculture	14	648.44
Sumsel Selatan	Rice agriculture	15	787.59
Sumsel Selatan	Urban	16	n/a
Sumsel Selatan	Clearing	17	715.17
Sumsel Selatan	Other	20	n/a
Sumut Utara	Primary dryland forest	1	37.83
Sumut Utara	Secondary dryland forest	2	37.83
Sumut Utara	Primary mangrove forest	3	37.83
Sumut Utara	Secondary mangrove forest	3	37.83
Sumut Utara	Primary swamp forest	5	37.83

Province	LULC Description	LULC Code	Average annual gross returns per ha (2006$)
Sumut Utara	Secondary swamp forest	6	37.83
Sumut Utara	Swamp	7	32.97
Sumut Utara	Swamp	7	32.97
Sumut Utara	Savanna and bush scrub	9	32.97
Sumut Utara	Savanna and bush scrub	9	32.97
Sumut Utara	Timber plantation	11	838.01
Sumut Utara	Tree crop plantation	12	675.07
Sumut Utara	Non-rice agriculture mixed bush	13	584.69
Sumut Utara	Non-rice agriculture	14	610.95
Sumut Utara	Rice agriculture	15	892.18
Sumut Utara	Urban	16	n/a
Sumut Utara	Clearing	17	753.04
Sumut Utara	Other	20	n/a

Table S4. Land management assumptions used for logging, timber, and non-timber perennial plantations

Land Use	Rotation	Citation
Oil palm	Monoculture: 25-yr rotation and 1-yr establishment time	Sofiyuddin et al. 2012
	Agroforestry: Yields 10% less than monoculture; 25-yr rotation and 2-yr establishment time	Sofiyuddin et al. 2012
Rubber	Monoculture: 30-yr rotation and 6-yr establishment time	Sofiyuddin et al. 2012
	Agroforestry: Yields 33% less than monoculture; 40-yr rotation and 9-yr establishment time	Leimona and Joshi 2010
Coconut	Monoculture and agroforestry: 40-yr rotation and 5-yr establishment time	Sofiyuddin 2012; FAO 2013
Coconut palace	Monoculture and agroforestry: 40-yr rotation and 5-yr establishment time	Sofiyuddin 2012; FAO 2013 - http://www.fao.org/docrep/004/ac126e/ac126e04.htm
Coffee	Monoculture and agroforestry: 25-yr rotation and 2-yr establishment time	http://www.worldagroforestry.org/SEA/Publications/files/workingpaper/WP0034-04.PDF
Pulp	Monoculture: 7-yr rotation	Manturana 2005
Timber	35-yr rotation (annual production = 1/35 of total ha)	Manturana 2005; Repetto, R., Gillis, M., 1988.

Table S5. Non-agriculture site characteristics used as explanatory variables in the land use change model.

Variable code	Description	Citation
PARCEL_ID	Unique 1 km2 grid cell	n/a
PROVINCE_NAM	Sumatra Province name	Minnemeyer et al. 2009.
PROVINCE_NUM	Province unique number	Minnemeyer et al. 2009.
LULC_06	2006 LULC class	MoF 2007
LULC_09	2009 LULC class	MoF 2010
EXCESS_SALTS	Soil salinity, soil sodicity and soil phases influencing salt conditions	Fischer et al. 2008
WORKABILITY	Soil texture, effective soil depth/volume, and soil phases constraining soil management (soil depth, rock outcrop, stoniness, gravel/concretions and hardpans)	Fischer et al. 2008
TOXICITY	Calcium carbonate and gypsum	Fischer et al. 2008
ROOTING_COND	Soil textures, bulk density, coarse fragments, vertic soil properties and soil phases affecting root penetration and soil depth and soil volume	Fischer et al. 2008
OXYGEN_AVAIL	Soil drainage and soil phases affecting soil drainage	Fischer et al. 2008
NUTRTIENT_RETENT	Soil Organic carbon, Soil texture, base saturation, cation exchange capacity of soil and of clay fraction	Fischer et al. 2008
NUTRIENT_AVAIL	Soil texture, soil organic carbon, soil pH, total exchangeable bases	Fischer et al. 2008
TEMP	Annual Mean Temp C	Kriticos et al. 2012
PPT	Annual Mean PPT	Kriticos et al. 2012
PEAT_SOIL	Peat soil (1 = yes; 0 = no)	Sekala (a local non-profit organization), from 3 atlases of peat land distribution in Sumatra, Kalimantan, and Papua (Wetlands International - Indonesia Program & Wildlife Habitat Canada, 2003, 2004, and 2001). Maps are available digitally online at <http://www.wetlands.or.id/publications_maps.php>.
CAPITAL_DIST	Distance in meters from national and the provincial capitals of Indonesia.	A subset of the world cities dataset produced by Environmental Systems Research Institute, Inc. (ESRI), in 2000. Refer to the ESRI metatadata file provided as an HTML file along with this data. The original data is provided by ESRI on the Maps & Data DVD provided with ArcGIS software. This dataset was prepared by the World Resources Institute for use in the

Variable code	Description	Citation
		Interactive Atlas of Indonesia's Forests (Minnemeyer et al. 2009)
URBAN_06_DIST	Distance from "urban" LULC class 16 in 2006 MoF LULC map	Derived from MoF 2007 and 2010.
MC_DIST	Distance in meters from main cities of Indonesia.	A subset of the Gridded Population of the World (GPW), Global Rural-Urban Mapping Project (GRUMP), Alpha version of version 1: settlement points. This data also provides with population counts of the settlements points for 2000, 1995, 1990.) The original GRUMP data was produced by the Socioeconomic Applications and Data Center (SEDAC) of CIESIN at Columbia University. This dataset was prepared by Minnemeyer et al. 2009.
COAST_DIST	Distance in meters from the coast	
ROAD_DIST	Distance in meters from roads circa 2003	It comes from the basemaps of Indonesia, developed by Bakosurtanal. The time period corresponds to the 2003 situation of roads including logging roads. This dataset was prepared by Minnemeyer et al. 2009.
RIVER_DIST	Distance in meters from major river	Derived from Hydrosheds (Lehner et al. 2009).
PA	In a national, Provincial, District and other protected areas	Derived from the World Database on Protected Areas: http://www.wdpa.org/Default.aspx
PA_DIST	Distance from national, Provincial, District and other protected areas	Derived from the World Database on Protected Areas: http://www.wdpa.org/Default.aspx
FOREST_A_05	Land allocation corresponds to one of the five major land-use categories: 1) non-forest areas, 2) production, 3) protection, 4) conservation, and 5) conversion.	This data was prepared by Minnemeyer et al. 2009, by combining two land allocation zoning databases : Penunjukan and Penunandt TGHK, both produced by the Ministry of Forestry of Indonesia. Fields description: <Penunjukan>: Allocation type given by Penunjukan data (In Bahasa) <PENUN_EN> : Allocation type given by Penunjukan data (In English) <PEN_TGHK>: Allocation type given by PenunandtTGHK data (In English) <Allocation>: : Allocation type given by the World Resources Institute (In English), which corresponds to one the 5 categories (conservation, protection, conversion, Non-forest land, Production).
LOG_C_05_DIST	Distance in meters from logging concessions (HPH - Hak Penebangan Hutan) in Indonesia, in 2005.	HPH licences are valid for 20 years but the rotation cutting cycle is 35 years. This data provides the name of the concession holder/group and the permit type title. HPH or IUPHHK-HA is a permit delivered by the Minister of Forestry. HPH are part of the

Variable code	Description	Citation
		production forest zone. The dataset was produced by MoF and prepared by Minnemeyer et al. 2009.
TIM_C_05_DIST	Distance in meters from boundaries of industrial forest timber plantations (HTI - Hutan Tanaman Industri) in Indonesia, in 2005.	This data provides the name of the concession holder/group, and the permit type title. HTI or IUPHHK-HT is a permit delivered by the Minister of Forestry which details land, seeding, planting, protecting, harvesting and marketing. HTI are held by a private company or local communities, as a way to increase production, forest potential, and quality within silviculture system. The dataset was produced by MoF and prepared by Minnemeyer et al. 2009.
T_CROP_C_05_DIST	Distance in meters from boundaries of non-timber tree crop plantations (Kebun), in Indonesia, in 2006.	A tree crop plantation is a permit outside the forest sector with changing allocation forest area. This data provides the name of tree crop plantation holder/group and the permit type title. This dataset was produced by the Minsitry of Forestry and prepared by WRI for use in the Interactive Atlas of Indonesia's Forests (2009).
TIM_C_05	In an industrial forest timber plantations (HTI - Hutan Tanaman Industri) in 2005.	This data provides the name of the concession holder/group, and the permit type title. HTI or IUPHHK-HT is a permit delivered by the Minister of Forestry which details land, seeding, planting, protecting, harvesting and marketing. HTI are held by a private company or local communities, as a way to increase production, forest potential, and quality within silviculture system. The dataset was produced by MoF and prepared by Minnemeyer et al. 2009.
LOG_C_05	In a logging concessions (HPH - Hak Penebangan Hutan) in 2005.	HPH licenses are valid for 20 years but the rotation cutting cycle is 35 years. This data provides the name of the concession holder/group and the permit type title. HPH or IUPHHK-HA is a permit delivered by the Minister of Forestry. HPH are part of the production forest zone. The dataset was produced by MoF and prepared by Minnemeyer et al. 2009.
T_CROP_CON_05	In a non-timber tree crop plantation (Kebun) in 2006.	A tree crop plantation is a permit outside the forest sector with changing allocation forest area. This data provides the name of tree crop plantation holder/group and the permit type title. The dataset was produced by MoF and

Variable code	Description	Citation
		prepared by Minnemeyer et al. 2009.

Table S6. Summary annual area, price, and yield data for non-timber agriculture by province and by year for 2004

Province	Commodity	Price US$ (2006$)	Area weight	Yield Tons/ HA	Gross return - weighted US2006$/HA	Monoculture: Annualized Gross return - weighted US2006$/HA	Agroforestry: Annualized Gross return - weighted US2006$/HA
Aceh	Corn	163	45%	3.0	223	…	…
Aceh	Soybean	418	43%	1.3	229	…	…
Aceh	Cassava	80	8%	12.3	80	…	…
Aceh	Sweet potato	114	4%	9.8	46	…	…
Aceh	**Total non-rice crop**				**577**		
Aceh	Oil palm	464	37%	2.5	428	348	324
Aceh	Rubber	1392	17%	0.7	170	99	67
Aceh	Coconut	58	17%	0.7	7	5	5
Aceh	Coconut palace	58	16%	0.7	7	4	4
Aceh	Coffee	690	14%	0.6	58	44	44
Aceh	**Total plantation**					**500**	**444**
Aceh	Rice	188	100%	4.2	**786**		
Bengkulu	Corn	163	62%	2.5	254	…	…
Bengkulu	Cassava	80	16%	11.7	150	…	…
Bengkulu	Sweet potato	114	12%	9.5	125	…	…
Bengkulu	Soybean	418	10%	0.9	40	…	…
Bengkulu	**Total non-rice crop**				**569**		
Bengkulu	Oil palm	464	37%	2.7	457	372	345
Bengkulu	Coffee	690	36%	0.7	185	140	140
Bengkulu	Rubber	1392	21%	0.8	234	136	79
Bengkulu	Cocoa	1162	3%	1.0	40	30	30
Bengkulu	Pepper	1956	3%	0.6	32	32	32
Bengkulu	**Total plantation**					**709**	**626**
Bengkulu	Rice	188	100%	3.7	**703**		
Jambi	Corn	163	50%	3.2	260	…	…
Jambi	Cassava	80	20%	12.5	205	…	…
Jambi	Sweet potato	114	19%	8.4	180	…	…
Jambi	Soybean	418	10%	1.4	61	…	…
Jambi	**Total non-rice crop**				**706**		
Jambi	Rubber	1392	39%	0.7	388	226	132
Jambi	Oil palm	464	33%	3.0	461	375	349
Jambi	Coconut	58	12%	1.4	9	6	6
Jambi	Coconut palace	58	11%	1.4	9	6	6
Jambi	Cinnamon	3469	5%	1.7	296	27	27
Jambi	**TOTAL**					**640**	**519**
Jambi	Rice	188	100%	3.7	**694**		
Lampung	Corn	163	57%	3.3	311	…	…

Province	Commodity	Price US$ (2006$)	Area weight	Yield Tons/ HA	Gross return - weighted US2006$/HA	Monoculture: Annualized Gross return - weighted US2006$/HA	Agroforestry: Annualized Gross return - weighted US2006$/HA
Lampung	Cassava	80	41%	17.5	583	…	…
Lampung	Soybean	418	1%	1.0	4	…	…
Lampung	Sweet potato	114	1%	9.7	8	…	…
Lampung	**Total non-rice crop**				**906**		
Lampung	Coffee	690	24%	1.0	166	125	125
Lampung	Coconut	58	22%	1.0	13	8	8
Lampung	Oil palm	464	21%	2.6	258	216	201
Lampung	Coconut palace	58	19%	1.0	11	7	7
Lampung	Sugar cane	58	14%	7.4	60	56	56
Lampung	**Total plantation**					**413**	**398**
Lampung	Rice	188	100%	4.2	**793**		
Riau	Corn	163	54%	3.2	278	…	…
Riau	Cassava	80	26%	10.8	227	…	…
Riau	Soybean	418	11%	1.0	47	…	…
Riau	Sweet potato	114	9%	7.8	80	…	…
Riau	**Total non-rice crop**				**632**		
Riau	Oil palm	464	48%	2.6	576	469	435
Riau	Coconut	58	20%	1.3	15	10	10
Riau	Coconut palace	58	17%	1.3	13	8	8
Riau	Rubber	1392	13%	0.8	149	87	51
Riau	Hybrid coconut	58	2%	1.3	2	1	1
Riau	**Total plantation**					**575**	**505**
Riau	Rice	188	100%	3.1	**588**		
Sumbar Barat	Corn	163	70%	3.6	416	…	…
Sumbar Barat	Cassava	80	18%	14.1	203	…	…
Sumbar Barat	Sweet potato	114	10%	12.5	136	…	…
Sumbar Barat	Soybean	418	3%	1.3	14	…	…
Sumbar Barat	**Total non-rice crop**				**768**		
Sumbar Barat	Oil palm	464	45%	3.1	647	527	489
Sumbar Barat	Rubber	1392	17%	0.8	193	112	65
Sumbar Barat	Coconut palace	58	14%	1.1	9	6	6
Sumbar Barat	Coconut	58	14%	1.1	9	6	6
Sumbar Barat	Cinnamon	3469	9%	1.0	320	27	27
Sumbar Barat	**Total plantation**					**678**	**593**
Sumbar Barat	Rice	188	100%	4.4	**834**		
Sumsel Selatan	Corn	163	47%	2.7	209	…	…
Sumsel Selatan	Cassava	80	39%	12.5	394	…	…
Sumsel Selatan	Soybean	418	7%	1.3	38	…	…
Sumsel Selatan	Sweet potato	114	7%	6.4	51	…	…

Province	Commodity	Price US$ (2006$)	Area weight	Yield Tons/ HA	Gross return - weighted US2006$/HA	Monoculture: Annualized Gross return - weighted US2006$/HA	Agroforestry: Annualized Gross return - weighted US2006$/HA
Sumsel Selatan	**Total non-rice crop**				**693**		
Sumsel Selatan	Rubber	1392	42%	0.8	491	286	166
Sumsel Selatan	Oil palm	464	33%	3.8	573	466	433
Sumsel Selatan	Coffee	690	18%	0.6	72	54	54
Sumsel Selatan	Coconut	58	4%	0.7	1	1	1
Sumsel Selatan	Coconut palace	58	3%	0.7	1	1	1
Sumsel Selatan	**Total plantation**					**808**	**656**
Sumsel Selatan	Rice	188	100%	3.6	**680**		
Sumut Utara	Corn	163	78%	3.3	421	…	…
Sumut Utara	Cassava	80	14%	12.5	136	…	…
Sumut Utara	Sweet potato	114	4%	9.6	48	…	…
Sumut Utara	Soybean	418	4%	1.1	19	…	…
Sumut Utara	**Total non-rice crop**				**625**		
Sumut Utara	Oil palm	464	52%	3.6	862	701	651
Sumut Utara	Rubber	1392	27%	1.0	366	213	124
Sumut Utara	Coconut palace	58	8%	1.0	5	3	3
Sumut Utara	Coconut	58	8%	1.0	5	3	3
Sumut Utara	Coffee	690	5%	0.9	28	21	21
Sumut Utara	**Total plantation**					**941**	**802**
Sumut Utara	Rice	188	100%	4.1	**778**		

Table S7. Summary annual area, price, and yield data for non-timber agriculture by province and by year for 2005

Province	Commodity	Price US$ (2006$)	Area weight	Yield Tons/HA	Gross return - weighted US2006$/HA	Monoculture: Annualized Gross return - weighted US2006$/HA	Agroforestry: Annualized Gross return - weighted US2006$/HA
Aceh	Corn	134	49%	3.2	210	…	…
Aceh	Soybean	389	40%	1.3	214	…	…
Aceh	Cassava	81	7%	12.4	74	…	…
Aceh	Sweet potato	107	4%	9.9	43	…	…
Aceh	**Total non-rice crop**				**555**		
Aceh	Oil palm	356	37%	2.5	356	300	279
Aceh	Rubber	1455	17%	0.7	192	116	67
Aceh	Coconut	103	16%	0.7	13	9	9

Province	Commodity	Price US$ (2006$)	Area weight	Yield Tons/HA	Gross return - weighted US2006$/HA	Monoculture: Annualized Gross return - weighted US2006$/HA	Agroforestry: Annualized Gross return - weighted US2006$/HA
Aceh	Coconut palace	103	16%	0.7	13	9	9
Aceh	Coffee	638	15%	0.6	61	48	48
Aceh	**Total plantation**					**481**	**411**
Aceh	Rice	204	100%	4.2	**907**		
Bengkulu	Corn	134	69%	2.6	258	…	…
Bengkulu	Cassava	81	15%	11.7	148	…	…
Bengkulu	Sweet potato	107	10%	9.5	113	…	…
Bengkulu	Soybean	389	6%	0.9	23	…	…
Bengkulu	**Total non-rice crop**				**542**		
Bengkulu	Oil palm	356	37%	3.2	444	374	278
Bengkulu	Coffee	638	31%	0.7	146	101	101
Bengkulu	Rubber	1455	18%	0.8	228	122	71
Bengkulu	Cocoa	901	3%	1.0	32	27	27
Bengkulu	Pepper	2029	3%	0.5	30	25	25
Bengkulu	**Total plantation**					**649**	**503**
Bengkulu	Rice	204	100%	3.5	**755**		
Jambi	Corn	134	51%	3.3	242	…	…
Jambi	Cassava	81	18%	12.8	196	…	…
Jambi	Sweet potato	107	19%	8.5	185	…	…
Jambi	Soybean	389	13%	1.3	68	…	…
Jambi	**Total non-rice crop**				**690**		
Jambi	Rubber	1455	38%	0.7	439	265	154
Jambi	Oil palm	356	36%	2.1	281	236	220
Jambi	Coconut	103	11%	1.4	16	11	11
Jambi	Coconut palace	103	11%	1.4	16	11	11
Jambi	Cinnamon	3911	4%	1.8	329	25	25
Jambi	**TOTAL**					**548**	**421**
Jambi	Rice	204	100%	3.7	**812**		
Lampung	Corn	134	61%	3.5	305	…	…
Lampung	Cassava	81	37%	19.0	612	…	…
Lampung	Soybean	389	1%	1.1	3	…	…
Lampung	Sweet potato	107	1%	9.7	8	…	…
Lampung	**Total non-rice crop**				**927**		
Lampung	Coffee	638	24%	1.0	160	121	121
Lampung	Coconut	103	21%	1.0	23	15	15
Lampung	Oil palm	356	21%	2.4	198	161	150
Lampung	Coconut palace	103	19%	1.0	21	14	14
Lampung	Sugar cane	52	15%	6.7	56	52	52

Province	Commodity	Price US$ (2006$)	Area weight	Yield Tons/HA	Gross return - weighted US2006$/HA	Monoculture: Annualized Gross return - weighted US2006$/HA	Agroforestry: Annualized Gross return - weighted US2006$/HA
Lampung	**Total plantation**					**364**	**353**
Lampung	Rice	204	100%	4.3	**928**		
Riau	Corn	134	52%	3.3	249	…	…
Riau	Cassava	81	23%	10.7	211	…	…
Riau	Soybean	389	17%	1.0	71	…	…
Riau	Sweet potato	107	8%	7.9	73	…	…
Riau	**Total non-rice crop**	0			**604**		
Riau	Oil palm	356	47%	2.5	435	366	354
Riau	Coconut	103	20%	1.4	30	20	20
Riau	Coconut palace	103	17%	1.3	25	13	13
Riau	Rubber	1455	13%	0.9	181	109	64
Riau	Hybrid coconut	103	3%	1.7	5	3	3
Riau	**Total plantation**					**512**	**454**
Riau	Rice	204	100%	3.2	**685**		
Sumbar Barat	Corn	134	75%	4.0	422	…	…
Sumbar Barat	Cassava	81	14%	15.1	185	…	…
Sumbar Barat	Sweet potato	107	8%	11.8	108	…	…
Sumbar Barat	Soybean	389	3%	1.3	16	…	…
Sumbar Barat	**Total non-rice crop**	0			**730**		
Sumbar Barat	Oil palm	356	45%	2.8	489	411	382
Sumbar Barat	Rubber	1455	16%	0.9	218	131	76
Sumbar Barat	Coconut palace	103	15%	1.1	17	11	11
Sumbar Barat	Coconut	103	15%	1.1	17	11	11
Sumbar Barat	Cinnamon	3911	9%	0.9	341	28	2
Sumbar Barat	**Total plantation**					**593**	**483**
Sumbar Barat	Rice	204	100%	4.5	**969**		
Sumsel Selatan	Corn	134	55%	2.8	220	…	…
Sumsel Selatan	Cassava	81	30%	12.5	317	…	…

Province	Commodity	Price US$ (2006$)	Area weight	Yield Tons/HA	Gross return - weighted US2006$/HA	Monoculture: Annualized Gross return - weighted US2006$/HA	Agroforestry: Annualized Gross return - weighted US2006$/HA
Sumsel Selatan	Soybean	389	8%	1.4	44	…	…
Sumsel Selatan	Sweet potato	107	8%	6.5	57	…	…
Sumsel Selatan	**Total non-rice crop**	0			**638**		
Sumsel Selatan	Rubber	1455	41%	0.9	557	336	195
Sumsel Selatan	Oil palm	356	34%	3.2	418	351	327
Sumsel Selatan	Coffee	638	17%	0.6	66	52	52
Sumsel Selatan	Coconut	103	4%	0.7	3	2	2
Sumsel Selatan	Coconut palace	103	4%	0.7	3	2	2
Sumsel Selatan	**Total plantation**					**744**	**578**
Sumsel Selatan	Rice	204	100%	3.7	**803**		
Sumut Utara	Corn	134	77%	3.4	371	…	…
Sumut Utara	Cassava	81	14%	12.5	146	…	…
Sumut Utara	Sweet potato	107	4%	9.6	47	…	…
Sumut Utara	Soybean	389	5%	1.1	23	…	…
Sumut Utara	**Total non-rice crop**	0			**586**		
Sumut Utara	Oil palm	356	54%	3.4	698	587	546
Sumut Utara	Rubber	1455	27%	1.0	419	252	147
Sumut Utara	Coconut palace	103	8%	0.9	8	5	5
Sumut Utara	Coconut	103	8%	0.9	8	5	5
Sumut Utara	Coffee	638	3%	1.3	26	21	21
Sumut Utara	**Total plantation**					**871**	**724**
Sumut Utara	Rice	204	100%	4.2	**910**		

Table S8. Summary annual area, price, and yield data for non-timber agriculture by province and by year for 2006

Province	Commodity	Price ha US$	Area weight	Tons/HA	Gross return - weighted US2006$/HA	Monoculture: Annualized Gross return - weighted US2006$/HA	Agroforestry: Annualized Gross return - weighted US2006$/HA
Aceh	Corn	164	54%	3.3	291	…	…
Aceh	Soybean	407	36%	1.3	190	…	…
Aceh	Cassava	59	7%	12.4	50	…	…

Province	**Commodity**	**Price ha US$**	**Area weight**	**Tons/HA**	**Gross return - weighted US2006$/HA**	**Monoculture: Annualized Gross return - weighted US2006$/HA**	**Agroforestry: Annualized Gross return - weighted US2006$/HA**
Aceh	Sweet potato	125	3%	9.8	37	…	…
Aceh	**Total non-rice crop**				568		
Aceh	Oil palm	417	41%	3.2	551	478	445
Aceh	Rubber	2107	16%	0.8	279	174	101
Aceh	Coconut	125	15%	0.8	14	10	10
Aceh	Coconut palace	125	14%	0.8	14	10	10
Aceh	Coffee	858	14%	0.7	80	96	96
Aceh	**Total plantation**					768	662
Aceh	Rice	232	100%	4.2	**976**		
Bengkulu	Corn	164	66%	2.6	280	…	…
Bengkulu	Cassava	59	20%	11.6	138	…	…
Bengkulu	Sweet potato	125	11%	9.5	133	…	…
Bengkulu	Soybean	407	3%	0.9	11	…	…
Bengkulu	**Total non-rice crop**				**562**		
Bengkulu	Oil palm	417	40%	3.3	543	471	438
Bengkulu	Coffee	858	29%	0.7	173	140	140
Bengkulu	Rubber	2107	17%	0.9	334	208	121
Bengkulu	Cocoa	970	3%	0.8	26	23	23
Bengkulu	Pepper	2523	2%	0.6	33	29	29
Bengkulu	**Total plantation**					**870**	**750**
Bengkulu	Rice	232	100%	3.7	**868**		
Jambi	Corn	164	48%	3.4	270	…	…
Jambi	Cassava	59	18%	13.0	135	…	…
Jambi	Sweet potato	125	19%	8.6	206	…	…
Jambi	Soybean	407	15%	1.3	79	…	…
Jambi	**Total non-rice crop**				**689**		
Jambi	Rubber	2107	34%	0.8	576	358	208
Jambi	Oil palm	417	44%	3.4	627	544	506
Jambi	Coconut	125	9%	1.4	16	11	11
Jambi	Coconut palace	125	9%	1.4	16	11	11
Jambi	Cinnamon	4503	4%	1.7	295	23	23
Jambi	**TOTAL**					**948**	**760**
Jambi	Rice	232	100%	3.9	**897**		
Lampung	Corn	164	53%	3.6	312	…	…
Lampung	Cassava	59	45%	19.4	517	…	…
Lampung	Soybean	407	1%	1.1	2	…	…
Lampung	Sweet potato	125	1%	9.7	9	…	…
Lampung	**Total non-rice crop**				**840**		

Province	Commodity	Price ha US$	Area weight	Tons/HA	Gross return - weighted US2006$/HA	Monoculture: Annualized Gross return - weighted US2006$/HA	Agroforestry: Annualized Gross return - weighted US2006$/HA
Lampung	Coffee	858	23%	1.0	195	158	158
Lampung	Coconut	125	21%	1.9	50	35	35
Lampung	Oil palm	417	22%	3.3	307	266	245
Lampung	Coconut palace	125	18%	1.0	24	12	12
Lampung	Sugar cane	27	15%	6.5	27	27	27
Lampung	**Total plantation**					**498**	**477**
Lampung	Rice	232	100%	4.3	**999**		
Riau	Corn	164	47%	3.4	261	…	…
Riau	Cassava	59	24%	10.8	151	…	…
Riau	Soybean	407	22%	1.1	93	…	…
Riau	Sweet potato	125	8%	7.9	76	…	…
Riau	**Total non-rice crop**				**580**		
Riau	Oil palm	417	51%	3.8	815	708	658
Riau	Coconut	125	18%	3.5	79	56	56
Riau	Coconut palace	125	16%	1.3	26	24	24
Riau	Rubber	2107	12%	1.0	269	167	97
Riau	Hybrid coconut	125	3%	1.8	6	3	3
Riau	**Total plantation**					**959**	**839**
Riau	Rice	232	100%	3.2	**731**		
Sumbar Barat	Corn	164	77%	4.7	591	…	…
Sumbar Barat	Cassava	59	14%	17.1	140	…	…
Sumbar Barat	Sweet potato	125	7%	13.0	120	…	…
Sumbar Barat	Soybean	407	2%	1.2	10	…	…
Sumbar Barat	**Total non-rice crop**				**861**		
Sumbar Barat	Oil palm	417	47%	3.4	662	575	534
Sumbar Barat	Rubber	2107	18%	1.0	394	245	142
Sumbar Barat	Coconut palace	125	13%	1.1	18	12	12
Sumbar Barat	Coconut	125	13%	1.1	18	10	10
Sumbar Barat	Cinnamon	4503	9%	0.8	324	25	25
Sumbar Barat	**Total plantation**					**868**	**725**
Sumbar Barat	Rice	232	100%	4.5	**1048**		
Sumsel Selatan	Corn	164	52%	2.9	251	…	…
Sumsel Selatan	Cassava	59	36%	13.1	277	…	…
Sumsel Selatan	Soybean	407	6%	1.4	32	…	…

Province	Commodity	Price ha US$	Area weight	Tons/HA	Gross return - weighted US2006$/HA	Monoculture: Annualized Gross return - weighted US2006$/HA	Agroforestry: Annualized Gross return - weighted US2006$/HA
Sumsel Selatan	Sweet potato	125	6%	7.0	54	…	…
Sumsel Selatan	**Total non-rice crop**				**614**		
Sumsel Selatan	Rubber	2107	38%	1.0	782	486	283
Sumsel Selatan	Oil palm	417	37%	3.4	519	451	419
Sumsel Selatan	Coffee	858	16%	0.6	83	67	67
Sumsel Selatan	Coconut	125	4%	1.8	8	6	6
Sumsel Selatan	Coconut palace	125	4%	0.8	3	2	2
Sumsel Selatan	**Total plantation**					**1012**	**777**
Sumsel Selatan	Rice	232	100%	3.8	**880**		
Sumut Utara	Corn	164	79%	3.5	454	…	…
Sumut Utara	Cassava	59	14%	12.6	105	…	…
Sumut Utara	Sweet potato	125	4%	9.7	51	…	…
Sumut Utara	Soybean	407	2%	1.2	12	…	…
Sumut Utara	**Total non-rice crop**				**622**		
Sumut Utara	Oil palm	417	55%	3.7	861	748	695
Sumut Utara	Rubber	2107	26%	1.1	576	359	209
Sumut Utara	Coconut palace	125	7%	0.9	8	6	6
Sumut Utara	Coconut	125	7%	1.9	17	12	12
Sumut Utara	Coffee	858	5%	1.0	38	30	30
Sumut Utara	**Total plantation**					**1154**	**951**
Sumut Utara	Rice	232	100%	4.3	**988**		

Table S9. Summary average annual area, price, and yield data for non-timber agriculture by province for years 2004-2006

		Avg 2004-2006	Avg 2004-2006	Avg 2004-2006
Province	**Commodity**	**Gross return - weighted US2006$/HA**	**Monoculture: Annualized Gross return - weighted US2006$/HA**	**Agroforestry: Annualized Gross return - weighted US2006$/HA**
Aceh	Corn	241	…	…
Aceh	Soybean	211	…	…
Aceh	Cassava	68	…	…
Aceh	Sweet potato	42	…	…
Aceh	**Total non-rice crop**	**567**		
Aceh	Oil palm	445	1009	937

		Avg 2004-2006	Avg 2004-2006	Avg 2004-2006
Province	**Commodity**	**Gross return - weighted US2006$/HA**	**Monoculture: Annualized Gross return - weighted US2006$/HA**	**Agroforestry: Annualized Gross return - weighted US2006$/HA**
Aceh	Rubber	214	816	474
Aceh	Coconut	11	59	59
Aceh	Coconut palace	11	59	59
Aceh	Coffee	66	382	382
Aceh	**Total plantation**		**583**	**506**
Aceh	Rice	**890**		
Bengkulu	Corn	264	…	…
Bengkulu	Cassava	145	…	…
Bengkulu	Sweet potato	124	…	…
Bengkulu	Soybean	25	…	…
Bengkulu	**Total non-rice crop**	**558**		
Bengkulu	Oil palm	481	1103	1025
Bengkulu	Coffee	168	432	432
Bengkulu	Rubber	265	904	522
Bengkulu	Cocoa	33	861	861
Bengkulu	Pepper	32	1100	1100
Bengkulu	**Total plantation**		**743**	**626**
Bengkulu	Rice	**775**		
Jambi	Corn	257	…	…
Jambi	Cassava	179	…	…
Jambi	Sweet potato	190	…	…
Jambi	Soybean	69	…	…
Jambi	**Total non-rice crop**	**695**		
Jambi	Rubber	468	800	465
Jambi	Oil palm	456	1038	964
Jambi	Coconut	14	103	103
Jambi	Coconut palace	14	105	105
Jambi	Cinnamon	307	546	546
Jambi	**TOTAL**		**712**	**567**
Jambi	Rice	**801**		
Lampung	Corn	309	…	…
Lampung	Cassava	571	…	…
Lampung	Soybean	3	…	…
Lampung	Sweet potato	8	…	…
Lampung	**Total non-rice crop**	**891**		
Lampung	Coffee	174	596	596
Lampung	Coconut	29	104	104
Lampung	Oil palm	254	1018	947
Lampung	Coconut palace	19	80	80
Lampung	Sugar cane	47	327	327
Lampung	**Total plantation**		**425**	**409**
Lampung	Rice	**907**		
Riau	Corn	263	…	…
Riau	Cassava	196	…	…
Riau	Soybean	70	…	…
Riau	Sweet potato	76	…	…

		Avg 2004-2006	Avg 2004-2006	Avg 2004-2006
Province	**Commodity**	**Gross return - weighted US2006$/HA**	**Monoculture: Annualized Gross return - weighted US2006$/HA**	**Agroforestry: Annualized Gross return - weighted US2006$/HA**
Riau	**Total non-rice crop**	**606**		
Riau	Oil palm	609	1078	1002
Riau	Coconut	41	162	162
Riau	Coconut palace	21	98	98
Riau	Rubber	200	985	573
Riau	Hybrid coconut	4	98	98
Riau	**Total plantation**		682	599
Riau	Rice	**668**		
Sumbar Barat	Corn	476	...	...
Sumbar Barat	Cassava	176	...	...
Sumbar Barat	Sweet potato	121	...	...
Sumbar Barat	Soybean	13	...	...
Sumbar Barat	**Total non-rice crop**	**787**		
Sumbar Barat	Oil palm	599	1136	1056
Sumbar Barat	Rubber	268	957	556
Sumbar Barat	Coconut palace	15	82	82
Sumbar Barat	Coconut	15	82	82
Sumbar Barat	Cinnamon	328	284	379
Sumbar Barat	**Total plantation**		**713**	**601**
Sumbar Barat	Rice	950		
Sumsel Selatan	Corn	227	...	...
Sumsel Selatan	Cassava	330	...	...
Sumsel Selatan	Soybean	38	...	...
Sumsel Selatan	Sweet potato	54	...	...
Sumsel Selatan	**Total non-rice crop**	**648**		
Sumsel Selatan	Rubber	610	951	553
Sumsel Selatan	Oil palm	503	1268	1178
Sumsel Selatan	Coffee	74	355	355
Sumsel Selatan	Coconut	4	90	90
Sumsel Selatan	Coconut palace	3	60	60
Sumsel Selatan	**Total plantation**		**855**	**670**
Sumsel Selatan	Rice	**788**		
Sumut Utara	Corn	415	...	...
Sumut Utara	Cassava	129	...	...
Sumut Utara	Sweet potato	49	...	...
Sumut Utara	Soybean	18	...	...
Sumut Utara	**Total non-rice crop**	**611**		
Sumut Utara	Oil palm	807	1302	1210
Sumut Utara	Rubber	454	1062	618
Sumut Utara	Coconut palace	7	71	71
Sumut Utara	Coconut	10	101	101
Sumut Utara	Coffee	31	626	626
Sumut Utara	**Total plantation**		**989**	**826**
Sumut Utara	Rice	**892**		

Table S10. Zoning crosswalk and designation for the Green Vision Scenario

Designation/zoning	Land use guidance	Rules to convert to the 5 2006 zoning classes
Important Ecosystem	Natural ecosystem conditions: Designated as conservation areas, protected forests, limited production forests by certification principles, eco-tourisms, and environmental service concessions.	Assign as protected area
	Degraded ecosystem conditions: Need to isolate the impacts and restore damaged environment as well as develop infrastructure for better management.	Assign protected area status
Ecosystem Network	Natural ecosystem conditions: Production forest areas by certification principles, community forests, and environmental service concessions.	Assign 2006 forest areas to one of the three working forest zoning categories (logging, timber plantation, tree crop plantation) based on the dominant 2006 zoning type by area by district.
	Degraded ecosystem conditions: Industrial timber plantation forests, to construct good infrastructure for production.	Assign 2006 "unrestricted" zoned areas to one of the three working forest zoning categories (logging, timber plantation, tree crop plantation) based on the dominant 2006 zoning type by area by district.
Development	Degraded ecosystem conditions: Convertible production forests, agricultural lands, settlement areas, industrial areas, mining areas, intensive infrastructures.	Assign as unrestricted.

Table S11. Zoning crosswalk and designation for the National Spatial Plan Scenario

Designation	Land use guidance	Rules to convert to the 5 2006 zoning classes
Hutan Produksi yang dapat dikonversi (HPK)	Production of forest that can be converted	Assign as unrestricted
Hutan lindung	Protected forest	Assign as protected area

Hutan produksi	Production forest	Keep forest area in its 2006 zoning category. Assign 2006 "unrestricted" zoned forest areas to one of the three 2006 working forest zoning categories (logging, timber plantation, tree crop plantation) based on the dominant 2006 zoning area by type and by district.
Hutan produksi terbatas	Limited production forest; Forests are allocated for timber production with low intensity. This limited production forests are generally located in the mountainous areas where steep slopes complicate logging operation.	Keep forest area in its 2006 zoning category. Assign 2006 "unrestricted" zoned forest areas to one of the three working forest zoning categories (logging, timber plantation, tree crop plantation) based on the dominant 2006 zoning area by type by district.
Kawasan budidaya	Cultivated area	Assign as unrestricted
Kawasan konservasi	Conservation area	Assign as protected area
Kawasan pertanian	Agricultural areas	Assign as unrestricted
Perkotaan	Urban	Drop
Tubuh air	Water	Drop