GIS for Land Use Planning in Liberia

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Abstract

Land use suitability modeling and optimization is a key land use planning tool for the Liberia Forest Initiative (LFI), a partnership of government, international, and non-governmental organizations dedicated to the rehabilitation and reform of Liberia's forestry sector. An iterative spatial suitability model was developed for each of three major land use categories: Commercial Forestry, Community Forestry, and Conservation. Model variables included land cover type, slope, population density, and distance from roads, settlements, and the Atlantic Ocean. The suitability results were integrated and reclassified to optimize the overall cumulative land suitability. Land use areas were delineated based on the optimal land use suitability, natural and man-made geographic features, and the value judgments of LFI stakeholder groups. The resulting optimal land use plan outlined twelve Protected Areas (approximately 1.1 million hectares, or twelve percent of Liberia's total land area), 2.7 million hectares for sustainable Commercial Forestry, and eleven Community Forests.

Background on the Liberia Forest Initiative (LFI)

Liberia is located on the Atlantic coast of West Africa, bordered by Sierra Leone, Guinea, and Cote d'Ivoire (Figure 1). Despite its small size (11 million ha), Liberia has a remarkable amount of remaining forest (4.5 million ha) (Christie, et al., in press), especially compared to other countries in West Africa. Liberian forests account for about 45% of the remaining original tropical rainforest of the Upper Guinea Forest ecosystem of West Africa, which has been reduced to less than 15% of its original size. The Upper Guinea Forest ecosystem is a Conservation International global "Biodiversity Hotspot".

Liberia's devastating recent civil war (1989-2003) destroyed much of the country's infrastructure and economy but, ironically, the conflict reduced pressure on forest loss due to a displaced population and a major reduction in industrial activities. During the war, timber revenues from illegal logging were a primary source of income fueling the conflict. In light of this, the United Nations Security Counsel in 2003 imposed sanctions on Liberian timber exports, pending major reforms of the forestry sector. The civil war ended in August 2003, and a fragile peace has provided the opportunity to rebuild Liberia's infrastructure, economy, and many aspects of Liberian society. Ellen Johnson-Sirleaf, Africa's first elected female head-of-state, was elected President of Liberia in November 2005.

Figure 1. Liberia and the Upper Guinea Forest ecosystem, West Africa (figure credit: Conservation International).

The Liberia Forest Initiative (LFI) originated in early-2004. Led by the US State Department, LFI provides coordinated support for the rehabilitation and reform of the Liberian forestry sector. LFI engaged a number of US government agencies, including the US Forest Service, US Agency for International Development (USAID), and the US Treasury Department, as well as non-governmental organizations such as Conservation International and the Environmental Law Institute. Later in 2004 and 2005, several multinational organizations, including the World Bank, the European Commission (EC), the United Nations Food and Agriculture Organization (FAO), the International Monetary Fund (IMF), and the World Conservation Union (IUCN) joined the initiative, giving the LFI partnership a strong multidisciplinary and multinational character.

The Liberia Forest Initiative (LFI) promotes and assists reforms in the Liberian forestry sector that will allow for transparent management of forest resources and ensure that these resources are used for the benefit of the Liberian people. LFI support to the Liberian forestry sector reform is organized around three main themes, the "3 C's": Commercial Forestry; Community Forestry, and Conservation. In addition, the LFI works on cross-cutting issues, such as: governance and the rule of law, transparency and information management, policy development, legislation, capacity building, and security.

In February 2006, following a comprehensive forest concession review, the new Johnson-Sirleaf government declared all existing commercial logging concessions null and void due to their failure to follow the rule of law, including widespread tax evasion and violations of human rights and environmental regulations (Rochow, et al., 2006). Based on progress toward reform in the sector, the United Nations lifted sanctions on timber exports in June 2006. The Liberian government is under extreme pressure to reestablish the forestry industry to increase government revenue and create jobs for its struggling economy. Coupled with environmental stewardship, this development need not come at the cost of the integrity of the remaining Upper Guinea forest ecosystem. The Liberian Government has a tremendous opportunity to establish a multiple-use forest management based on the suitability of forest areas, before long-term commercial timber concessions are allocated.

To these ends, the Liberian Government passed the Forestry Reform Act of 2006, a new forestry policy that has embraced multiple uses and sustainable management of its natural resources. The law requires the Liberia Forestry Development Authority (FDA) to: 1) Establish a Strategic Forest Management Plan, 2) Allocate commercial forestry contracts through competitive bidding based on the Plan, and 3) Ensure increased consultation, access and user rights for communities as a whole.

The FDA and LFI used ArcGIS modeling capabilities and input from diverse stakeholders to develop the first GIS land suitability maps of the Liberian forest endowment. By maximizing land use suitability and optimizing a balanced multiple-use forest management plan that includes input from diverse stakeholders, we hope to achieve a long-term, sustainable, and equitable land management framework that benefits all Liberian people.

Suitability Model

A spatial "weighted overlay" was used to model suitability for the three major Land Use Categories: 1) Community Forestry, 2) Commercial Forestry, and 3) Conservation (The terms "conservation", "preservation" and "protection" are equivalent and used interchangeably for the purposes of this paper. "Preservation" is used in this context for the suitability models). The modeling allows us to take into account multiple characteristics that affect the appropriateness of any given location for a specific land use, balance or rank those characteristics according to their relative importance, and ultimately calculate an overall suitability of the land for a particular land use. This can be an extremely powerful tool for examining, planning, and communicating various potential land use scenarios, but it is important to understand that the models alone cannot ultimately provide a single land use "answer". All of the results and outputs of the modeling exercise were vetted and validated through LFI partner stakeholder groups. Suitability values calculated from the model are a result of: 1) the chosen suitability criteria, 2) the quality of the source GIS and tabular data used to represent these criteria, 3) the weight given to the criteria variables, and 4) the relative rankings of multiple criteria. Considerable thought and effort, therefore, were given to defining these criteria, clarifying what they were intended to represent, and identifying the appropriate and available source data used to represent them. Sensitivity analysis was used to assess the validity of results, incrementally adjust the model outputs, game different scenarios, and identify criteria and variables that might be exerting a disproportionate influence on the output. The modeling was an iterative and interactive process with the involvement of numerous LFI experts and interest groups.

For each Land Use Category, the following process was carried out:

1) Define and quantify the various criteria or variables that make any given location more or less suitable for a particular land use category.
2) Define weights (from least to most suitable) for the quantified values, or ranges of values, for each criterion within a land use category, and reclassify the values to a normalized scale. For this model, the scale 1-5 (1 = least suitable, 5 = most suitable) has been used.
3) Rank the multiple criteria within a land use category, so that the total for all variables equals 100 percent.

For each step of the process, the variables, their weights, and their ranks become the Parameters of the model. Any or all of the parameters can be adjusted, the model can be re-run, and the outcomes reviewed. This process models *degrees* of suitability by converting and assessing all data in a raster format. This gives the model significant more flexibility over a strict "yes/no" vector model, and can be much better tuned to the nuances of continuously variable real world data. For example, the relative suitability of an area for Preservation may increase incrementally as population density decreases. In a vector model, the result can only be suitable ("yes") or unsuitable ("no"), and a finite suitability threshold (e.g. a specific distance from a populated place) must be defined. The raster model also allows us to evaluate multiple criteria simultaneously. In this model, therefore, the suitability for any particular land use is not exclusive, i.e. any given parcel of land may be suitable for more than one use. Every parcel of land, in fact, has some *degree* of suitability for *all* of the modeled land use categories. (Absolute criteria can still be applied for locations that are *always* suitable or unsuitable for a particular use. For example, National Parks are identified as *always* unsuitable for Commercial Forestry.)

All of the data review, manipulation, new data creation, analysis, and GIS modeling for this project were carried out in ESRI's ArcGIS 9.1 (ArcInfo license) with key Extensions, including Spatial Analyst and Xtools Pro. All models were built and documented using the ArcGIS Model Builder functionality.

The model variables were developed, sensitivity-tested, refined and validated with LFI partners and stakeholder groups over the period December 2005-June 2006. Early work focused on the compilation and evaluation of the available data, and preliminary development of the suitability models. We created a Model Variable Worksheet (Table 1) to summarize the criteria used in each suitability model, including all variables, their reclassification value classes, class weights, and relative ranks. This table is both a summary of all of the model parameters, and a worksheet for gaming different model scenarios. The following fields area presented in the Worksheet:

1) Category. This is the Land Use Category (Commercial, Community, or Conservation/Preservation) whose suitability is being modeled.
2) Variable. These are the specific criteria that influence the suitability of land for the particular category being modeled.

3) Relative Rank (100%): This is the relative rank or importance of each variable, relative to other variables in the model, expressed as a percent influence. The sum of all variables in the model must total 100 percent.
4) Value Classes. This field describes the quantified values and units for each specific criterion, and the value classes used in reclassifying the data to the normalized scale.
5) Weight (1-5). This field defines weights (from least to most suitable) for the quantified values, or ranges of values (value classes), for each criterion within a category, reclassified to a normalized scale. For this model, the scale 1-5 (1 = least suitable, 5 = most suitable) has been used. A value of "0" signifies that the criteria is absolute, that therefore *always* unsuitable for the particular land use.

Category	Variable	Relative Rank (100%)	Value Classes	Weight (1-5)
PRESERVATION	**Population Density**	**0%**	**POPULATION/KM^2**	
		(alternate variable)	0-10	5
			10.1-30	4
			30.1-100	3
			100.1-200	2
			200.1-1000	1
PRESERVATION	**Distance From Roads**	**8%**	**METERS**	
	(Roads Class 1-3)		0-1,000	2
			1,000-3,000	3
			3,000-5,000	4
			5,000+	5
PRESERVATION	**Distance from Edge**	**78%**	**METERS**	
	Landcover Class 3.3		0-1,000	5
	(Closed Dense Forest)		1,000-3,000	4
			3,000-5,000	3
			5,000+	2
PRESERVATION	**Proximity to Ocean**	**14%**	**METERS**	
			0-1,000	5
			1,000-3,000	4
			3,000-5,000	3
			5,000+	2
PRESERVATION	**Designated Protected Area**	**(YES)**	**DESIGNATION**	
			Protected	YES
	Total	100%		

Category	Variable	Relative Rank (100%)	Value Classes	Weight (1-5)
COMMERCIAL	**Population Density**	**20%**	**POPULATION/KM^2**	
			0-10	5
			10.1-30	5
			30.1-100	4
			100.1-200	2
			200.1-1000	1
COMMERCIAL	**Land Cover Type**	**60%**	**CLASS**	
			3.1	2
			3.2	4
			3.3	5
			Other	1
COMMERCIAL	**Distance From Roads**	**20%**	**METERS**	
	(Roads Class 1-3)		0-3000	5
			3001-8000	4
			8000+	3
COMMERCIAL	**Designated Protected Area**	**(NO)**	**DESIGNATION**	
			Protected	0
COMMERCIAL	**Slope (Gradient)**	**(NO)**	**PERCENT**	
			Above 30	0
	Total	100%		

Category	Variable	Relative Rank (100%)	Value Classes	Weight (1-5)
COMMUNITY	**Population density**	**25%**	**POPULATION/KM^2**	
			0-10	2
			10.1-30	4
			30.1-100	5
			100.1-200	3
			200.1-1000	1
COMMUNITY	**Distance From Roads**	**25%**	**KILOMETERS**	
	(Roads Class 1-3)		0-1.5	5
			1.5-3	4
			3-5	3
			5-10	2
			10+	1
COMMUNITY	**Land Cover Type**	**25%**	**CLASS**	
			2.1	1
			2.2	3
			2.3	4
			3.1	5
			3.2	3
			3.3	3
			Other	1
COMMUNITY	**Distance from Settlements**	**25%**	**KILOMETERS**	
			0-3	5
			3-5	4
			5-7	3
			7-10	2
			10+	1
COMMUNITY	**Designated Protected Areas**	**(NO)**	**Within Protected Area**	**0**
	Total	100%		

Weight Explanation
Least Suitable = 1
Most Suitable = 5
Always Unsuitable = 0
Always Suitable = YES

Table 1. Model Variables Worksheet

The variables shown in the worksheet are the Model Parameters. As variables, they can be changed to produce different outcomes through the model. The power of the models is this ability to game different scenarios by assigning different values to the Model Parameters, inspecting and validating the outcomes, and running this process through multiple iterations. From these iterations, suitability patterns and the influence of the different Model Parameters become apparent, and final preferred suitability models can be refined.

Suitability model rasters were interpolated at a one-kilometer cell size. This is a relatively detailed evaluation on the national scale. Nonetheless, features whose dimensions are less than the cell size (one kilometer) are difficult to represent. For example, 5- to 50-meter "buffer" zones along rivers cannot be modeled at this scale, even though these areas may be considered unsuitable for Commercial Forestry. All model results were displayed in a green-to-red color ramp, with green being most suitable, and red being least suitable, for each given result.

GIS Data Sources

GIS data for Liberia was compiled from multiple sources, including the Liberia Forestry Initiative (LFI), the Liberia FDA, the World Bank, the United Nations Humanitarian Information Centre for Liberia (UNHIC), Conservation International (CI), the U.S. National Intelligence Mapping Agency (NIMA), the U.S. National Aeronautics and Space Administration (NASA), and Fauna and Flora International (FFI). The best available data was compiled and extensively evaluated for quality, limitations, and utility for the land use planning effort.

For each forest use category and suitability model, we attempted to answer the questions: "What are the criteria intended to represent?" and "What GIS data are available or would be needed to represent and quantify these criteria?" In many cases, new data were derived by processing existing data, for example, the derivation of a population density raster from populated places data, or the derivation of a percent slope raster from a Digital Elevation Model (DEM) dataset. Some key datasets included: 1) Land Cover Type, 2) Roads, 3) Population Density, 4) Slope, 5) Settlements, 6) Existing Protected Areas.

Existing data was acquired in several different coordinate systems. All processing and models were developed in a standardized coordinate system, to wit:

WGS_1984_UTM_Zone_29N
Projection: Transverse Mercator
False Easting: 500000.000000
False Northing: 0.000000
Central Meridian: -9.000000
Scale Factor: 0.999600
Latitude of Origin: 0.000000
Linear Unit: Meter (1.000000)
Name: GCS_WGS_1984

Model Parameters

The Model Parameters and suitability maps presented with this report have been developed through an extensive and iterative collaboration of LFI partners, stakeholder working groups, and other interested parties. All models were subjected to sensitivity analysis and validation through these LFI partners.

To some extent, the suitability models were limited by the available GIS data. In many instances, available GIS data was used to proxy other criteria. The data sources, premises and assumptions that went into the selection of the Model Parameters are detailed in Nebel (2006a and 2006b).

Data Processing

ArcGIS 9.1 Model Builder was used to construct and run all of the suitability models. This provides a complete documentation of the processes used, and allows for multiple iterations of the model with changing variables.

The same basic process was used for all suitability models. Most GIS datasets were in vector file formats, and needed to be converted to raster data for the models. Many of the model parameters involved distance from specific features, and this calculation was accomplished by creating distance rasters from vector features, using the Spatial Analyst Euclidean Distance tool. The distance rasters were reclassified based on the Value Classes parameter. The reclassified rasters were then combined using the Weighted Overlay function and the Relative Rank model parameters. Additional steps were added to account for the absolute model parameters, for example, to set the existing protected areas always *suitable* for Preservation and always *unsuitable* for Commercial Forestry or Community Forestry.

Preservation Suitability

The Preservation suitability model used the following datasets: Distance from Roads, Distance from Forest Edge (closed dense forest, Land Cover Type 3.3), Distance from Ocean, and Existing Protected Areas. Areas considered most suitable for Preservation were distant from roads, within or near closed dense forests, and near the Atlantic Ocean. Existing Protected Areas were considered *always* suitable for Preservation. There are two such areas in Liberia: the Sapo National Park, and the Nimba Nature Reserve. Other parameters that were considered as model variables, but not used in the final model result, included Population Density, Distance from Settlements, Key Biodiversity Areas, Endangered Species, Land Block Size, and Distance from Rivers. Weights and Relative Ranks were developed by Conservation International, through regression analysis, correlated to biological diversity data (from Fauna and Flora International {FFI} biological transects). See Table 1 for all model parameters.

Sensitivity Analysis

Sensitivity analysis of the model output was performed by changing both the Model Variables and their Relative Ranks. Five unique model outputs were generated (Figures 2 through 6). The resulting suitability values are summarized in Table 2. The key field to compare is the sum of the high suitability value cells (in millions of hectares), since these will influence the result of the optimization model (below).

Preservation Model 1 (Figure 2) used the Variables “Distance from Edge”, “Proximity to Ocean”, and “Distance from Roads” in the Relative Ranks 78%-14%-8%, as outlined in the Model Variable Worksheet (Table 1). These are the preferred Parameters of the Conservation stakeholder working group. For all of the model outputs, the existing protected areas (Sapo and Nimba) are automatically assigned a most suitable (value = 5) result.

We tested the sensitivity by adjusting the relative rank, putting less emphasis on the Distance from Edge variable, and more emphasis on the Distance from Roads variable, i.e. 50-14-28 (%). This resulted in some incremental change, especially on the less suitable end of the spectrum, but did not qualitatively change the spatial extent of the most suitable areas (Preservation Model Alt 2, see Figure 3 and Table 2).

Next, we completely reversed the relative rank of the Distance from Edge and Distance from Roads variables, i.e. 8-14-78 (%). Again, there is some incremental change, but no significant qualitative shift in the result (Preservation Model Alt 3, Figure 4). These results give us a high level of confidence that the original result is reasonable.

Finally, we inserted other variables into the model: Population Density (population per square kilometer) and Proximity to Rivers. We gave each variable the same relative rank, i.e. 20/20/20/20/20 (%). (Please see Preservation Model Alt 4, Figure 5). At first glance, it might appear to be significantly different from the first three results, in part because the only areas that received a most suitable outcome are the already-protected areas. Nonetheless, the spatial distribution pattern of more suitable areas is not qualitatively different from the other results. The difference appears primarily due to the Proximity to Rivers variable. If this variable is removed (Preservation Model Alt 5, Figure 6), or if the distance classes are increased to expand the influence of the rivers, the differences between results are not as dramatic.

The bottom line is that we see a qualitatively and quantitatively consistent result that is not fundamentally affected by any over-influencing variables, i.e. sensitivity does not appear to be an issue. All of the results mimic Landcover to a large degree, but the sensitivity analysis shows that Landcover is <u>not</u> the controlling variable (e.g. compare results from Model 1/Figure 3 and Model Alt 3/Figure 4). Distance from Rivers, if it were to be used as a variable, is potentially an over-influencing factor, so its Parameters would need to be refined and re-tested for sensitivity. Based on this analysis, we conclude that the original model Parameters, i.e. Model 1 (Figure 2) produce a valid and acceptable Preservation suitability result.

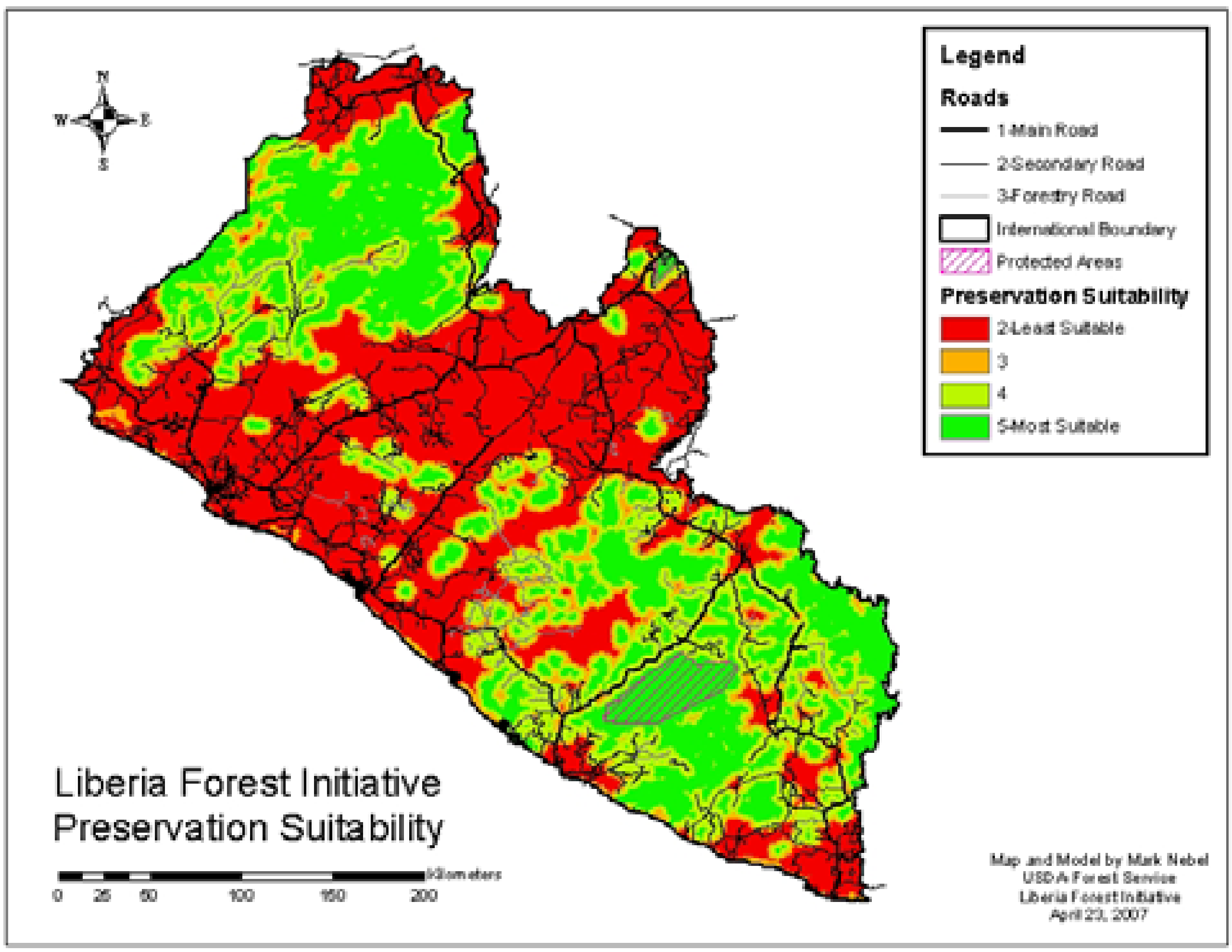

Figure 2. Preferred Preservation Suitability Model. Parameters (Relative Rank %): Distance from Forest Edge (78%)/Distance from Ocean (14%)/Distance from Roads (8%).

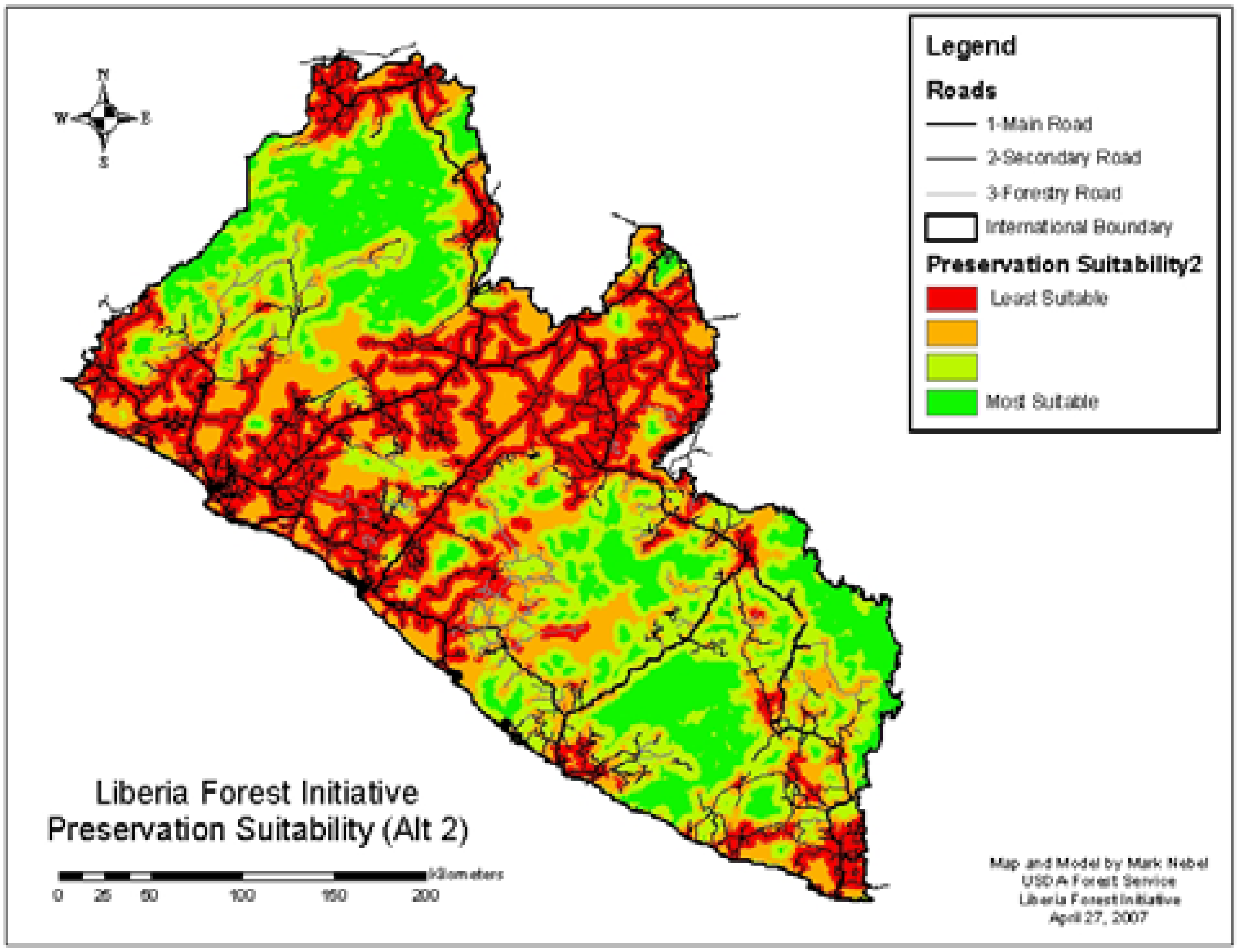

Figure 3. Preservation Suitability Model Alternative 2. Parameters (Relative Rank %): Distance from Forest Edge (50%)/Distance from Ocean (14%)/Distance from Roads (28%).

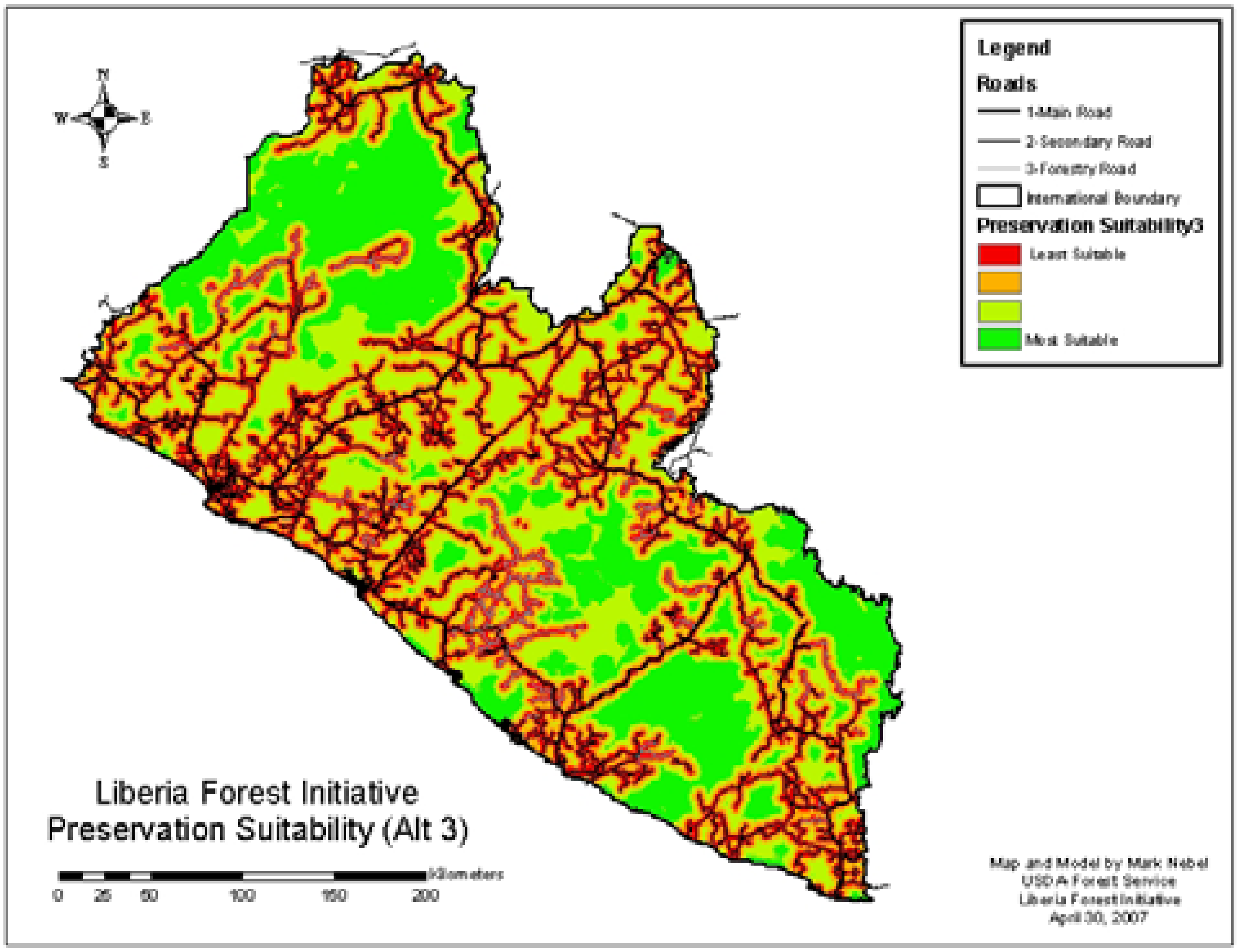

Figure 4. Preservation Suitability Model Alternative 3. Parameters (Relative Rank %): Distance from Forest Edge (8%)/Distance from Ocean (14%)/Distance from Roads (78%).

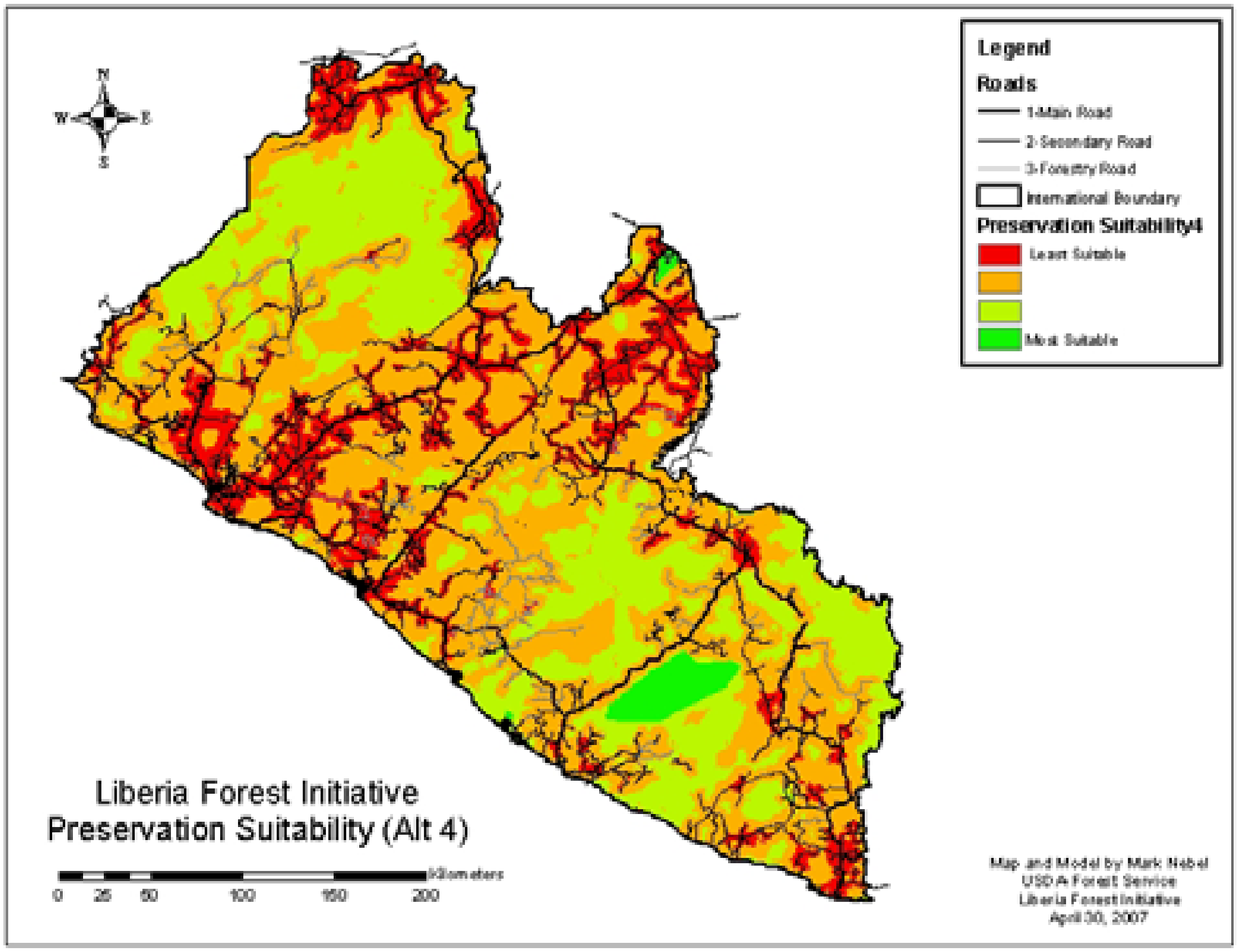

Figure 5. Preservation Suitability Model Alternative 4. Parameters (Relative Rank %): Distance from Forest Edge (20%)/Distance from Ocean (20%)/Distance from Roads (20%)/Distance from Rivers (20%)/Population Density (20%).

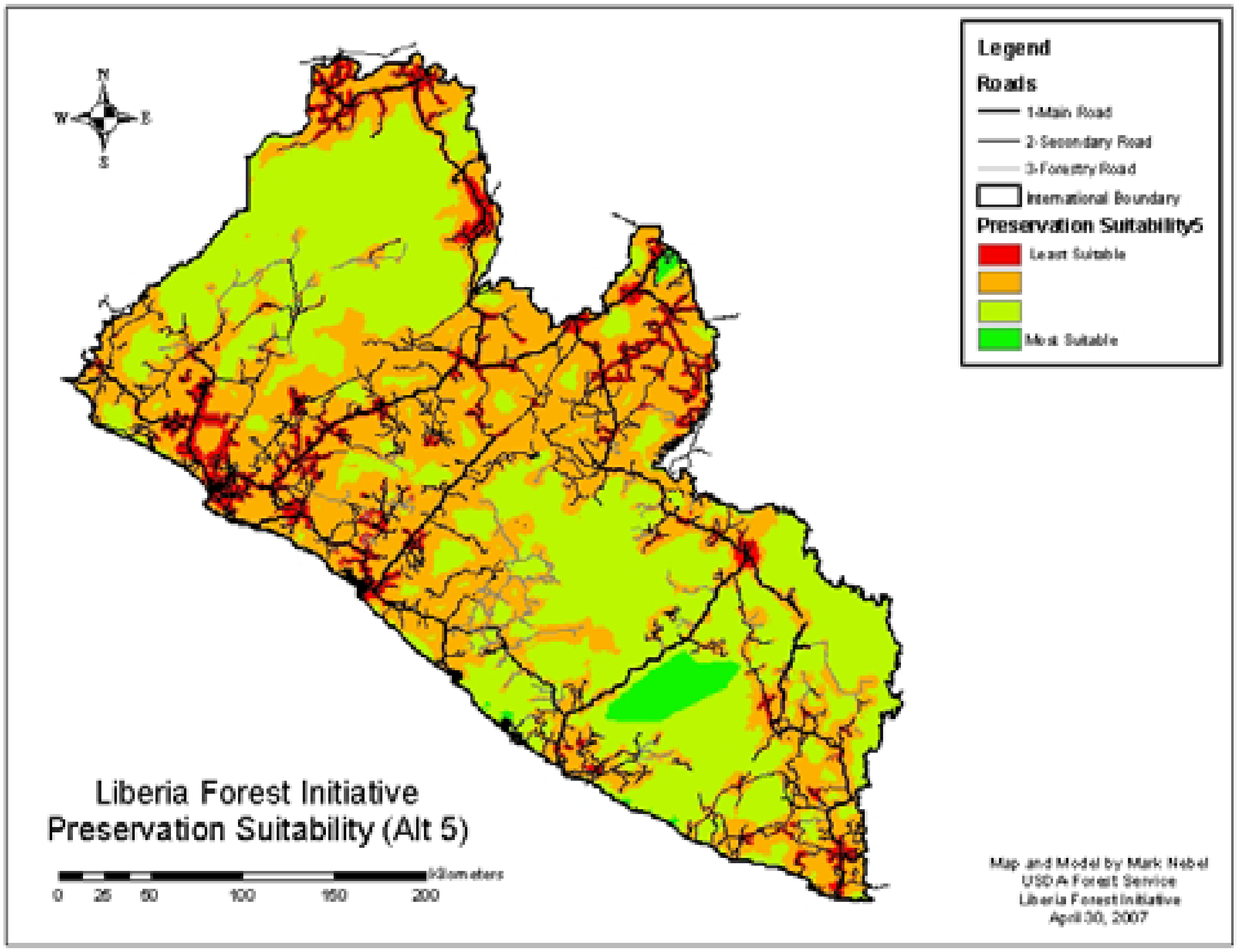

Figure 6. Preservation Suitability Model Alternative 5. Parameters (Relative Rank %): Distance from Forest Edge (25%)/Distance from Ocean (25%)/Distance from Roads (25%)/Population Density (25%).

PRESERVATION MODELS

Suitability Model Alternative	Suitability Value 0	1	2	3	4	5	4 + 5	Comments
	(millions of hectares)							
Model 1	0	0	4.145	0.919	2.196	2.321	4.517	Distance from Forest Edge/Ocean/Roads; 78/14/8
Model 2	0	0	2.838	2.596	2.320	1.826	4.146	50/14/28
Model 3	0	0	2.743	2.243	2.274	2.321	4.595	8/14/78
Model 4	0	0	1.722	5.028	2.663	0.167	2.830	Add 'Population' and 'Rivers' (sensitive); 20/20/20/20/20
Model 5	0	0	0.792	4.465	4.149	0.174	4.323	Add 'Population' only; 25/25/25/25

COMMUNITY MODELS

Suitability Model Alternative	Suitability Value 0	1	2	3	4	5	4 + 5	Comments
	(millions of hectares)							
Model 1	0.165	0	0.628	2.615	4.985	1.146	6.131	Pop density/roads/landcover/settlements; 25/25/25/25
Model 2	0.165	0.008	1.165	3.653	3.854	0.694	4.548	10/40/40/10
Model 3	0.165	0	0.110	2.334	5.553	1.377	6.930	Promote 3.2 and 3.3 Landcover; 25/25/25/25
Model 4	0.165	0.008	0.114	3.670	4.343	1.239	5.582	Promote 3.2 and 3.3 Landcover; 10/40/40/10

COMMERCIAL MODELS

Suitability Model Alternative	Suitability Value 0	1	2	3	4	5	4 + 5	Comments
	(millions of hectares)							
Model 1	0.694	0	2.917	2.934	1.003	1.981	2.984	Pop density/landcover/roads; 20/60/20
Model 2	0.694	0	0.099	3.075	4.184	1.478	5.662	Pop density/landcover/roads; 33/34/33
Model 3	0.694	0	0.002	0.91	7.019	0.905	7.924	Pop density/landcover/roads; 60/20/20
Model 4	0.694	0	0.269	0.292	5.717	2.558	8.275	Pop density/landcover/roads; 20/20/60
Model 5	0.694	0.098	5.127	0.627	0.978	2.005	2.983	Pop density/landcover/roads; 10/80/10

All area values are in Millions of Hectares
4 + 5 is the total of the highly suitable values.

Table 2: Sensitivity analysis summary and comparison of suitability results for alternative suitability model parameters.

Commercial Forestry Suitability

The Commercial Forestry suitability model used the following datasets: Population Density, Land Cover Type, Distance from Roads, Protected Area Status, and Percent Slope. Areas considered most suitable for Commercial Forestry are low in population, have a dense forest land cover, and have good road access. Existing protected areas and areas having a slope greater than 30 percent were designated *always* unsuitable for Commercial Forestry. Other parameters that were considered as model variables, but not used in the final result, included Unencumbered Land Ownership, Timber Species Composition, Land Block Size, Recent Logging Areas, Economic Viability, Watercourses and Buffers, and Known Mining Areas and Mineral Deposits. Weights and Relative Ranks were developed by the LFI Commercial Forestry stakeholder group.

Sensitivity Analysis

Sensitivity analysis was performed by varying the Relative Rank of the Population Density, Land Cover Type, and Distance from Roads variables. Five alternative models were evaluated (Figures 7 through 11, and Table 2). The model is sensitive to all three variables, i.e. the suitability result varies significantly as the Relative Ranks of the variables are changed. For example, if the Distance from Roads variable is given a high Relative Rank (Model Alt 4, Figure 10), the “most suitable” land base expands dramatically. A similar result occurs when Population Density is given a higher Relative Rank (Model Alt 3, Figure 9). However, both results were considered invalid by the LFI Commercial Forestry stakeholder working group, because these expanded land base areas included much land that is not forested, and these areas would be unsuitable for Commercial Forestry. The consensus of the working group is that the Land Cover Type variable is the most important criterion, should therefore receive the highest Relative Rank, and produced the most valid suitability result.

The Class 4 (secondary forest) roads were added to the Distance from Roads variable calculation, but this did not fundamentally affect the outcome of the model, so the LFI consensus was to leave them out of the model. (All other models used roads in classes 1-3, i.e. major roads and primary forest roads).

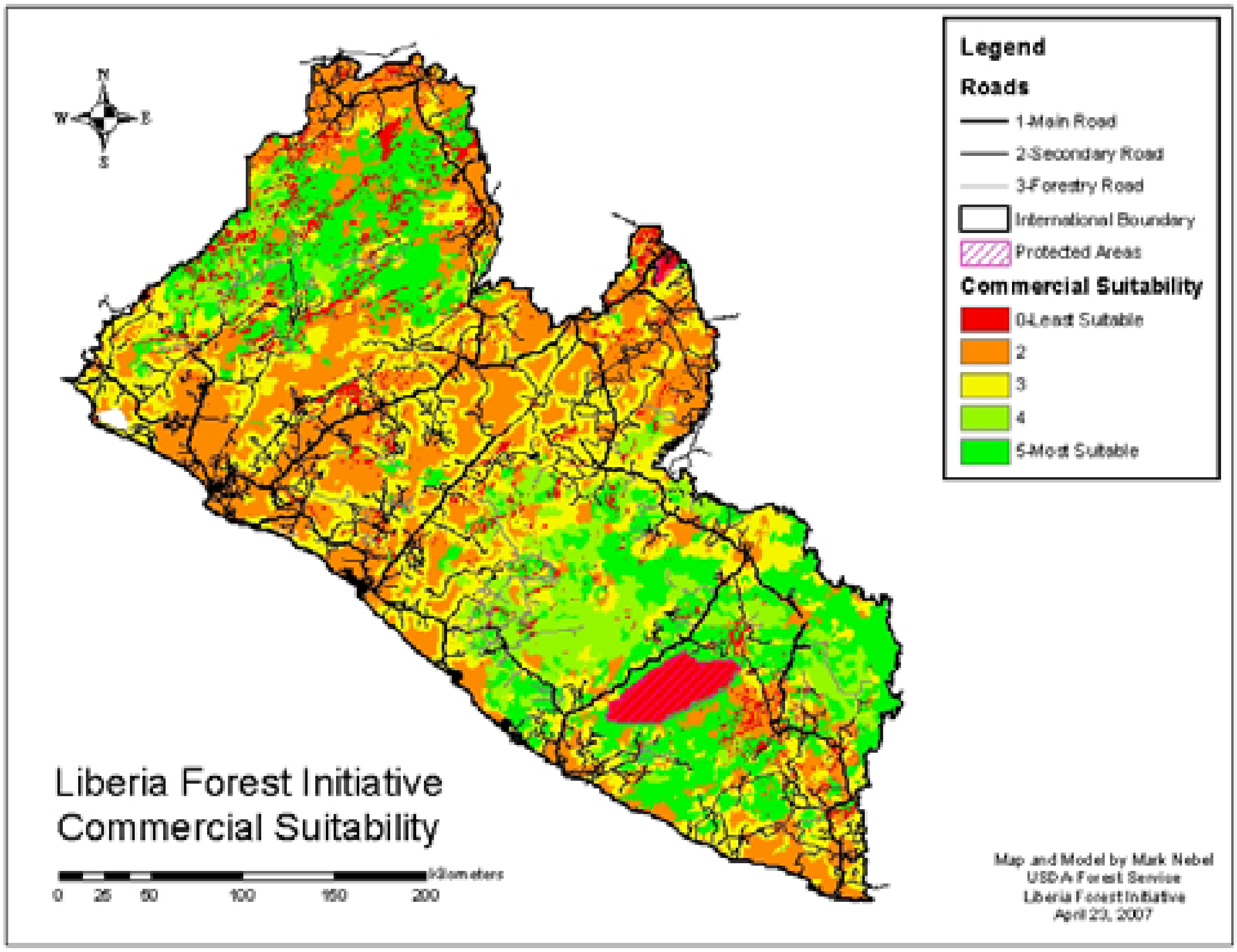

Figure 7. Preferred Commercial Forestry Suitability Model. Parameters (Relative Rank %): Population Density (20%)/Land Cover Type (60%)/Distance from Roads (20%).

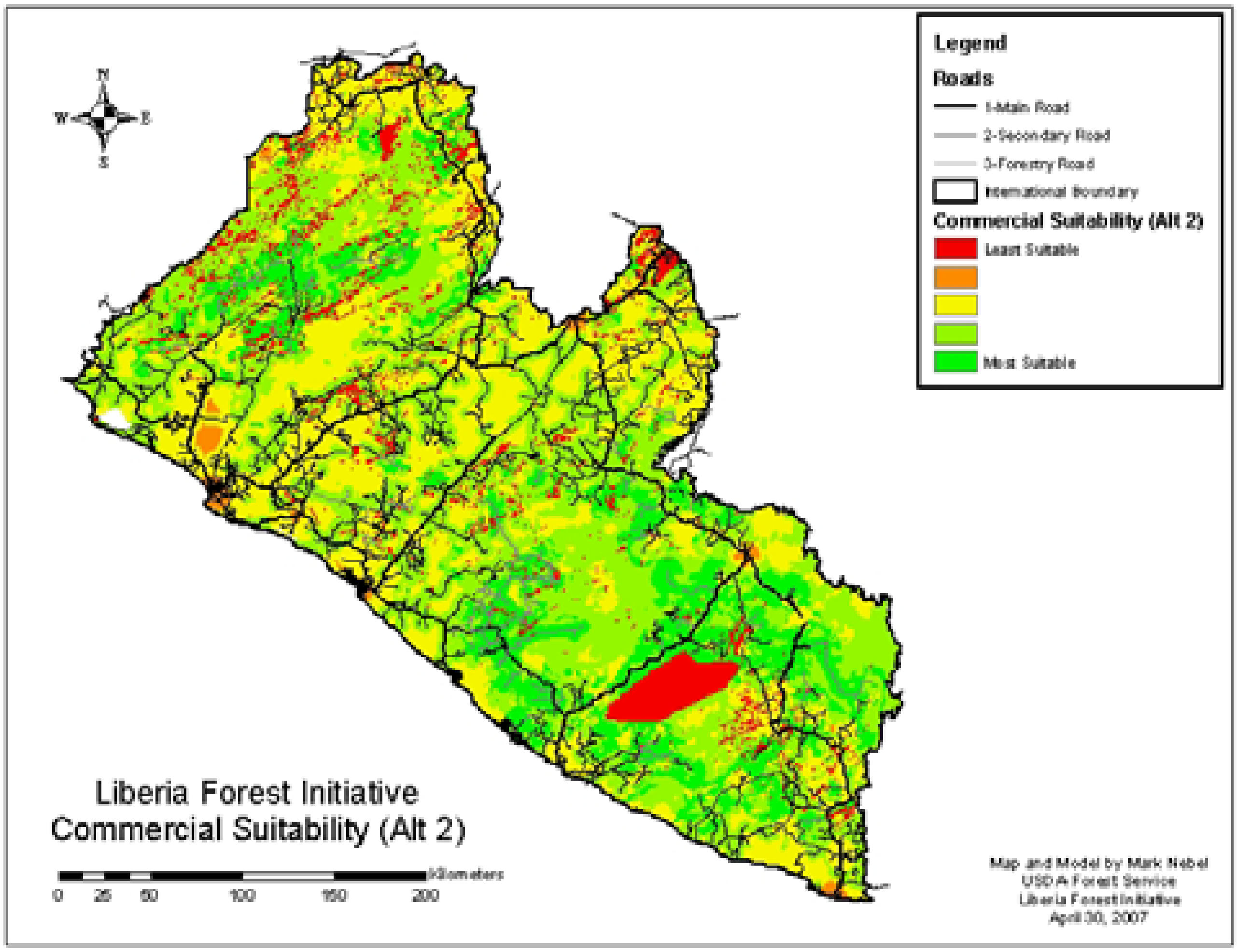

Figure 8. Commercial Forestry Suitability Model Alternative 2. Parameters (Relative Rank %): Population Density (33%)/Land Cover Type (34%)/Distance from Roads (33%).

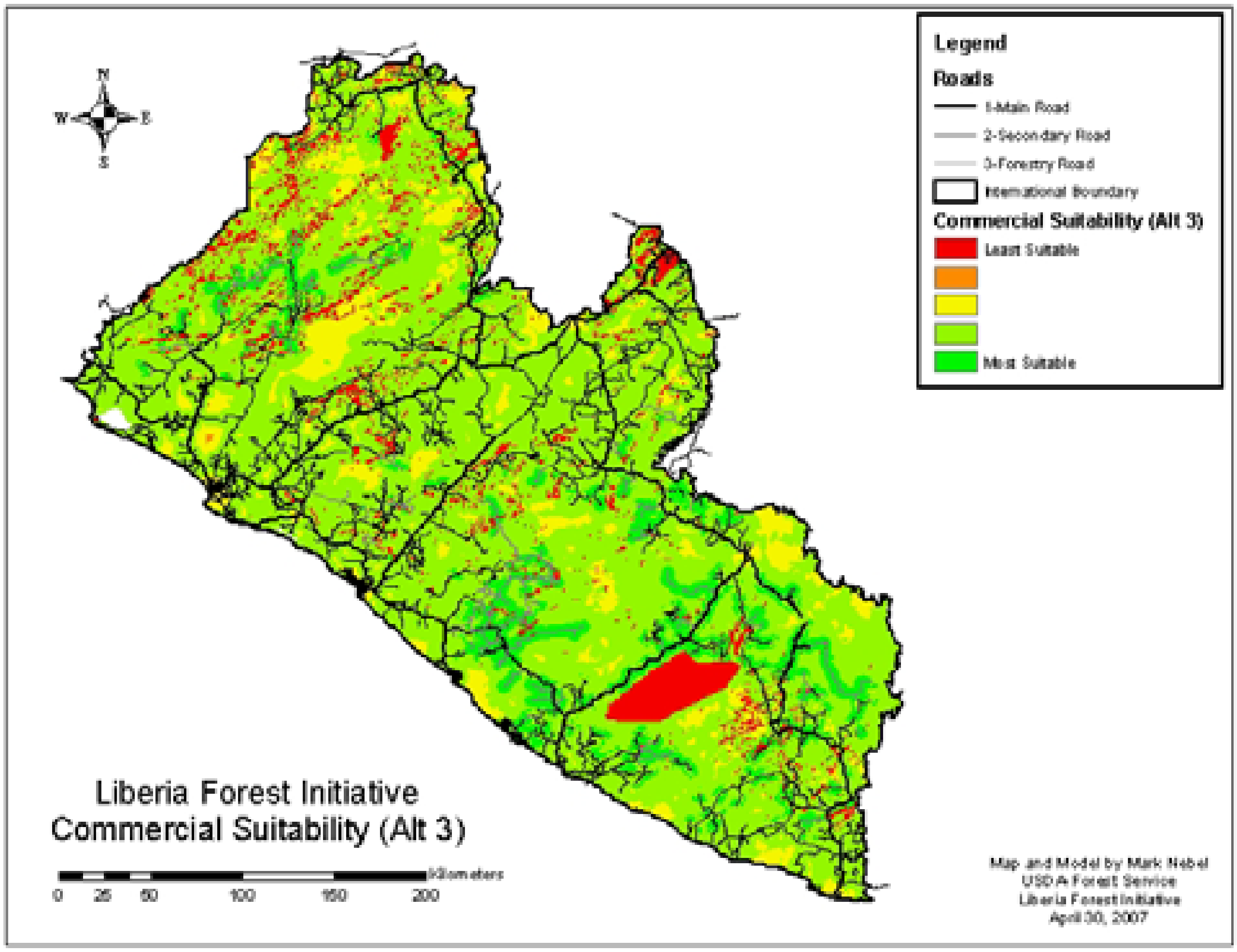

Figure 9. Commercial Forestry Suitability Model Alternative 3. Parameters (Relative Rank %): Population Density (60%)/Land Cover Type (20%)/Distance from Roads (20%).

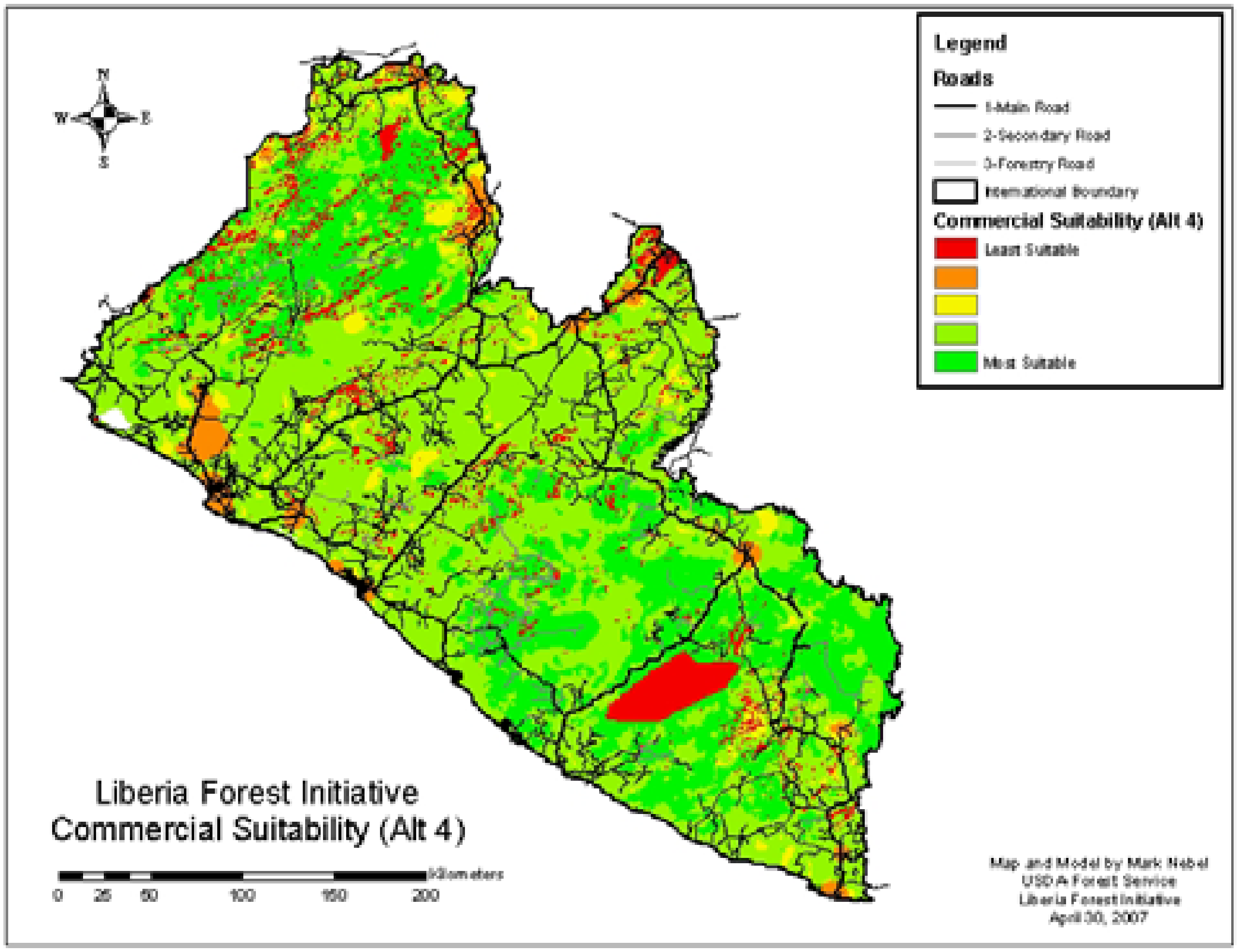

Figure 10. Commercial Forestry Suitability Model Alternative 4. Parameters (Relative Rank %): Population Density (20%)/Land Cover Type (20%)/Distance from Roads (60%).

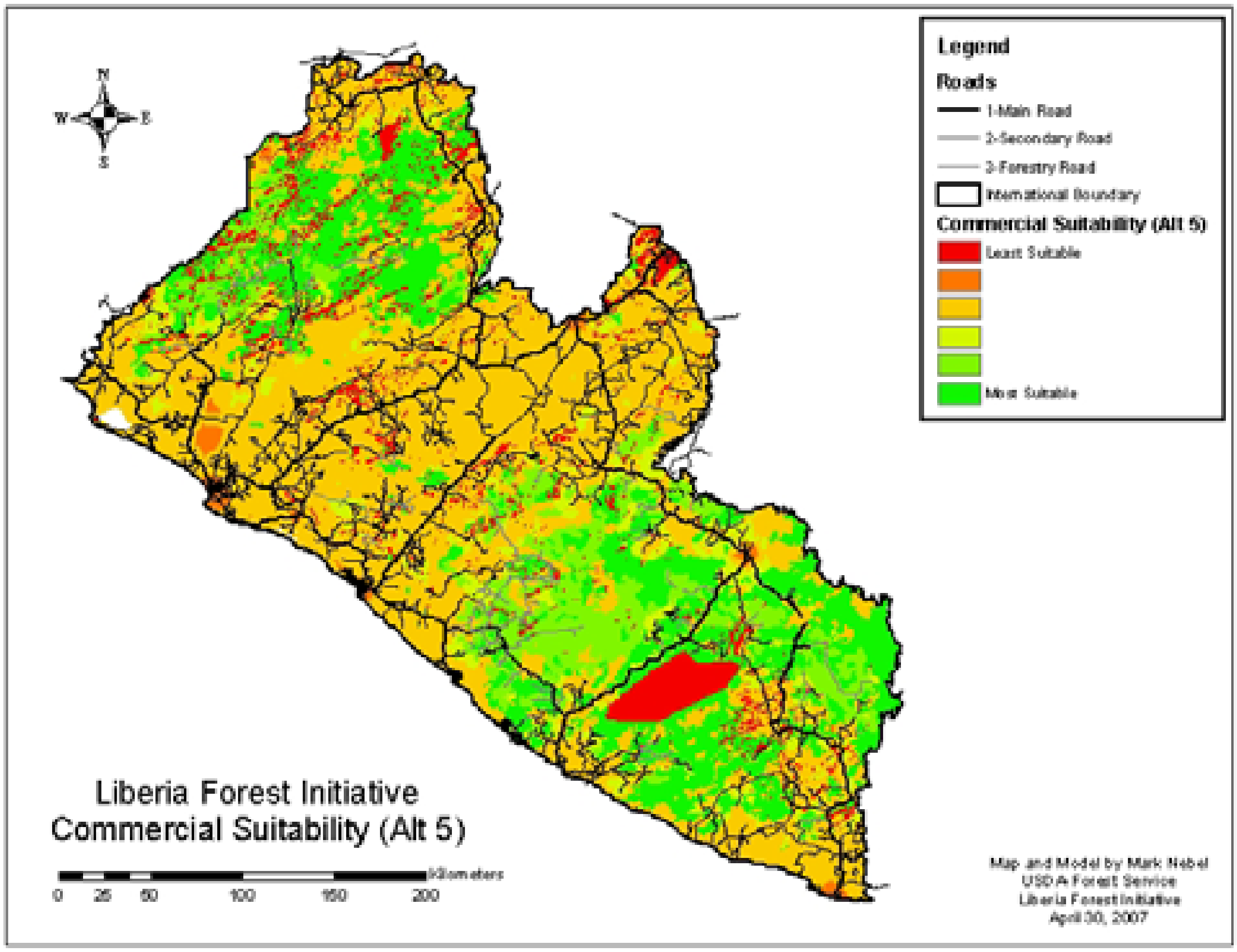

Figure 11. Commercial Forestry Suitability Model Alternative 5. Parameters (Relative Rank %): Population Density (10%)/Land Cover Type (80%)/Distance from Roads (10%).

Community Forest Suitability

The Community Forest suitability model used the following datasets: Population Density, Land Cover Type, Distance from Roads, Distance from Settlements, and Protected Area Status. Areas considered most suitable for Community Forestry a have moderate population, a mixed forest and agricultural land cover, and are near roads and settlements. Existing protected areas are designated *always* unsuitable for Community Forestry. Model Variable Weights and Relative Ranks were developed by the LFI Community Forestry stakeholder group (Table 1). The group decided to give all of the Model Variables an initial equal Relative Rank, and to test the effect of varying the Weights and Ranks by sensitivity analysis.

Sensitivity Analysis

Four alternate models were evaluated. Figure 12 is the preferred model of the Community Forestry stakeholder group. Sensitivity analysis was conducted to evaluate the effect of changing the Relative Ranks of the model variables, from an initial equal Relative Rank (Population Density 25%, Distance from Roads 25%, Land Cover Type 25%, and Distance from Settlements 25%). The Relative Ranks were changed to 10%-40%-40%-10%, effectively increasing the effect of the Distance from Roads and Land Cover Type variables. This resulted in a slight decrease in the number of hectares having a most suitable result, but did not qualitatively change the pattern of the distribution of those areas (Figure 13 and Table 2).

The Community Forestry stakeholder working group also wanted to evaluate the effect of increasing the Weight of the primarily densely forested Land Cover (classes 3.2 and 3.3 of Bayol and Chevalier, 2004) to highly suitable. This change was applied to both of the above alternatives, but did not fundamentally affect the result, either qualitatively or quantitatively (See Table 2, Figures not shown). Since the effect of theses change was minimal, the model is considered not sensitive to either of the variables, and the working group reached consensus to stay with the original equal Relative Ranks, and the moderate suitability Weights for the forested Land Cover Types.

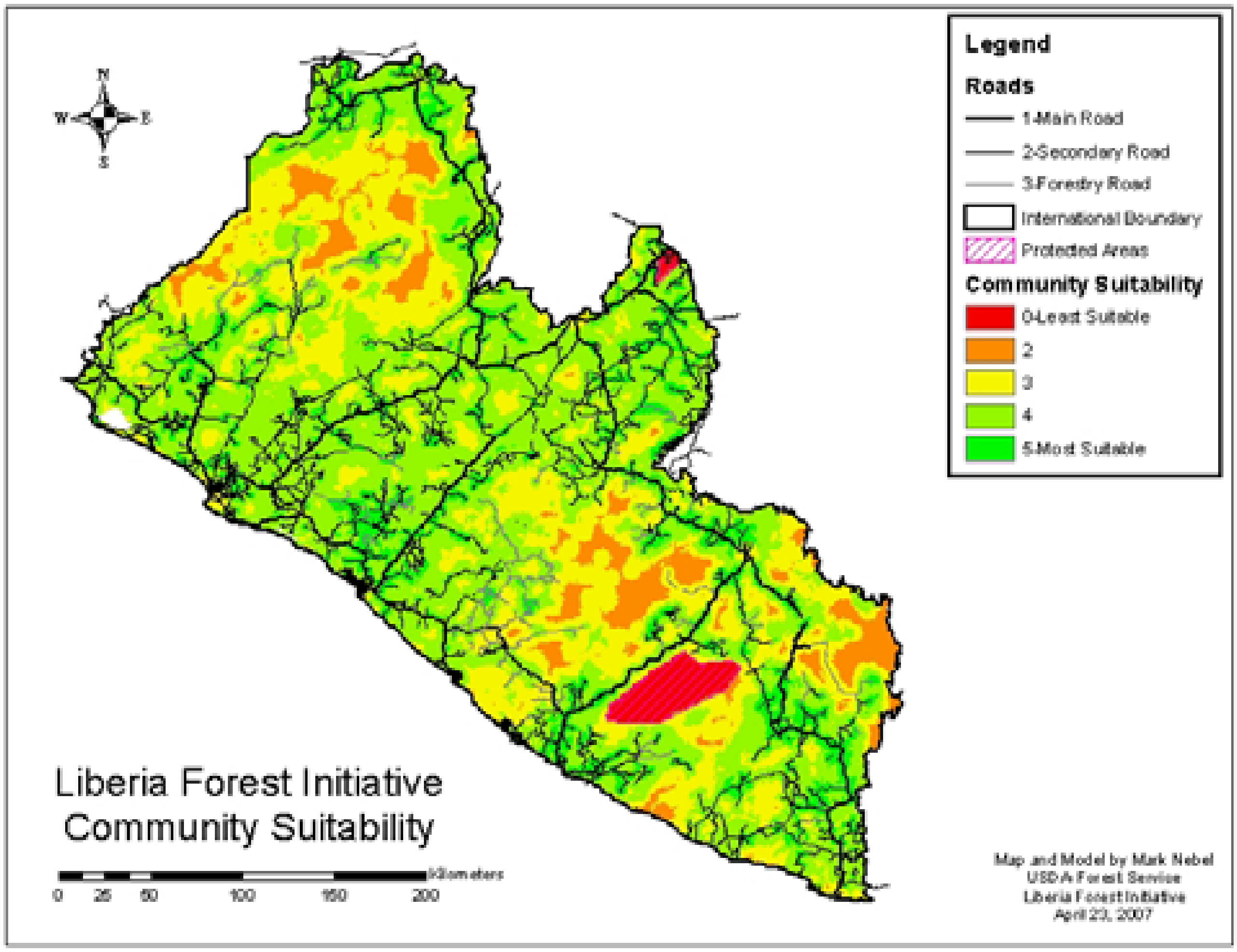

Figure 12. Preferred Community Forestry Suitability Model. Parameters (Relative Rank %): Population Density (25%)/Distance from Roads (25%)/Land Cover Type (25%)/Distance from Settlements (25%).

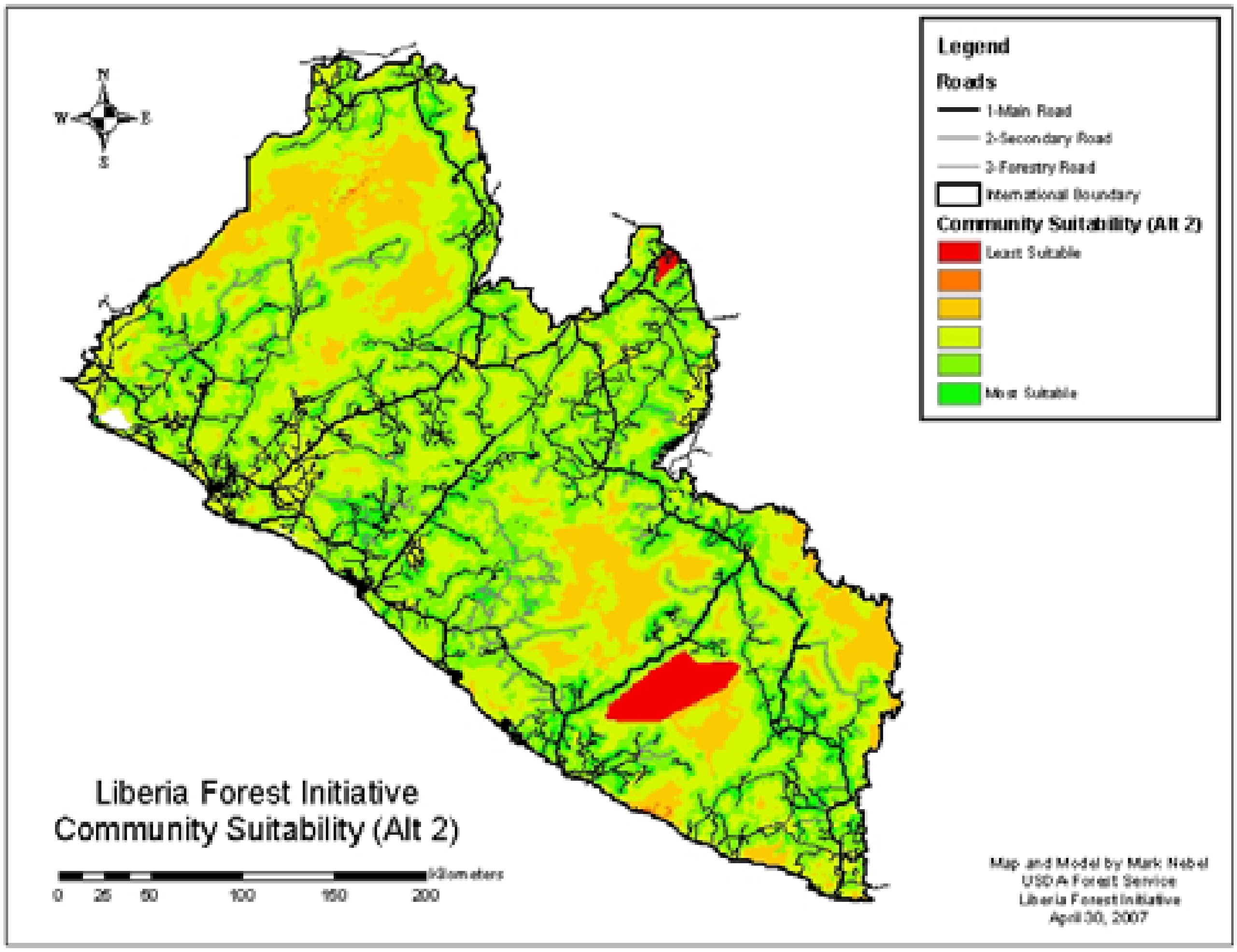

Figure 13. Community Forestry Suitability Model Alternative 2. Parameters (Relative Rank %): Population Density (10%)/Distance from Roads (40%)/Land Cover Type (40%)/Distance from Settlements (10%).

Reclassification and Optimal Suitability

The suitability of land for a particular use is fundamentally independent of its suitability for other uses. In the simplest case, the suitabilities of any particular tract of land for different uses are compatible and complementary with each other. For example, an area of closed dense forest with very steep slopes is, at the same time, both highly suitable for Preservation and highly unsuitable for Commercial Forestry. However, any particular piece of land can be, and often is, suitable for more than one use, resulting in competing suitability. Without the steep slopes of the prior example, an area of closed dense forest could be highly suitable for Preservation or Commercial Forestry.

The goal of optimizing land use is to integrate multiple, sometimes competing, land use suitabilities in order to maximize the allocation of land for all uses. The desired result is a mix of land use that yields the highest overall cumulative land suitability, in order to optimize land use for all uses, within the context of overall land management objectives.

Because of the different emphases of the Community Forestry model, the Community Forestry suitability is largely complementary to both the Preservation and Commercial Forestry suitability. For example, the Preservation and Commercial Forestry suitability models value the dense forest above all other Land Cover Types, but the Community Forest model places a higher value on forests with an agricultural component. And, whereas Community Forests are preferable located near the settlements they would serve, Commercial Forestry and Preservation are more suitable away from human habitation. This presents the simplest scenario, in which non-competitive suitability results do not need to be reconciled or optimized against other conflicting uses.

The Preservation and Commercial Forestry models, however, result in a more complex scenario with significant variability, including both areas of compatible suitability and large areas of competing high suitability. The latter is, in large part, due to the important Weight and Relative Rank of the Land Cover Type (3.3, closed dense forest) variable in both of these respective suitability models. For these complex outputs, a Suitability Matrix is a useful method to evaluate the relative suitability of the Preservation and Commercial Forestry land uses, and assign an optimal suitability for each model cell.

Each cell (in this case, one-kilometer-square areas) has a suitability value for each particular land use in their respective suitability models. Preservation suitability values range from 2 (least suitable) to 5 (most suitable), and Commercial Forestry suitability values range from 0 (always unsuitable) to 5 (most suitable). For every cell in the model area, there can be any combination of suitability values from the Preservation and Commercial Forestry models. These suitability values can be Combined in ArcGIS Spatial Analyst, so that every unique combination of suitability values from the Preservation and Commercial Forestry inputs can be identified. These, in turn, can be assigned a new unique value in a new output raster layer.

The resulting Combined Suitability raster contains nineteen (19) different combinations of suitability values (Figure 14). Table 3 shows these combinations, their unique identification Combine ID, and the total area (in hectares) falling under each combination. The combinations of unique pairs can also be represented in a simple Suitability Matrix (Table 4). Reclassifying these unique values in terms of their optimal land use is an incremental process. Each cell was ultimately reclassified in one of four Optimal Suitability categories: 1) commercial "c", 2) preservation "p", 3) commercial or preservation "pc", and 4) mixed other use "m".

The cells at the extremes of the value spectrum were classified first. These cells represent the areas where there is little conflict between competing uses. For example, cells that have a high Preservation suitability value ('4' or '5'), and a relatively unsuitable Commercial Forestry value ('0' to '3'), become optimal land use "p" (preservation). Conversely, cells that have a less suitable Preservation value ('2' or '3'), and a more suitable Commercial Forestry value ('4' or '5'), become optimal land use "c" (commercial).

Cells that had a relatively low suitability value for both Preservation and Commercial Forestry were reclassified "m" (mixed other use). These cells primarily represent areas where agriculture is already a significant or predominant part of the land cover. These areas are optimally suitable for either Community Forestry and/or Agriculture.

The remaining cells are those where the suitability for both Commercial Forestry and Preservation is high. An iterative process, similar to the sensitivity analysis in the suitability modeling, was used to reclassify each combination of remaining cell values in the combined suitability raster, until consistent, valid (per the stakeholder groups, landcover types, and other model variables), repeatable patterns emerge, and contiguous areas with the same classification develop and "hold together". These contiguous blocks are important for ultimately creating the proposed boundaries for manageable commercial forestry concessions and protected areas. (See the "Delineation of Land Use Areas" section, below.)

The resulting Optimal Use is shown in both Tables 3 and 4. In summary, Commercial Forestry is the Optimal Suitability for any cell that has a high Commercial Forestry suitability value ('4' or '5') and any Preservation suitability value less than "most suitable" (i.e. '2' to '4'). Preservation is the Optimal Use for cells that have a most suitable ('5') Preservation suitability and any Commercial Forestry suitability value less than "most suitable" (i.e. '0' to '4'). Preservation is also the Optimal use for cells where the Preservation suitability value is '4', coupled with an "always unsuitable" (i.e. '0') Commercial Forestry suitability. Cells where both the Preservation and Commercial Forestry suitability values were “most suitable” (i.e. ‘5’) were classified as Optimal Use “pc” (commercial <u>or</u> preservation), meaning that either use is optimal. All other cells were reclassified “mixed other use”.

In addition to the iterative reclassification process, several alternate methods were tested to generate an Optimized Suitability output pattern with contiguous, manageable land blocks. All of these methods fall under the category of “generalization” in ArcGIS Spatial Analyst (see also the “Generalization” section, below). These generalization tools can be used to iteratively shrink, expand, and/or smooth the boundaries of the output areas, and are sometimes an effective method for establishing more contiguous output areas. All of these alternatives were rejected, however, since they resulted in a loss of detail in the resulting raster. Some generalization is unavoidable to produce a finished map product (see the “Delineation of Land Use Areas” section, below), but it was deemed more important to retain the detail at this stage of the analysis.

The total area (in hectares) falling into the various combined suitability and Optimal Land Use categories is also summarized in Table 3.

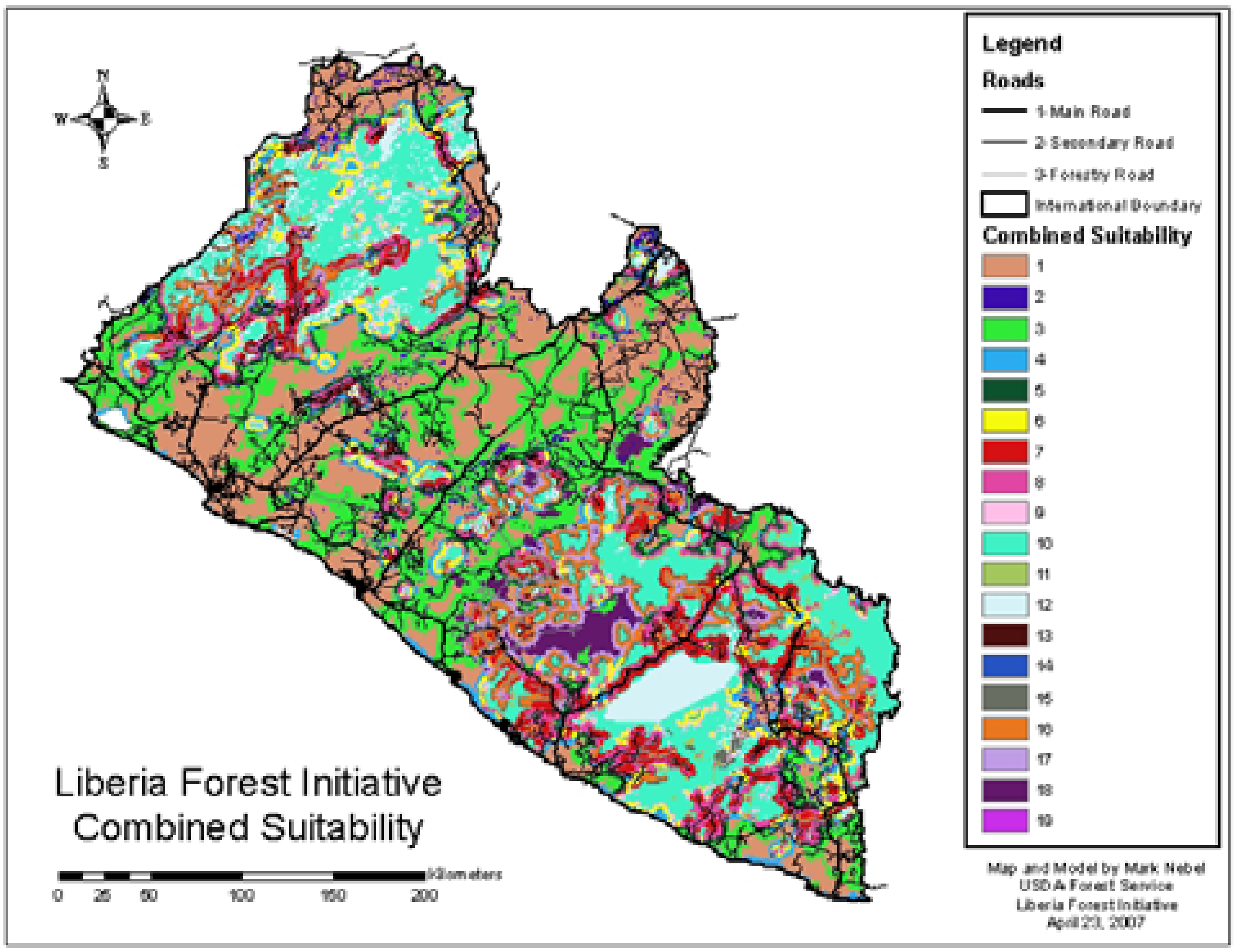

Figure 14. Combined Suitability shows the nineteen unique combinations of Preservation and Commercial Forestry suitability.

Suitability				**Optimal Hectares**			
Preservation	Commercial	Combine ID	Optimal Suitability	Preserve	Commercial	Both	Neither
5	0	12	p	364,300			
5	2	9	p	199,100			
5	3	11	p	113,400			
5	4	15	p	165,800			
5	5	10	pc			1,469,800	
4	0	13	p	143,600			
4	2	6	m				376,800
4	3	8	m				697,000
4	4	16	c		465,000		
4	5	7	c		510,700		
3	0	14	m				40,100
3	2	4	m				290,900
3	3	5	m				388,500
3	4	17	c		189,900		
3	5	19	c		200		
2	0	2	m				146,300
2	2	1	m				2,050,600
2	3	3	m				1,735,300
2	4	18	c		182,000		
				986,200	**1,347,800**	**1,469,800**	**5,725,500**

Combine ID is a unique identifier for each combination of Preservation and Commercial suitability values.

c = commercial forestry
p = preservation
pc = commercial or preservation
m = mixed other use

Table 3. Crosswalk of Preservation and Commercial Forestry suitability combinations and their corresponding optimal suitability.

	Commercial Suitability				
	5	4	3	2	0
Preservation Suitability					
5	pc	p	p	p	p
4	c	c	m	m	p
3	c	c	m	m	m
2	x	c	m	m	m

Optimal Suitability Codes
c = commercial forestry
p = preservation
pc = commercial or preservation
m = mixed other use
x = not applicable

Table 4. Suitability matrix for Preservation and Commercial Forestry suitability combinations, and their corresponding optimal suitability.

Delineation of Land Use Areas

Generalization

The most useful resulting map products should display Optimal Land Use zones with well-defined boundaries and manageable, relatively contiguous shapes and sizes. Several steps were needed to convert the suitability and optimization model results to a useable map product, while at the same time achieving the highest overall cumulative land suitability possible.

The optimization produced a nationwide one-kilometer-cell grid with four categories of Optimal Suitability (Figure 15). Some continuity of contiguous blocks having the same Optimal Suitability was developed during the optimization process. Due to the shape and relatively small size of the output grid cells, the resulting Optimal Suitability zones locally retain blocky, irregular boundaries, patchwork patterns, and isolated “island” suitability cells. This is a normal and expected pattern when combining and reclassifying even simple suitability datasets.

Automated generalization of these zones during reclassification, to produce smoother boundaries, was tested. All of the generalization methods expand and/or shrink the suitability value zones, in order to produce less ragged boundaries between the zones. Many variables can be manipulated to affect the outcome of the generalization. For example, priorities can be assigned to expand either the larger or smaller zones (based on total area). This can result in either the growth or elimination of smaller zones. If the priority is placed on the smaller zones, these zones expand and coalesce. If the priority is reversed, the larger total area zones expand to absorb and eliminate the smaller areas. In this example, the larger “commercial” and “commercial or preservation” zones absorb and eliminate most of the “preservation” zones. We rejected all of the automated generalization outputs, preferring to retain the detail of the Optimal Suitability dataset and manually delineate Land Use Area boundaries.

All of the suitability and optimization model results were developed as grid cell (or raster) datasets. For a more useful finished product, we converted the raster-based data to an Optimal Land Use polygon (vector) feature class format. The conversion to polygon format and the generalization of the datasets were both accomplished as part of the Delineation of Land Use Area Boundaries, below.

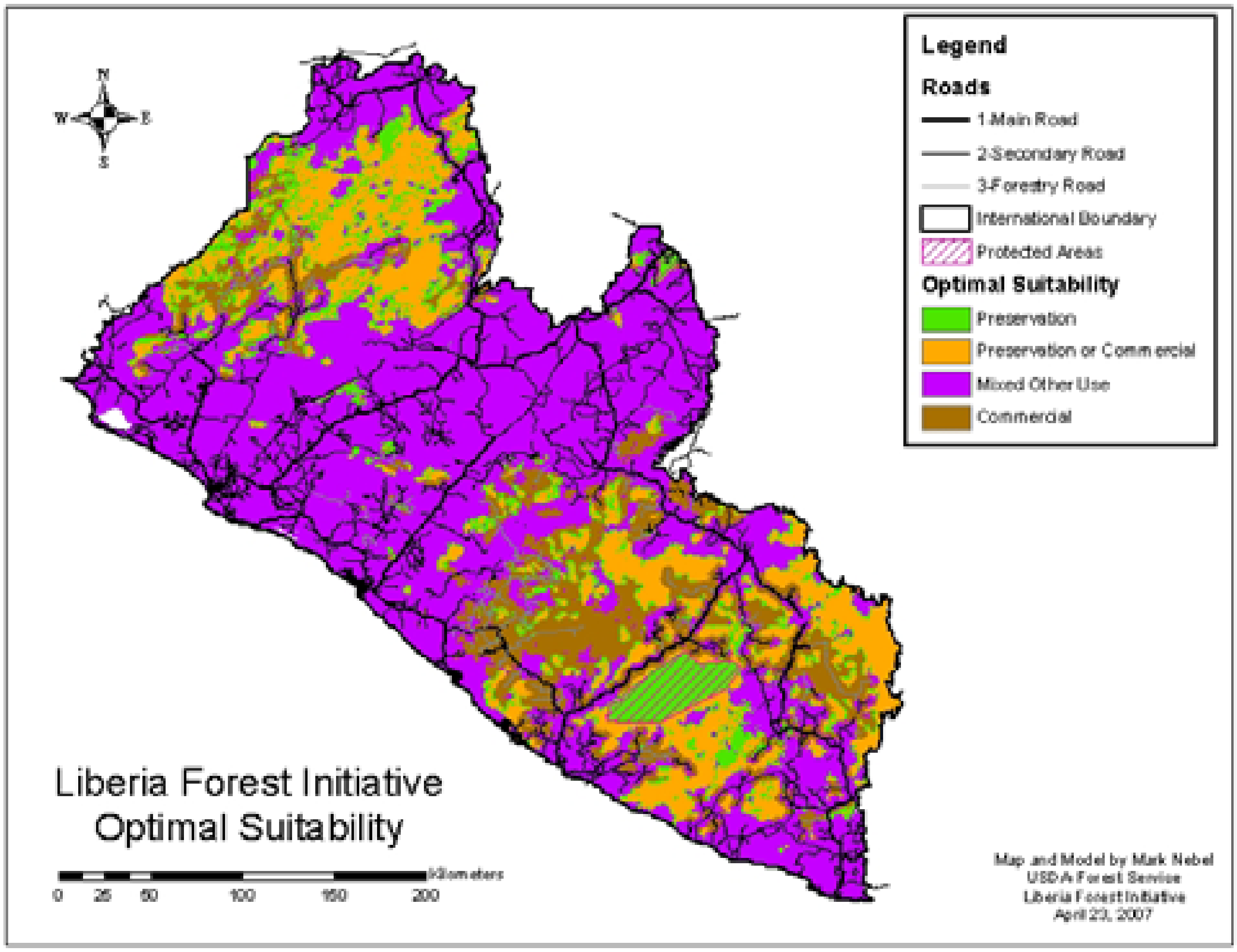

Figure 15. Optimal Suitability.

Delineation of Land Use Area Boundaries

All of the modeling products come together to produce a finished set of map products, chief among them an optimal Land Use Area map. As described above, some measure of generalization is necessary, along with conversion of the raster cell data to polygon data, while at the same time achieving and retaining the highest overall cumulative land suitability possible.

All of the Land Use Area Boundaries were delineated manually, on-screen in ArcMap, by the author of this report, Dr. Mark Nebel. Since an automated process was not used, the boundaries are partly subject to the professional judgment of the author and LFI stakeholder group partners, but were always drawn using the following criteria:

1) Optimize the overall cumulative land suitability. Boundaries were manually drawn to smooth the boundaries between zones in the Optimal Suitability raster. Simple algebraic algorithms were sometimes used to determine the best boundary path.

2) Use simple, easily identifiable area boundaries. We strived to keep the Land Use Area boundaries simple, to correspond as much as possible with existing easily identifiable features, and to require a minimum of on-the-ground surveying and boundary demarcation. To this end, Land Use Area boundaries were delineated along the following features, in order of priority:

a. Geographic Features
    i. Major Rivers
    ii. Smaller Rivers
    iii. Topographic Features (50K and 250K topographic quad maps)
b. Man-Made Features
    i. Roads
c. Geopolitical Boundaries
    i. International Boundary
    ii. County Boundary
d. Straight-line Boundaries (usually E-W or N-S)

3) Reflect the extensive and iterative interests, validation, and feedback of LFI partners and stakeholder working groups. In some cases, this involved value judgments by the stakeholder groups. For example, the general location of each Community Forest was selected by the Community Forestry stakeholder working group. And areas that were Optimally Suitable for "commercial or preservation (pc)" were ultimately allocated to either Commercial Forestry or Protected areas.

Boundaries were delineated for the "3 C's" of Land Use, i.e. Commercial Forestry, Conservation (Preservation/Protected), and Community. Boundary delineation was an iterative process. Initial broad scale boundaries were rough-sketched to encompass large areas having the same Optimal Suitability. The initial sketches were then reviewed, validated, and refined by LFI stakeholder groups. Based on feedback and collaboration with the stakeholder groups, the Optimal Land Use Area boundaries were refined, re-delineated, and redrawn at successively more detailed scales. The Optimal Land Use Areas do not overlap, but many of them share a common boundary. Optimal Land Use for all land use types are shown in Figure 16.

In some locations, this process necessarily forced the inclusion of small areas having a less-than-optimal suitability within the boundaries of a larger Optimal Land Use Area. For example, small areas of steep slopes or agriculturally impacted forest are locally included within a Commercial Forestry Land Use Area. Locally, the recommendations of LFI stakeholder groups took precedence over the Optimal Suitability models, particularly where existing GIS data proved inadequate in the representation of important features. These exceptions are described in the "Protected Area Design", "Commercial Forestry Area Design", and "Community Forest Area Design" sections below.

Protected Area Design

Liberia is a signatory to the United Nations Convention on Biological Diversity treaty (ratified November 8, 2000), in which it pledged to "set aside at least 10% of the land area for Strict Protection and 30% of the land area for protection and multiple-use for partial protection". The minimum 10% area (approximately 950,000 hectares) provided a gross target for the design of Protected Areas.

Protected Areas were designed and delineated in collaboration with the LFI Conservation stakeholder working group. In addition to the suitability modeling, additional factors were considered when delineating Protected Area boundaries, including the presence of endangered species (IUCN "Red List") and/or high biological diversity, distance from settlements, and mangrove areas. Liberia's National Biodiversity Strategy and Action Plan provided additional guidance. Towns and densely populated areas were avoided wherever possible.

Optimal Protected Areas were eventually refined, through multiple versions, to twelve (12) Protected Areas, plus the two existing preserves (Sapo National Park and Mount Nimba Nature Reserve), for a total of fourteen Protected Areas covering 1,141,813 hectares--approximately 12% of

Liberia's total land mass. Each area was given a name descriptive of its location and/or distinguishing feature(s). Protected Areas range in size from 10,482 hectares (Nimba West) to 164,628 hectares (Foya). For comparison, the existing Mount Nimba Nature Reserve is 13,569 hectares, and Sapo National Park is 150,482 hectares.

On average, the designed Protected Areas are 93.6% highly suitable for Preservation, 65.4% highly suitable for Commercial Forestry, and 16.7% highly suitable for Community Forestry (Table 5). Most individual Protected Areas were highly suitable for Preservation, with the exception of Lake Piso and Margibi Mangrove areas. These areas are not well-represented by the Suitability Model output, primarily due to the inability to model mangrove areas with the available Land Cover data, and the relatively narrow coastal zone accounted for in the "Distance to Ocean" model variable. Both of these areas are high Preservation priorities for the LFI Conservation stakeholder group.

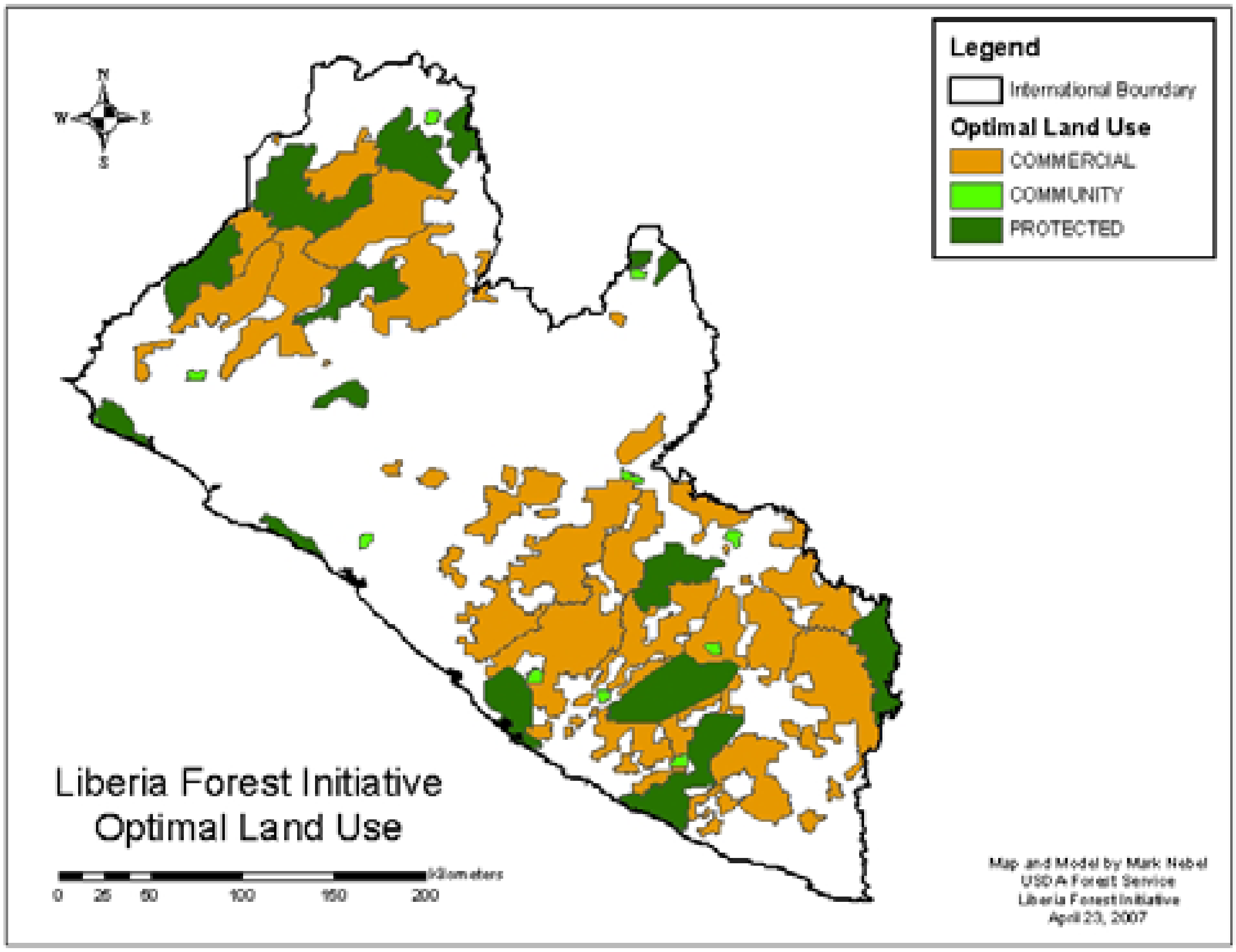

Figure 16. Optimal Land Use.

Commercial Forestry Area Design

The Commercial Forestry stakeholder working group set a target of fourteen (14) commercial forestry concessions totaling 1-2 million hectares in area. This target was chosen to meet projections for sustainable forest harvests, job creation, and needed taxation income for the government of Liberia.

In addition, in the United Nations Convention on Biological Diversity treaty, Liberia pledged to "set aside at least 10% of the land area for Strict Protection and 30% of the land area for protection and multiple-use for partial protection". The 30% area (approximately 2.8 million hectares) provided another gross target for the design of Commercial Forestry Areas, which are expected receive some degree of environmental protection (as National Forests) under Liberian law.

Based on the Optimal Suitability model and collaboration with the LFI Commercial Forestry stakeholder group, 53 Commercial Forestry areas (2,737,372 total hectares, approximately 26% of Liberia's total land mass) were delineated, ranging in size from 1,000 to 229,000 hectares (Figure 16). The smaller areas are envisions for short-term timber sale contracts, while the large areas would be appropriate for long-term logging concessions. Some large Commercial Forestry areas are contiguous and could be combined to form still larger single concessions. Where possible, major rivers and important roads were used as Commercial Forestry Area boundaries.

On average, the designed Commercial Forestry Areas are 80.3% highly suitable for Commercial Forestry, 85.5% highly suitable for Preservation, and 34.2% highly suitable for Community Forestry (Table 5). Some small areas of land relatively unsuitable for Commercial Forestry are included within the boundaries. These inclusions are typically characterized by locally steep slopes, or forests with an agricultural component or near communities.

Many Commercial Forestry Areas are also highly suitable for Preservation. These are large areas where Optimal Suitability is 'pc', i.e. either Commercial Forestry or Preservation. Based on the land use targets of the stakeholder groups and Liberia's economic realities, these areas were primarily allocated to Commercial Forestry. The Commercial Forestry Areas are largely unsuitable for Community Forests.

Community Forest Area Design

The Community Forestry stakeholder working group delineated 11 Community Forest Areas. The working group agreed on a target size of approximately 5000 hectares maximum for each Community Forest, as this was believed to be a reasonable management size, and was thought to be consistent with other countries in the region (e.g. Cameroon) that had developed Community Forestry programs.

The stakeholder working group strived to identify suitable Community Forests in different parts of Liberia. The areas chosen were based on the firsthand knowledge of the areas by members of the Community Forestry stakeholder group, coupled with the Suitability Model results. Target areas were identified to serve one or more communities, and the boundaries of the Community Forests were interactively delineated and refined based on the Community Forest Suitability, the target area size (<= 5000 hectares), and easily identifiable natural boundaries.

Eleven Community Forests (Figure 16) were delineated, ranging in size from 1,881 to 6,061 hectares, and totaling approximately 52,000 hectares. Designed primarily for demonstration purposes, this is a minimum number of Community Forestry areas. Indeed, the suitability model results indicate a high potential for additional Community Forests, consistent with the suitability modeling and other compatible forest uses.

A summary of Suitability by Land Use Area type is shown in Table 5. On average, the designed Community Forest Areas are 98.7% highly suitable for Community Forestry, 38.5% highly suitable for Preservation, and 18.5% highly suitable for Commercial Forestry.

Suitability Value	Community Suitability (sq. km)							Preservation Suitability (sq. km)						Commercial Suitability (sq. km)							
	0	**2**	**3**	**4**	**5**	**Low%**	**High%**	**2**	**3**	**4**	**5**	**Low%**	**High%**	**0**	**2**	**3**	**4**	**5**	**Low%**	**High%**	**Total Hectares**
LAND USE CATEGORY																					
Commercial	0	3531	14430	8709	619	65.8%	34.2%	1937	2021	10861	12477	14.5%	85.5%	1490	1744	2107	8586	13345	19.6%	80.3%	**2,737,372**
Protected	1649	2625	5020	1796	68	83.3%	16.7%	398	319	1657	8935	6.3%	93.6%	3018	789	792	955	5584	41.3%	65.4%	**1,141,813**
Community	0	0	7	176	336	1.3%	98.7%	203	116	195	5	61.5%	38.5%	27	140	256	25	71	81.5%	18.5%	**52,193**
HISTORIC LAND USE PROPOSALS																					
Proposed Protected	1649	2025	4197	1728	127	80.9%	19.1%	920	872	1964	6130	18.1%	81.9%	2423	1134	814	1846	3505	45.0%	55.0%	**1,001,792**
National Forests	6	3956	7290	2204	185	82.5%	17.5%	1491	1327	4324	6508	20.6%	79.4%	898	348	1128	5266	6013	17.4%	82.6%	**1,368,904**

Suitability Values derived from Suitability Models.

Low% where Suitability Value = 0 to 3

High% where Suitability Value = 4 to 5

Columns omitted where Suitability Values are zero across all Land Use Types.

Area in square kilometers, unless otherwise indicated.

Total square kilometers and hectares are not identical for all suitability types, due to data gaps and rounding.

Table 5. Overall Suitability of delineated Land Use Areas, and of Historic Land Use Proposals.

Optimal Land Use Plan

Summary Statistics

In summary, 84.4 % of the Commercial Forestry Areas are Land Cover Class 3.2 or 3.3 (open dense forest and closed dense forest, respectively). Protected Areas, similarly, have 82.2% of their landcover in these two classes. Community Forests have a much lower proportion (19.3%) of their land in these dense forest classes, and have their majority (80.4%) in the mixed forest-agriculture landcover classes (2.2, 2.3, and 3.1). All of these results are reflective of the Land Cover Type variable in the suitability models.

We briefly compared the results of this planning effort with a previously Proposed Protected Area Network (per Conservation International, and Bayol and Chevalier {2004}). The current LFI land use planning process, described in this report, resulted in 1.14 million hectares of Protected Areas, compared with approximately 1.00 million hectares in the historic Proposed Protected Area network (both calculations include Sapo National Park and Nimba Nature Reserve)—an increase of 140,000 hectares (or 14 percent). At the same time, the overall average Preservation Suitability of the network increased from 81.9% to 93.6%. See Table 5.

We also compared the Commercial Forestry Areas with Liberia's existing National Forest system. This comparison is not entirely equivalent, since likely not all of the Commercial Forestry Areas will equate to National Forests, and there are significant areas of overlap between the historic National Forests and historic Proposed Protected Areas. Nonetheless, the total area available for Commercial Forestry doubled, from approximately 1.37 million hectares to 2.74 million hectares, while retaining a relatively high average Commercial Suitability (82.6% to 80.5%, respectively). See Table 5.

Next Steps

GIS has been an important and powerful tool for the development of a Strategic Forest Management Plan for Liberia. The suitability and optimization models developed for this program are a starting point in the evolution and implementation of this national strategy. The models and delineated boundaries put forward in this paper will be refined over time, as additional data become available, and as the plan is vetted through additional experts, stakeholder groups, and the Liberian people.

Some additional data needs have already been identified which could affect the Plan and outcomes, including data on: 1) Deeded lands, tribal lands, and any other pre-existing land encumbrances, 2) Mineral deposits and occurrences, and 3) Forest inventory data. Other data needs may become apparent as the process moves forward.

Acknowledgements

Thanks are due to the many people and organizations that supported this assignment. Bob Simpson was again my host and expeditor. Tyler Christie from Conservation International provided important data, facilitated many meetings, and spurred everyone to meet our ambitious schedule and goals. In particular, I would like to acknowledge all of the people and organizations that participated in the Commercial, Conservation, and Community stakeholder working groups, and staff at the Liberia Forestry Development Authority. Your information, insights, feedback, and hard work were invaluable. Many thanks to all of you! I look forward to our continued working relationship and the future of sustainable forestry in Liberia.

Finally, I could not have participated in this project without the unwavering support of my family and of the Lassen National Forest.

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