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Oil palm plantations in Colombia: a model of future expansion

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ABSTRACT

Biofuels are promoted worldwide as an alternative for the replacement of fossil fuels, especially in the transportation sector, although the extent to which biofuels can meet this need is unclear. Currently, oil palm is the most important crop used for biodiesel production in the world. The growth of oil palm plantations in Asia has often occurred at the expense of forest areas creating environmental concerns. Colombia is the fifth largest oil palm grower worldwide, and policies that provide subsidies have been enacted to ensure that Colombia plays an important role in future biodiesel markets. At that same time, many sectors of society are concerned that the negative effects of biofuels may be worse than the benefits. In this paper we analyze the land use transitions generated by the expansion of oil palm crops between 2002 and 2008; we identify the factors associated with the expansion and project the future expansion of plantations in Colombia by applying spatial regression analysis and econometric models. To model future expansion, we started with a map of oil palm plantations in 2008. An econometric model that incorporates the impact of governmental policies (normative and economic that support the biofuel sector) through a Time Series Intervention Model Analysis was used to estimate the cultivated area in 2020. To spatially project these estimates a spatial logistic regression model that incorporates biophysical and socioeconomic variables was used. Finally, future land use transitions associated with the expansion of oil palm plantations were analyzed. The results show that present and future oil palm expansion is concentrated in areas dominated by pastures, and to a lesser extent areas that are a mix of agricultural land and natural forests. Our results also suggest that it is highly unlikely that the government will reach its goal of over 3 million hectares of oil palm plantations by 2020 and the goal of biodiesel blends supplying 20% of the national fuel needs.

1. Introduction

The growth of biofuels production is associated with the rapid increase in the global demand for primary energy. It is estimated that global demand for energy will increase by 36% between 2008 and 2035, and that fossil fuels will remain the primary energy source until 2035. However, the development of new energy alternatives is being driven by the need to avoid emissions from fossil fuels and identify sources of sustainable,

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low-cost energy able to guarantee the energetic security of all countries (BP, 2011; IEA, 2010).

Biofuels are promoted worldwide as an alternative to replace fossil fuels used in the transportation sector, although the extent to which biofuels could meet this need is unclear (Gallagher, 2008). In 2007, about 13 million hectares or 1% of the arable land in the world was used for biofuel crops. It has been estimated that by 2030 these crops could represent 4% of arable land, but biofuel production would still account for only a small fraction of the total fuel requirements for transportation (Sheil et al., 2009).

Although biofuels are often seen as environmentally friendly, many concerns have been raised about the possible environmental impacts of the expansion and intensification of biofuel production (Ewing and Msangi, 2009; Gallagher, 2008; Gasparatos et al., 2011; Searchinger et al., 2008). These impacts include: (i) competition for lands that are used to produce food; (ii) increase pressure on water resources; (iii) the expansion of plantations into natural ecosystem areas; and (iv) increasing greenhouse gas emissions due to land use changes.

The relation between the expansion of crops to produce biodiesel and forest loss in tropical countries has been well documented in Malaysia and Indonesia (Dillon and Laan, 2008; Wilcove and Koh, 2010). Between 1990 and 2005, approximately 59% of oil palm expansion in Malaysia (FAO, 2005) and 56% of palm plantations in Indonesia occurred at the expense of natural forests. In contrast, in Brazil the expansion of sugarcane crops for ethanol production has not been a direct cause of deforestation in the Amazon region, because expansion has occurred mainly on pastures lands (Goldemberg and Guardabassi, 2009). Nevertheless, the expansion of sugarcane has contributed indirectly to deforestation by displacing pastures used for grazing toward the south-eastern states of the Amazon (Gao et al., 2010). A large component of the impact of biofuel production also depends on the type of land use or land cover that it replaces (Achten and Verchot, 2011). Most studies have focused on how biofuels help to avoided emissions from fossil fuels or on life cycle analyses (e.g. emissions associated with production, processing and transport) of biofuels, but emissions from land use change have been largely ignored. For example, conversion of tropical forest will result in large losses of carbon to the atmosphere, and the benefits of biofuels can take hundreds of years to replace the original carbon debt (Lapola et al., 2010; Achten and Verchot, 2011). It is also critical to understand what happens to land use activities, such as food production, when they are displaced by biofuel production (Hellmann and Verburg, 2011).

Colombia is the main oil palm producer in America. Commercial production began fifty years ago, and is currently consolidated in four geographic regions (Ospina, 2007). In 2010, oil palm plantations covered 404,104 ha, and approximately 160,000 ha were used for biodiesel production (FEDEPALMA, 2011). The expanding national and international biofuel market has stimulated much interest in biodiesel production in Colombia, especially given that the government has the ambitious goal of producing biodiesel, by replacing 20% of diesel with biofuel by 2020 (DNP, 2010). By 2010, most regions of the country had implemented the mandatory 7% volume blend, lower than the initially planned goal of 10%; this increase in the domestic consumption oil palm biodiesel has reduced oil palm exports (FEDEPALMA, 2011). To meet the 20% national goal an additional 600,000 ha of oil palm are needed, for which the government has implemented a subsidy program designed to promote the expansion of oil palm plantations in several areas of the country (Consulting Biofuel, 2007). In another document the Ministry of Agriculture has even set a target of 3 million hectares for the oil palm industry (Bochno, 2009). To achieve these goals a set of normative tools, such as statutory mandates for mixtures and economic incentives that include price supports, subsidies, tax exemptions or preferential taxes were designed (DNP, 2008). These policy tools reduce the risk and uncertainty from the prices of both raw materials and energy inputs. In response to these expectations, two studies were done to identify suitable areas to grow oil palm (CENIPALMA-CORPOICA, 1999; IDEAM-IGAC, 2009). But these had serious limitations as areas of current productive plantations appear as non-suitable in their analysis.

The purpose of this paper is to examine the impacts and the factors associated with recent and future projected expansion of oil palm plantations in Colombia. First, we analyze the impact of new oil palm plantations during the period 2002–2008 by determining the land use transitions of these plantations. Second, we apply an econometric model time series to forecast the area of oil palm plantations in 2020; this model incorporates the impact of governmental policies (normative and economic that support the biofuel sector) through an ''intervention analysis''. Third, we construct a probability map of future oil palm plantation expansion based on a logistic regression model that incorporates biophysical and socioeconomic variables to spatially project the estimates of cultivated areas for 2020. Finally, we analyze the probable future land cover/use transitions associated with the 2008–2020 projected expansion of plantations.

2. Materials and methods

2.1. *Study area*

Colombia is located in northeast South America, in the inter-tropical zone. The total area is approximately 1.14 million km^2, of which approximately 50% is covered with forest. The country is geographically heterogeneous due to high variation in climate, physiography, vegetation, soils, and biota. A major feature is the Andean region which runs across the central portion separating the Eastern and Western lowlands where most forests still occur. With about 45 million inhabitants, Colombia is the fourth most populated country in America. The population is concentrated in the Andean and Caribbean regions; approximately 76% of the inhabitants live in urban areas (Etter et al., 2006).

As a result of the high ecological variability between regions, Colombia has one of the highest levels of species diversity per unit of area worldwide: in only 0.77% of the world's land area it contains 10% of its known species (IDEAM, 2004). In spite of its natural richness, Colombia has experienced rapid transformation processes by which natural ecosystems have been replaced or fragmented. Currently deforestation rates are approximately 238,000 hectares

(Cabrera et al., 2011). The causes of deforestation are diverse and depend on the specific conditions of each region, but they are usually related to the expansion of the agricultural frontier for cattle grazing, forest fires, wood extraction and the growth of illicit crops (Cabrera et al., 2011).

The most extensive land use is cattle grazing which spans over more than 70% of the agricultural land, usually exhibiting low productivity levels (McAlpine et al., 2009). Only 9.6% of agricultural land is used for crops (4.1 million ha in 2011). Annual crops represented 33% of the cultivated area, whereas permanent crops and plantations represented 59%, the remaining 8% was classified as fallow land. During the period 2002–2008 annual crops increased by 1.7%, while the area of permanent crops and plantations increased 25.6% (MADR, 2011).

Oil palm plantations account for less than 1% of the total agricultural lands and 0.3% of the country area (FEDEPALMA, 2011). In 2010 oil palm made up 2.6% of the agricultural GDP and 0.22% of total GDP (MADR, 2011). Oil palm plantations are located in four zones: north, central, eastern and the western zones (Fig. 1). The eastern zone has the most plantations and contributes 39.1% of the area planted with oil palm. The oldest plantations are located in the north (28.5%) and central zones (28%). The western zone contributes only 4.5% of the cultivated area in the country (FEDEPALMA, 2011).

In some cases oil palm plantations have been located in regions with persistent intensification of the armed conflict and with problems of illegal redefinition of rights of land ownership (Seeboldt and Salinas, 2010). The expansion of oil

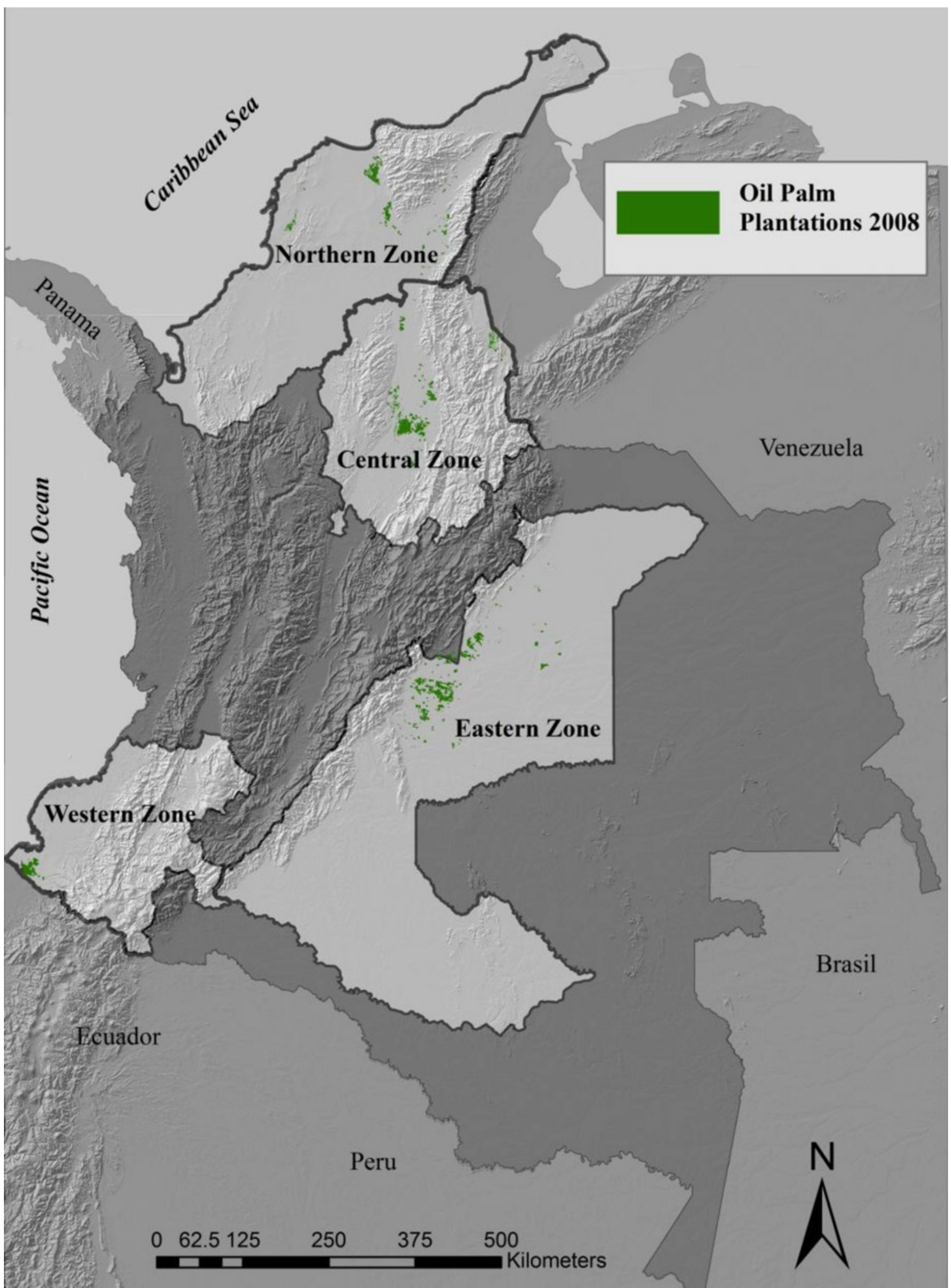

Fig. 1 – Location of oil palm plantation areas in 2008, and plantation zones in Colombia as defined by FEDEPALMA.

palm plantations has been allegedly associated with a ''land expropriation-peasant expulsion-commercial plantation implementation'' cycle (Fajardo, 2009), in some areas of the northern zone.

Although limited in area, the expansion of oil palm in the western zone mainly occurred in areas that were previously forested (Seeboldt and Salinas, 2010). However, due to the high humidity and cloudiness, the bud rotting disease reduced plantations from 33,700 in 2006 to 18,000 ha in 2010 (FEDEPALMA, 2010b). In addition, poor infrastructure, armed conflicts, and the existence of Collective Territories of Afro-Colombian communities have limited the development of the oil palm industry in this region (Seeboldt and Salinas, 2010; BID-MME, 2012).

2.2. *Data*

The type of data, units, and sources of the information used in the analysis and modeling are presented in Table 1.

To identify the previous land use in areas that have been transformed into oil palm plantations during the period 2002–2008, we used a national land cover map (IDEAM, 2007) and updated a plantation growth map for 2002–2008. This plantation map was constructed using information on the establishment date of plantations from the 2007 oil palm plantations map based on satellite and field data (FEDEPALMA, 2007), updated by us to 2008 using Landsat-ETM imagery (http://glovis.usgs.gov/) and expert knowledge. The 2002 land cover classes were reclassified it into 11 classes, as follows: (1) heterogeneous agricultural areas (including crops mosaic, mosaics of crops and natural areas, and mosaics of crops, pastures and natural areas), (2) undifferentiated annual crops (cereals, vegetables, tubers and other seasonal crops), (3) undifferentiated permanent crops (sugar cane, coffee, cocoa), (4) rice crops, (5) banana, (6) pastures, (7) savannas (open grassland, dense grassland), (8) secondary regrowth (includes fragmented forests), (9) plantation forests, (10) natural forests (dense forests, open woodlands), and (11) other coverage (swamps, water, bare soil, areas where mining extraction takes place, and urban areas).

To create the Time Series Intervention Model, we used the statistics of oil palm plantation areas for the period 1967–2009 (FEDEPALMA, 2001, updated to 2009 with annual statistics). To account for the intervention policies to promote the biofuel sector introduced in 2002 (DNP, 2008), a dummy variable was added to the model. The dummy variable was assigned a 0 value for all years before the intervention policy and a value of 1 after the intervention.

To calculate the plantation area required to provide the oil needed to comply with the mandates of biofuel blends, we used the data on domestic diesel demand projected for 2020 (UPME, 2008). We assumed a gradual increase in crop productivity from the current 3.5 Mg/ha to 4.1 Mg/ha in 2020 (FEDEPALMA, 2011), and the gradual increase of blends from 5% in 2008, 7% in 2010, 10% in 2014, and 20% in 2020 (UPME, 2008).

Table 1 – Data sources used in the different modeling and analysis procedures.

Analysis	Variable group	Variable	Source	Type of data	Units
Logistic regression	Dependent	Oil palm presence	Map oil palm plantations in Colombia (FEDEPALMA, 2007) and Landsat imagery	Dichotomic	–
	Explanatory variables	Mean annual temperature	WorldClim (Hijmans et al., 2005)	Continuous	°C
		Annual rainfall of driest month	WorldClim (Hijmans et al., 2005)	Continuous	mm
		Relative humidity	Climatological maps (IDEAM, 2005)	Categorical	–
		Solar radiation	Solar radiation map (IDEAM, 2005)	Categorical	–
		Effective depth	Soil map of Colombia (IGAC, 2003)	Categorical	–
		Altitude	90 m DEM (IGAC, 2009)	Continuous	m
		Slope	90 m DEM (IGAC, 2009)	Continuous	%
		Distance to oil palm extraction plants	Oil palm map (FEDEPALMA, 2007)	Continuous	km
		Distance to road	Distance map to nearest road network (IGAC, 2007)	Continuous	km
		Distance to populated centers	Base map (IGAC, 2009)	Continuous	km
		Distance to main cities	Base map (IGAC, 2009)	Continuous	km
		Population density	National municipality statistics (DANE, 2010)	Continuous	pers/km^2
		Natural protected areas	National Natural Parks map (IDEAM-IGAC, 2009)	Dichotomic	–
		Indigenous reserves	Indigenous reserve map (DANE-IGAC, 2005)	Dichotomic	–
		Afro-descendant communities	Afro-descendant communities map (DANE-IGAC, 2005)	Dichotomic	–
Land use transitions		Land cover type	Ecosystem map of Colombia (IDEAM, 2005)	Categorical	ha
		Oil palm plantation growth area 2002–2008	Oil palm plantations maps 2002 and 2008 (FEDEPALMA, 2007) and Landsat imagery	Dichotomic	ha
Econometric analysis	Dependent	Oil palm areas (1967–2009 series)	Statistics (FEDEPALMA, 2001, 2010a)	Continuous	ha

To perform the spatial analyses of oil palm expansion, the 2008 oil palm map and a set of map grids of biophysical and socioeconomic variables representing the suitability factors of plantation expansion in the country were constructed. An exploratory analysis to verify possible correlations between independent variables was performed. The eighteen variables finally included in the model are presented in Table 1. All maps were projected to the same coordinate system, with a spatial resolution of 500 m. The ArcGis.v10 and Idrisi15. ANDES-version software were used for the spatial analyses.

2.3. *Modeling and analysis*

The study included four independent types of analysis: (1) a map overlay to analyze the transitions of land use, to determine which land cover classes and areas were replaced by oil palm plantations during the period 2002–2008; (2) a Time Series Intervention Model Analysis to project the cultivated area for the year 2020, which incorporated the impact of government policies (normative and economic policies that support the biofuel sector); (3) a logistic regression model that incorporated biophysical and socioeconomic explanatory variables, to produce a probability map of oil palm presence to be used to project for the future expansion of oil palm plantations and (4) a map overlay to analyze the transitions of land use using the probability map to project the likely land cover/use classes that would be impacted by the future expansion of oil palm plantations. The methodological procedure used to integrate econometric analysis with the spatial modeling analysis is presented in Fig. 2.

2.3.1. *Analysis of land use transitions for the 2002–2008 period*

To quantify the land use transitions we performed a GIS map overlap procedure of the 2002–2008 plantation growth area with the reclassified 2002 land cover/use map. This provided the information on the spatial location and the quantity of land cover/use classes transformed into oil palm plantations. The statistics were calculated for each of the four geographic palm plantation zones (Fig. 1).

2.3.2. *Projections of the future expansion area in different scenarios*

To estimate the increase of oil palm plantations by 2020, we performed four calculations: (i) a simple linear trend based on the historic data; (ii) an econometric model that incorporated the historic trend and the policy interventions and subsidies; (iii) the projected demands that follow from the planned increases in the biofuel mixtures (7% in 2010, 10% in 2014, and 20% in 2020); and (iv) the trend that incorporated the expected national goal of 3 million hectares (Bochno, 2009).*Econometric Intervention Analysis model*. The Intervention Analysis is an econometric method that examines the impact of external events such as public policies on the historical trend of a time series. According to Vallejo (1996), quantifying the impact of an intervention variable helps explain the behavior of the time

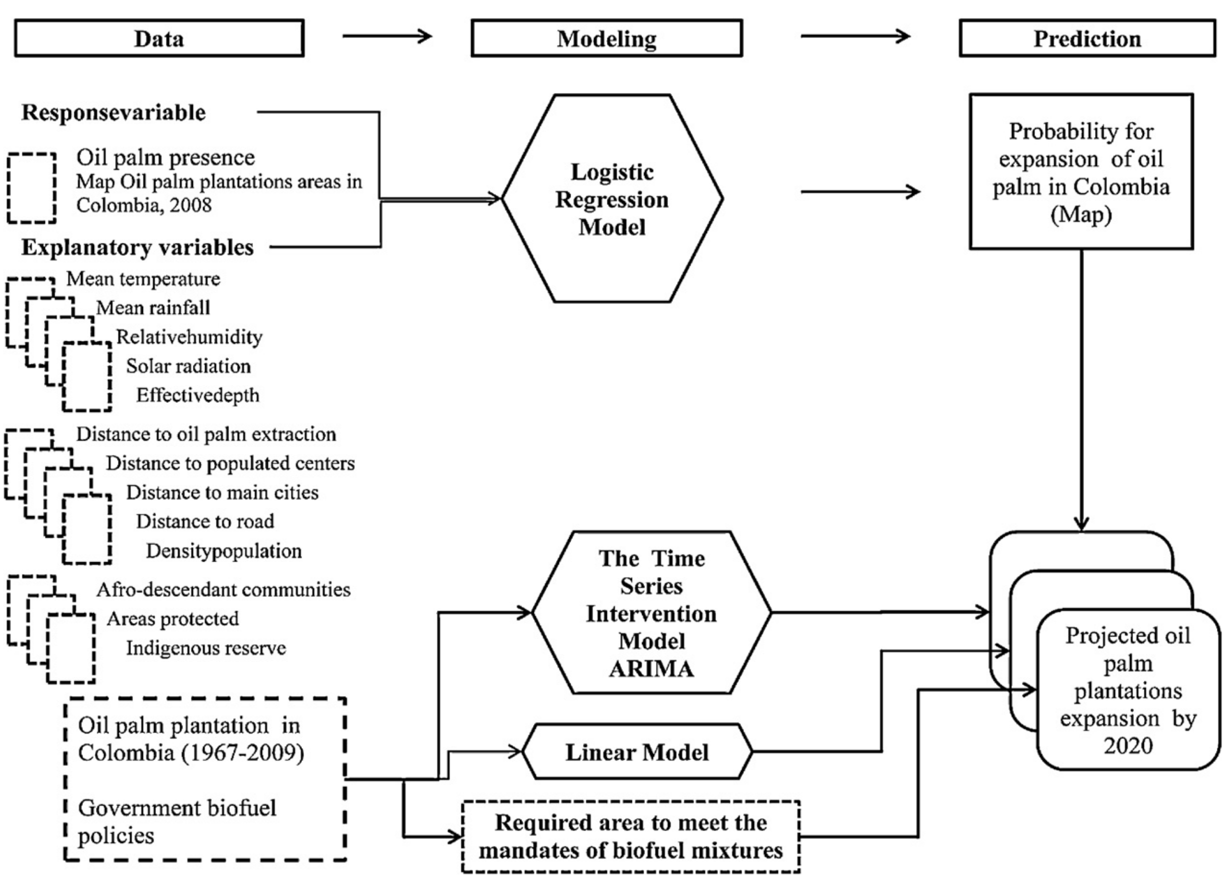

Fig. 2 – Methodological diagram showing data inputs, modeling sequences and outputs.

series and enhance the parameter estimations and model results. The Time Series Intervention model is an extension of the ARIMA (p, d, q) method, in which an additional explanatory variable that accounts for changes in policies affecting the process is included (Enders, 1995). The model is formally expressed as follows:

$$y_t = a_0 + \sum_{i=1}^{p} a_i y_{t-i} + \sum_{i=0}^{q} \beta_i \varepsilon_{t-i} + \theta X_t + u_t \quad (1)$$

where y_t is the dependent variable, which in this case is defined as the absolute variation the area of oil palm plantations in hectares at each time step; ε_t is the error; a_i, β_i, and θ are parameters to be estimated; p is the lag order of the dependent variable; q is the order of the moving mean component; d the differentiation degree of the series; X is the *dummy* variable representing the policy intervention and u_t is the estimated error.

2.3.3. *Spatial modeling to identify the most probable areas of future oil palm plantation expansion*

The suitability for a particular land use can be explained by a wide range of factors such as biophysical and climatic conditions of the site, as well as economic and political factors, such as taxes, subsidies, access to credit, technology production and transportation costs, and land use planning policies that restrict or encourage certain land uses (Koomen et al., 2007). The logistic regression model is appropriate when used to predict the probability of a particular event occurring or not occurring (binary dependent variable) (Aldrich and Forrest, 1984). These models are characterized by binary dependent variables, while explanatory variables can be continuous, categorical or dichotomous. In our case we are interested in assessing the likelihood of the presence (1) or absence (0) of oil palm cultivation in a particular area, given certain biophysical (climate and soils) and infrastructure for production conditions. The general specification of the model is based on studies of land use and cover change by Etter et al. (2006) and Lambin and Meyfroidt (2010). For our study, the logistic regression model is represented by the following equation:

$$Log\left(\frac{Y}{1-Y}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_{16} X_{16} + \varepsilon \quad (2)$$

where, Y is the binary dependent variable, which takes the value of one (1) in the presence of oil palm plantations or zero (0) in the absence of oil palm plantations in each analyzed cell; $X_1, X_2, X_3, \ldots, X_{16}$, are the explanatory variables that include that biophysical and socio-economic factors used to explain the presence/absence of the crop; $\beta_0, \beta_1, \beta_2, \ldots, \beta_{16}$ are the parameters to be estimated and ε is the regression error. The explanatory variables included in our model were: slope, altitude, relative humidity, rainfall of driest quarter, mean annual temperature, solar radiation, effective soil depth, distance to roads, population density, distance to major cities, distance to extraction plants, distance to population centers, presence of Afro-colombian territories, presence of indigenous reserves and presence of national parks (Table 1).

The output of this model was a probability map of the presence of oil palm plantations. The probability map was then used to show where future oil palm plantations are expected to expand based on the amount of change by 2020 for each scenario.

2.3.4. *Analysis of probable future land use transitions (2008–2020)*

To assess future land use transitions, we overlapped the predicted distribution of new oil palm plantations for the period 2008–2020 with the reclassified 2002 land cover/use map. Because we do not have future land use maps, by using the 2002 map this analysis we are assuming that the areas outside the oil palm plantations will remain unchanged; therefore, this analysis ignores other possible land use transitions (e.g. pastures to crops, crops to pastures). Although this is a limitation, the analyses are meant to provide an indication of the regional differences of the most probable transitions. The statistics were calculated for the four zones of oil palm production in the country.

3. Results

3.1. *Land use transitions in the oil palm producer zones for the period 2002–2008*

Although transitions varied slightly from region to region, in general the main transition to oil palm plantations was from pastures (Table 2). Of the 155,100 ha of new oil palm plantations between 2002 and 2008, 79,000 ha (51%) occurred in pastures, 29.1% in croplands, and 16.1% in natural vegetation (forest and savannas) and regrowth forests. The transition from pastures was more dominant in the east and central zones, while the transitions from heterogeneous agricultural areas were highest in the north zone. In the western zone there were no changes in the area of palm oil plantations during the period analyzed.

In the eastern and central zones oil palm plantations showed the largest expansion with 68,600 and 68,500 ha respectively. In the eastern zone 58% occurred at the expense of pastures, 11% of savannas, and 12% of irrigated rice crops (Table 2). In the central zone 51% originated from areas that were in pastures in 2002, and approximately 20% and 11% of the transformation occurred in heterogeneous agricultural areas and natural forests, respectively; while 4.3% of the change took place in secondary vegetation. In the northern zone, 18,000 ha of new plantations occurred between 2002 and 2008, mostly from pastures (26%), followed by heterogeneous agricultural areas (24%).

3.2. *Projections of oil palm plantations area growth under different scenarios*

The four projected growth trend scenarios of oil palm plantations for 2010–2020 are very different (Fig. 3). The extrapolation of the linear trend based on data from 1967–2002 predicts 330,982 ha of oil palm plantations by 2020. The econometric time intervention model, which includes the effect of the subsidy policies after 2002, predicts 647,687 ha by 2020. The third projection is based on the additional production requirements needed to meet the increasing biodiesel mixture targets established by the government, and this

Table 2 – Land cover transitions toward oil palm in the producer zones for the period 2002–2008 (000s).

Cover type	Northern zone			Central zone			Western zone			Eastern zone			Total	
	Area in 2002 (ha)	Change to oil palm (ha)	%	Area in 2002 (ha)	Change to oil palm (ha)	%	Area in 2002 (ha)	Change to oil palm (ha)	%	Area in 2002 (ha)	Change to oil palm (ha)	%	Change to oil palm (ha)	%
Heterogeneous agricultural areas	2,821.30	4.2	23.6	3403.1	13.7	20.0	1666.3	0	0.0	1462.2	3.8	5.5	21.8	14.0
Undifferentiated annual crops	70.956	0.7	4.1	42.6	0.1	0.2	10.5	0	0.0	2.2	0.0	0.0	0.9	0.6
Undifferentiated permanent crops	125.706	7.2	39.8	88.3	4.2	6.2	143.8	0	0.0	93.6	2.9	4.3	14.3	9.2
Banana	59.422	0.1	0.8	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.1	0.1
Rice	52.852	0.0	0.0	0.1	0.0	0.0	0.0	0	0.0	141.0	8.0	11.7	8.0	5.2
Pastures	6,286.76	4.7	26.0	2598.4	34.7	50.7	703.9	0	0.0	3865.8	39.6	57.7	79.0	50.9
Forest plantations	31.098	0.0	0.0	2.0	0.1	0.2	19.9	0	0.0	3.7	0.0	0.0	0.1	0.1
Natural forests	3,758.62	0.6	3.3	3753.1	7.4	10.9	4377.7	0	0.0	16031.4	3.9	5.7	12.0	7.7
Savannas	458.732	0.0	0.0	603.0	1.5	2.1	0.0	0	0.0	7010.6	7.6	11.1	9.1	5.8
Secondary vegetation	874.978	0.4	2.4	996.0	2.9	4.3	1217.2	0	0.0	1618.8	0.7	1.1	4.1	2.6
Other covers	2651.068	0.0	0.0	1191.1	3.7	5.3	863.9	0	0.0	1862.4	2.0	3.0	5.7	3.7
Total	17,191.5	18.0	100	12,677.8	68.5	100	9,003.4	0	100	32,091.7	68.6	100	155.1	100

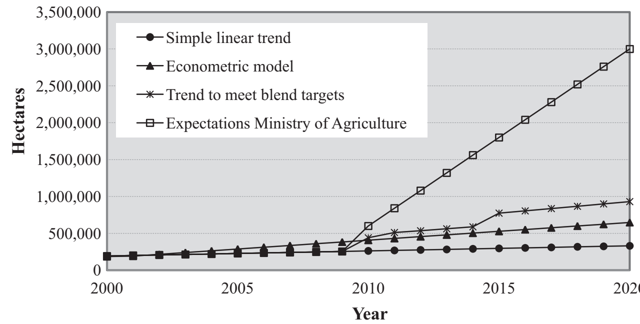

Fig. 3 – Four comparative projections for the expansion of oil palm plantations for 2000–2020 according to the different scenarios considered: simple linear trend based on the pre-intervention 1967–2002; econometric model including policy intervention effects; government biodiesel blending targets; and the Ministry of Agriculture expectations.

predicts approximately 930,000 ha. None of these models are close to the expectations of the government to reach 3 million hectares by 2020 (Bochno, 2009).

The econometric time intervention model explained 70% of the variance of the dependent variable, i.e. increase in the area of oil palm plantations (Supplementary Table 1). The *dummy* intervention variable that captures the effect of policies to promote biofuels since 2002 was statistically significant ($p < 0.01$), which indicates that the policies implemented for the sector in 2002 had a significant positive effect, generating important changes in entrepreneurial decisions, which resulted in a 50% increase in the area oil palm plantations between 2002 and 2008.

3.3. *Projected spatial oil palm expansion scenarios*

The variables that best explained the presence of oil palm plantations in Colombia included: altitude, rainfall of driest quarter, distance to roads and distance to extraction plants (Supplementary Table 2). Other significant variables included slope, distance to populated centers and solar radiation. The low significance of national parks and indigenous reserves is explained by the fact that the extent of these protected areas is very small compared to the total national area; even though some of these areas have suitable climatic and soil characteristics their national conservation status restricts certain type of land use activities.

The spatial expression of the logistic model (Fig. 4a), shows that although large areas of suitable land for oil palm are located in the vicinity of existing plantations, large areas can also be found in other locations. Fig. 4b shows the spatial distribution of oil palm plantations for the three different scenarios of the projected expansion area of plantations constructed from the probability map. The models suggest that under current conditions much of the oil palm expansion is likely to occur in the central zone and in the northern zones in areas of Tolima, Cundinamarca, Antioquia, Bolivar and Córdoba. All these areas are also characterized by important food production (e.g. rice, bannana and livestock) which could

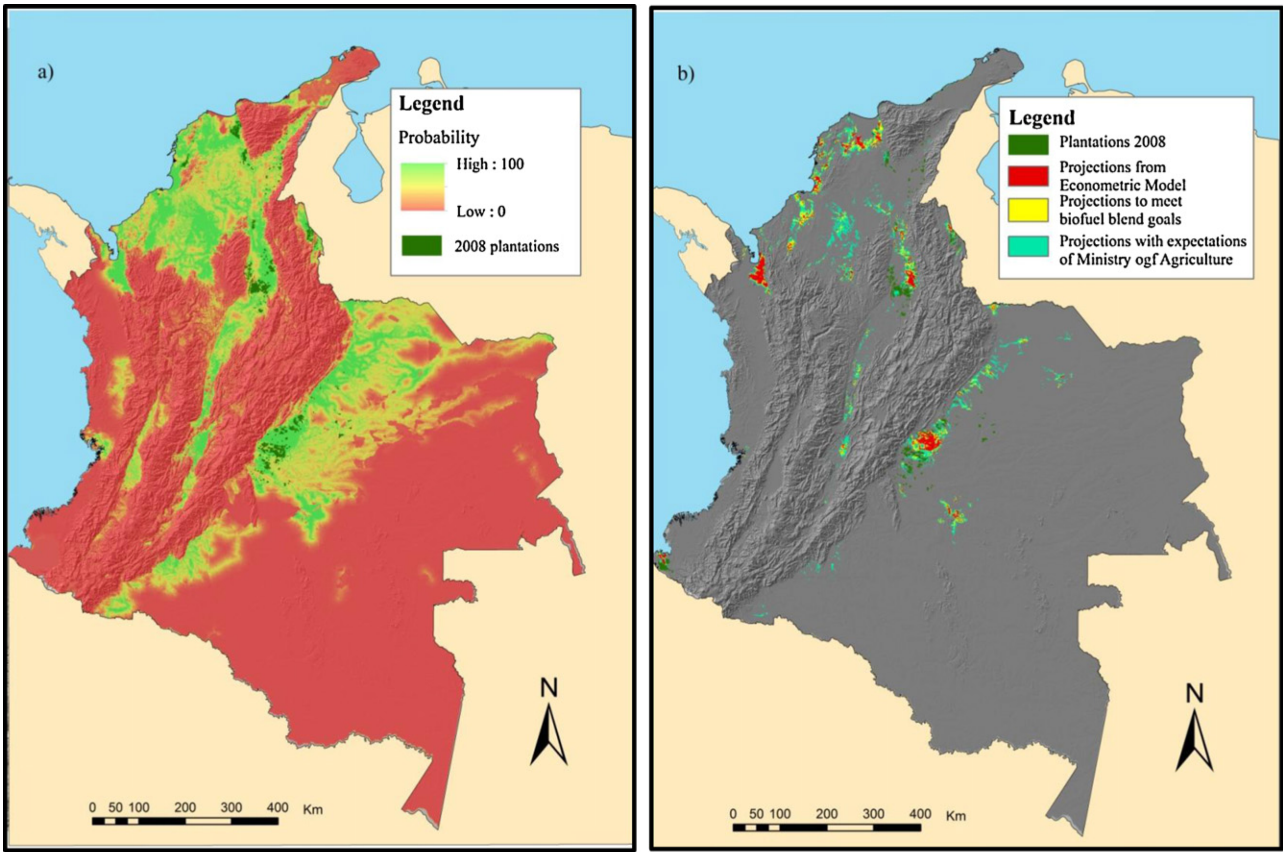

Fig. 4 – Spatial model of future oil palm plantations expansion in Colombia: (a) expansion probabilities according to the logistic model; (b) most probable spatial expansion of oil palm in 2020 according to the total projected area from the econometric model (647,687 ha), the calculated biofuel blending goals (930,000 ha), and the Ministry of Agriculture expectations (3,000,000 ha).

generate substitution risks, threatening the food security of these regions. Another new expansion zone is predicted to the south of the eastern zone in the colonization front of the Northern Amazon region.

3.4. *Analysis of future oil palm land use transitions*

If the future expansion of oil palm, as predicted by our model, is approximately 361,000 ha (Fig. 4b), 49.4% will replace current pasture areas while 19% will replace heterogeneous agricultural areas (i.e. a combination of crops, fallows, secondary vegetation and pastures). Approximately 12.7% (40,000–50,000 ha) of new plantations are expected to replace natural vegetation areas (i.e. forests, shrublands and savannas), the majority savannas and forests of the eastern zone. The analyses also showed that approximately 6,750 ha of rice in the eastern zone, and 22,200 ha of banana in the northern zone could be replaced by oil palm plantations by 2020. In the western zone, future oil palm expansion (13,000 ha by 2020) are expected to replace agricultural areas (4,200 ha), natural forests (3,500 ha) and secondary vegetation (4,000 ha) (Table 3). Two large areas (23,750 ha) in important agriculture areas which have no plantations at present were assigned high probabilities for future plantations: (1) Tolima, an area important for rice production, and (2) Urabá a region with extensive banana plantation, mainly for export.

4. Discussion

This study is the first comprehensive nationwide assessment of the past and future expansion of oil palm and the relation with land cover changes in Colombia. Our results contradict the existing literature and projections oil palm plantations in Colombia in two important aspects. First, the historical impacts and most likely future impacts of oil palm plantations occurred or will occur primarily in areas that have already been cleared (e.g. cattle pastures, agricultural lands), and not in areas of natural vegetation (e.g. forest, savannas). Second, our analyses suggest that the total area of oil palm plantations in 2020 will be much lower than current estimates.

4.1. *The conversion of other land cover land use classes to oil palm plantations*

Between 2002 and 2008, more than 100,000 ha of new oil palm plantations were established in Colombia (Table 2), more than 50% of which were established in areas previously used as

Table 3 – Predicted future land use transitions to oil palm plantations (2008–2020) according to the spatial projection of the area from the econometric model.

Cover type	Northern zone		Central zone		Eastern zone		Western zone		Rest of country		Total	
	Change to oil palm (ha)	%	Change to oil palm (ha)	%	Change to oil palm (ha)	%	Change to oil palm (ha)	%	Change to oil palm (ha)	%	Change to oil palm (ha)	%
Heterogeneous agricultural areas	45,375	27.6	7,350	13.1	6,400	6.2	4,175	32.3	4,775	20.1	68,076	18.9
Undifferentiated annual crops	300	0.2	625	1.1	50	0.0	0	0.0	50	0.2	1,025	0.3
Undifferentiated permanent crops	4,675	2.8	0	0.0	0	0.0	0	0.0	0	0.0	4,675	1.3
Banana	22,200	13.5	0	0.0	0	0.0	0	0.0	0	0.0	22,200	6.1
Rice	1,575	1.0	0	0.0	6,750	6.5	0	0.0	1,550	6.5	9,875	2.7
Pastures	64,275	39.0	39,150	69.6	65,475	63.3	100	0.8	9,475	39.9	178,477	49.4
Forest plantations	25	0.0	0	0.0	0	0.0	0	0.0	0	0.0	25	0.0
Natural forests	5,450	3.3	2,825	5.0	8,100	7.8	3,500	27.1	3,650	15.4	23,525	6.5
Savannas	1,375	0.8	0	0.0	6,500	6.3	0	0.0	975	4.1	8,850	2.5
Secondary vegetation	5,300	3.2	825	1.5	1,625	1.6	4,025	31.1	1,700	7.2	13,475	3.7
Other covers	14,150	7.9	5,475	8.9	8,600	7.7	1,125	8.0	1,575	6.2	30,925	7.9
Total	164,700		56,250		103,500		12,925		23,750		361,125	

pastures. This transition could be interpreted as positive given that oil palm plantations are more productive than most pasture lands (McAlpine et al., 2009), they provide more jobs (Barrientos and Castrillón, 2007) and they can contribute to climate mitigation by the uptake of carbon (Germer and Sauerborn, 2008; Etter et al., 2011). New oil palm plantations (20%) also replaced agricultural lands, particularly areas that were previously used for the production of rice, banana and mixed agriculture. The social, economic, and environmental impacts of these transitions are less obvious, and will depend on the local context and need more detailed studies. Pérez (2011) and Infante and Tobón (2010) for example, point to the likely increases in land, labor wages and agricultural input prices, which displace subsistence crops to more marginal lands and impact on local food prices and food security.

Less than 15% of the new oil palm plantations impacted natural vegetation (e.g. forest, savannas). A possible explanation for the low level of forest clearing is that it will add to the costs of establishing plantations. Furthermore, these areas are unlikely to have the infrastructure (e.g. roads, electricity) that an agricultural region would have. Most of the forest loss has occurred in transformed landscapes with highly fragmented forest remnants, not in continuous forests of the agricultural frontier. However our study possibly underestimated the impacts of palm plantations on natural areas because we did not quantify the effects of indirect land use transitions (Croezen, 2010). Indirect land use transitions could be important when oil palm plantations are displacing previous landowners (e.g. subsistence farmers, cattle ranchers), who then colonize new areas by clearing forest to continue their farming and cattle activities. However, the recent main cause of deforestation in Colombia has been the land clearing for the production of illicit coca crops (Dávalos et al., 2011), mostly beyond the agricultural frontier (Cabrera et al., 2011).

Even though we have emphasized the low impact of new plantations on natural areas in the past, our models suggest that by 2020 approximately 37,000 ha of forest and woody vegetation could be cleared for plantations (10% of all transitions). If the current estimates of deforestation are correct (238,000 ha per year), (Cabrera et al., 2011), this would only account for 1–2% of the total area deforested in Colombia in the coming 8–10 years. Another important area of future expansion is the in the Casanare and Arauca Departments of the eastern zone. These areas still has extensive areas of diverse natural savannas, but the transformation of this region has already been predicted independent of oil palm expansion (Etter et al., 2011). But, in the regions where these changes are to occur, there will also be impacts on water quality and quantity and the price of land (De Fraiture et al., 2008; Pérez, 2011). This is where our spatial analyses of future transformation can assist in identifying high probability of change areas. In these areas, monitoring, policy, or preventive actions could be taken to prevent or reduce the rates of transformation and other negative impacts. For example, although the western zone is not experiencing expansion at present, if in the future the problems caused by diseases and poor infrastructure are overcome, our model suggests that a significant proportion of oil palm expansion in this area would occur in forested areas. Actions taken now (e.g. regional zoning plan) could help to reduce future negative impacts.

4.2. The future distribution of oil palm plantations: how much and where?

Two important aspects of projecting future changes of oil palm plantations are to estimate how much new area will be established and where these changes will occur.

First, our econometric model, which incorporated government policies and subsidies, estimated a growth of approximately 650,000 ha of oil palm plantations by 2020, that is close to the estimate of 743,000 ha of the palm growers association (FEDEPALMA, 2010a), but much lower than the 930,000 ha estimate needed to meet the demand of a 20% blend in biodiesel and the Ministry of Agriculture goal of 3 million hectares (Fig. 3). To achieve the goal of 20% diesel–biofuel mixture, we believe that a major policy change (e.g. large incentives) or an external shock (e.g. dramatic increase in the price of oil, technological changes) will be necessary. The 3 million hectares goal of the government is highly unlikely because to add an additional 2.5 million hectares of oil palm plantations in the next 8 years, would require an investment of at least 37.5 billion USD (assuming total establishment costs USD 15,000 ha^{-1}), equivalent to approximately 1% of the annual GDP spread over the next 8 years 2012–2020. An investment of this magnitude would require a significant increase in subsidies and capital from the government or from the foreign investors. Our model assumes that the present levels of subsidies, the production technologies, and infrastructure cannot deliver the needed increases in palm oil area. A change in these factors will alter the estimates of the model. For example, the recent free trade agreements with the United States and the European Union could alter our estimates. Given that the production costs of biofuels is currently higher in Colombia than in United States and the European Union (Infante and Tobón, 2010; USDA, 2008), it is even possible that these agreements could have the indirect effect of reducing future oil palm plantations in Colombia.

Second, regarding where oil palm expansions would take place in the future, our model predicted a very different spatial scenario compared with two previous studies CENIPALMA-CORPOICA (1999) and IDEAM-IGAC (2009) that assessed suitable areas for oil palm cultivation in Colombia. We attribute these differences to the modeling approaches and the data used in the models. CENIPALMA-CORPOICA (1999) used a general suitability approach based on a few soil and climate variables (rainfall, drainage, slope and effective depth), but they did not include economic or infrastructure variables. IDEAM-IGAC (2009) applied the FAO Land Evaluation framework (FAO, 1976) that included biophysical, ecological and socio-economic characteristics weighed against the crop requirements, to produce four suitability classes.

We question the maps of these studies because large areas of highly productive active oil palm plantations in Meta, Casanare and Santander Departments were classified as moderate to severe crop limitations. We also found strong discrepancies of our results with those of the mentioned studies in the location and extent of the ''higher suitability'' areas, especially in the eastern zone (Arauca, Casanare and Vichada Departments), central zone (Santander and Cundinamarca Departments) and northern zone (Atlántico and Bolivar Departments). Possible reasons for these differences are besides the methodological, probably the result of the difficulty to match the coarse databases of the available variable maps to the finer scale crop requirement data. Another aspect is that these two models identify coarse suitability areas, not permitting to identify temporally framed hotspots of change, which our study does. Our model although based on current plantation areas, projects important potential crop expansion areas outside of traditional oil palm growing regions, such as in areas of Tolima, Antioquia, Cundinamarca and Urabá (Fig. 4).

We could not take into account the possible impacts of uncertain but important social and political aspects in Colombia, such as the evolution of the internal armed conflict (Seeboldt and Salinas, 2010) and of the land tenure issues (Fajardo, 2009), which may play a role on where and when the future expansion of oil palm plantations will take place.

Finally, our results should be put in context of a national scale analysis, the available data, and the assumptions based on the currently used technologies, market trends, oil prices, prices of raw materials, low supply of biodiesel to the foreign market, subsidies context. Any modifications to these factors will have an impact in the future of the industry. The future developments of the oil palm industry will certainly have impacts on the prices of land, labor supply and food price and supply (Hellmann and Verburg, 2011). To address this, a careful analysis of the macroeconomic effects of the changes in variables associated with oil palm expansion and the likely impacts on the food sector and food security are needed. They should incorporate data and criteria to locate and exclude restriction in areas with high social, conservation or ecological services values (MEA, 2005). Approaches that include a combination of general equilibrium models and multi-criteria analysis, such as those developed by Irwin and Geoghegan (2001) and Lotze-Campen et al. (2009) could be well suited to this end. These analyses would be particularly relevant to analyze the impacts in areas that have been predicted by our models to have high chances of being converted in the future.

5. Conclusions

Our study suggests that although oil palm is an important component of the Colombian agro-export and energy strategies, the government's future expectations do not match reality. It is highly unlikely that the government's expectations of an increase of 3 million hectares of oil palm plantations will be achieved. Even with strong government support the projected oil palm plantations in Colombia will not reach more than one million hectares by the year 2020. Therefore, the expected biodiesel blends (20%) do not appear to be feasible. However, the accelerated processes of transformation and the fragmentation of ecosystems that Colombia is experiencing are likely to be increased by the central government's decision to grow its internal consumption and encourage the country to become a strong competitor in the international market for biofuels. The spatial modeling exercises and econometric analyses developed for this study demonstrate that in the three main producing areas of palm oil in the country, the crop has mainly expanded into areas previously used as pastures. A lower proportion of the land use change has been from heterogeneous agricultural areas and natural forest to palm oil crops. It is necessary to refine the spatial scale of analysis and incorporate detailed regional information to determine local impacts on strategic regional ecosystems, food systems and water resources. This analysis should focus on areas that are most likely to be involved in expansion of palm crops, such as the eastern and central areas.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2013.01.003.

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