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Roads, petroleum and accessibility: the case of eastern Ecuador

Chris W. Baynard · James M. Ellis · Hattie Davis

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Abstract Oil exploration and production (E&P) activities in remote regions are often considered a catalyst for landscape change through the direct alterations created by infrastructure features, as well as through the accessibility provided by roads. The construction, expansion and improvement of transportation routes in isolated areas can attract newcomers and resource users who engage in illegal logging, poaching, commercial agriculture, as well as planned and spontaneous colonization. These actions can lead to larger-scale surface disturbances that may also affect indigenous territories and natural preserves. However, do these parallel activities and outcomes always accompany E&P development, or can controlled access minimize changes? To answer this question we utilized an “accounting from above” approach that uses remote sensing and GIS techniques to analyze surface disturbance patterns linked to infrastructure features for both E&P and parallel activities. Our study area included four neighboring oil blocks in eastern Ecuador’s tropical forest, displaying three types of E&P development: public-access, controlled-access and roadless. The first objective was to determine the spatial relationship between infrastructure pattern, disturbance regimes and the type of road access for the year 2000 using

land-use land-cover maps, soils data, protected areas and colonization zones. The second objective was to examine the statistical relationships between agricultural conversion and the above factors. Spatial analysis findings suggest that areas of overlap where colonization zones, public-access roads and fertile soils meet are most prone to deforestation. Statistical findings from a linear regression model suggest that the presence of public-access non-oil roads are significant at explaining the conversion of natural vegetation (forest) to agriculture, while the presence of protected areas helps explain the conservation of forested land.

Keywords Oil · Roads · Land-use land-cover · Colonization · Ecuador · Exploration and production (E&P)

Introduction

Oil exploration and production (E&P) activities in remote regions can lead to landscape change through the establishment of infrastructure features, as well as through the access created by roads built to reach oil fields. Meanwhile, the presence of parallel economic activities such as logging, hunting, rubber tapping, gold mining or agricultural colonization can create their own set of roads and open up previously inaccessible areas. The lowland tropical forest zone of eastern Ecuador, known as the *Oriente*, has been an important region for oil production since the early

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1970s, as well as an area of government-sponsored and spontaneous colonization, regional development, commercial agriculture and traditional indigenous groups (Southgate 2009, 2010; Southgate et al. 2009; Reider 2010; Mena et al. 2006, 2011; WCS 2010; Wunder 2003; Bilsborrow et al. 2004; Pan et al. 2010).

Some researchers working in Ecuador's Oriente note that current deforestation patterns and disruption to indigenous communities can be traced to oil roads (ORs) built in the 1970s to service oil exploration and production (E&P) activities that in turn provided access to formerly remote regions and led to modern-day land claims, colonization and land conversion (Mena et al. 2006, 2011; WCS 2010; Finer et al. 2008, 2009, 2010; Suárez et al. 2009; Walsh et al. 2008; Messina et al. 2006; Pichón 1997; Mainville et al. 2006).

Other researchers such as Wasserstrom (2010), Southgate (2009, 2010), Reider (2010), Janks et al. (1994) and Uquillas (1985) point out that the expansion of ORs and the building of non-oil roads (NRs) in the Oriente were tied to national policies promoting colonization (both government planned and spontaneous), with triple aims of producing energy, converting the Oriente to a "productive" space and securing territorial borders.

Parallel developments

For much of the twentieth century "Roadway systems were considered part of the required infrastructure for increasing productivity in a region, their physical structure a benign necessity in the promotion of progress" (Coffin 2007: 396–397). During the 1970s, many areas of Amazonia experienced infrastructure building spurred by policies tied to this notion of development. In Brazil, for example, "Early efforts focused on the provision of a broad tax exemption and subsidized credit package to stimulate the economy, and road construction to integrate the region with the economic, political, and cultural core of the country" (Simmons et al. 2007: 131).

The infrastructure expansion that began with a series of government-sponsored road building and settlement programs included the Trans-Amazon highway, the Northern Perimeter highway and the Cuibá-Santarém highway (Goodland and Irwin 1974). With new access, thousands of settlers entered

Amazonia and pursued large-scale cattle ranching and peasant agriculture (Goodland and Irwin 1974). These openings led to the establishment of new agricultural frontiers, particularly for soybeans and cattle ranching; increased fire advancement on forests; prompted legal and illegal timber harvesting; and resulted in land speculation and colonization (Bowman et al. 2011; Brandão and Souza 2006; Ferraz et al. 2006; Soares-Filho et al. 2004; Peres et al. 2010; Schmink and Wood 1992; Nepstad et al. 2001). In some cases "as soon as there was even the prospect of a new road, migrant farmers would move into the area, taking de facto possession of a small plot" (Schmink and Wood 1992: 79).

Oriente development

In 1963, just before big oil discoveries were made in Ecuador's Oriente, the military government outlined plans to address landlessness and colonization. In their General Plan of Economic and Social Development (Plan) the authors stated that: "Colonization is a function of public interest and it proposes the best advantage of lands that are apt for agricultural exploitation, with the establishment of farming families on their own lands, the betterment of their quality of life and the adoption of an adequate and rational agro-economic technique" (JNPCE 1963: 5; authors' translation).

The document outlined plans to "orient and help spontaneous colonization in the zones in which appreciable phenomena of spontaneous colonization settlements are marching ahead" and implement "semi-directed colonization in new zones that the State will support and open to colonization" via infrastructure, technical, economic and social assistance (JNPCE 1963: 8; authors' translation). Subsidies, credit at negative interest rates, very low gasoline prices, land speculation and tax holidays to cattle ranchers and large palm oil producers contributed to land clearing (Wunder 2003; Reider 2010; Southgate 2009; Wasserstrom 2010). Indigenous communities were also affected. With much of their original territories viewed as public lands and challenged by settlers, the government eventually responded by setting up legally protected (and smaller) reserves for them (Uquillas 1985; Bremner and Lu 2006; Wasserstrom 2010; Southgate 2009; Reider 2010).

Other policies and laws such as the Agrarian Reform and Colonization Law (1964)¹, the *Ley de Tierras Baldías y Colonización* (Vacant Land and Colonization Law-1964) and the Special Law for Awarding Vacant Lands to Spontaneous Settlers (1973) contributed to the development of the Oriente by requiring colonists to clear forests for pasture and crops as a way to gain land titles, a policy that also applied to indigenous groups (Benítez 1990; Canelos 1980; Díaz 2007; FLACSO no date; Southgate 2009; Hiraoka and Yamamoto 1980; Wunder 2003).²

The *Ley de Caminos* (Law of Roads-1964), for example, stated that: (1) All terrestrial transit ways built for public service and declared for public use are all public roads; (2) All private roads that have been used by inhabitants of the zone for more than 15 years are also considered public roads; and (3) All roads will be under the control of the Ministry of Public Works (authors' translation).

In the Plan, the JNPCE also emphasized that “the agro-economic characteristics of the zone should be such that permit the development of a colonization that is useful to the country economically as well as socially” (JNPCE 1963: 9; authors' translation). This indicated that better soils areas (also located close to population centers) would likely be targeted by the demarcated government-sponsored settlements, resulting in additional roads (by planned and spontaneous colonists) and the deeding of parcels along surveyed lines (Greenberg et al. 2005; Pan and Bilsborrow 2005; Pan et al. 2010)—see Fig. 1.

These plots were primarily 50-hectare parcels (250 m by 2,000 m) with the narrow side abutting roads and trails (Hiraoka and Yamamoto 1980; Pan et al. 2004)—see Fig. 2. Subsequent lines of settlement were often built behind existing roads and farms, leading to the common fish-bone pattern found in Amazonia (Greenberg et al. 2005; Hiraoka and Yamamoto 1980; Gondard and Mazurek 2001; Southworth et al. 2011; Pan et al. 2010). The successions of parallel lines of farms, known as *respaldos*, could reach three to eight deep (Greenberg et al. 2005; Pan and Bilsborrow 2005; Gondard and Mazurek 2001). Additionally, general poor soil quality

(in most areas) and exhaustion may have led colonists to clear new plots, contributing to additional land conversion (Wunder 2003).

Thus, energy policy was coupled to colonization and agricultural policies that were possibly linked to soil fertility. The northeast Oriente was not only developed for oil, but for settlements, commercial crops, cattle ranching, palm oil plantations and securing borders (Southgate 2009; Rubenstein 2001; Wunder 2003). In this scenario, the biggest drivers of landscape change were “small-scale migrant farmers [which] have been identified as the proximate actors in the ongoing process of deforestation and direct agents of land conversion from forest to agriculture” (Pan and Bilsborrow 2005: 236–237). Messina et al. (2006: 115) add that the architects of this problem were Ecuadorian officials “who failed to address the emerging land ownership and colonization problems” and turned to settlement programs as a complementary response to landlessness (Southgate et al. 2009).

E&P and land conversion

Whether built for logging, rubber tapping, mining or E&P, changes resulting from road building (in remote regions) can be minimized through controlled access, planned placement of roads and skid trails; road closings and reclamation; reducing the number of roads built; limiting use, seasonal traffic restrictions, and reducing road width and paving (Lee and Boutin 2006; Negishi et al. 2006; Thomson et al. 2005; Jackson et al. 2002; Musinsky et al. 1998; Johns et al. 1996; Hutton and Skaggs 1995; Southworth et al. 2011; Diamond 2006). In the case of the Oriente, where petroleum is a key economic activity,³ our research question is: does oil development in frontier regions necessarily lead to significant LULC or can controlled access minimize these changes?

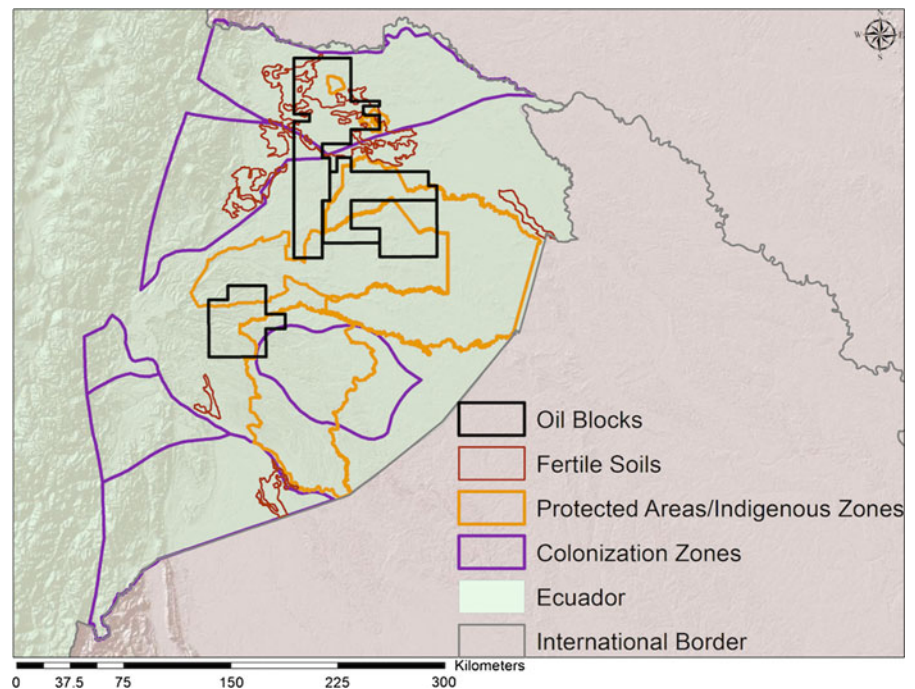
To better understand the pattern and extent of surface disturbances linked to infrastructure expansion, we examined three types of E&P development: public access, controlled access and roadless for the

¹ Cabrera (2004)

² While a similar agrarian law has existed in Brazil, a recent change to Peru's agrarian law meant that “unworked land could be expropriated, which also stimulated forest clearing to establish clear tenure” (Southworth et al. 2011: 1060–1061).

³ Ecuador became a net oil exporter in 1972 (Wunder 2003). In 2011 was the fifth largest producer in South America and the fourth largest supplier of crude to the US. The oil industry provides about 50 % Ecuador's export earnings and 33 % of tax revenues (EIA 2011) and most of the production comes from the northern part of the Oriente (Wunder 2003).

Fig. 1 This map shows the four oil blocks examined in this study and their spatial relationship to government-sponsored colonization zones, fertile soils, oil deposits and protected areas/indigenous zones



year 2000.⁴ We applied the landscape infrastructure footprint (LIF) methodology (Baynard 2011), which utilizes remote sensing and GIS techniques to gauge the spatial relationship between E&P development and landscape alterations. In this paper we linked infrastructure features to land-use land-cover (LULC) maps, soils, protected areas/indigenous zones, oil deposits and colonization zones (see Fig. 1).

By relying on the use of metrics and standardization, this “accounting from above” approach provides a useful application of geospatial data and techniques for enhancing environmental performance standards (EPS) for E&P companies. Furthermore, this paper builds on limited but growing work regarding energy development using geospatial applications to measure the extent, pattern and effect of E&P activities on the landscape. This includes research in tropical regions (Musinsky et al. 1998; WCS 2010; Baynard 2011; Janks et al. 1994; WCS 2010), the western US (Morton et al. 2002, 2004; Thomson et al. 2005; Wilbert et al. 2008; the Wilderness Society 2006), arctic Russia (Kumpula et al. 2011) and Southern Sudan (Prins 2009).

⁴ We focused on CLIRSSEN 2000 LULC data because of its availability for the entire Oriente; an unusual data set for the region.

Road building in the Oriente

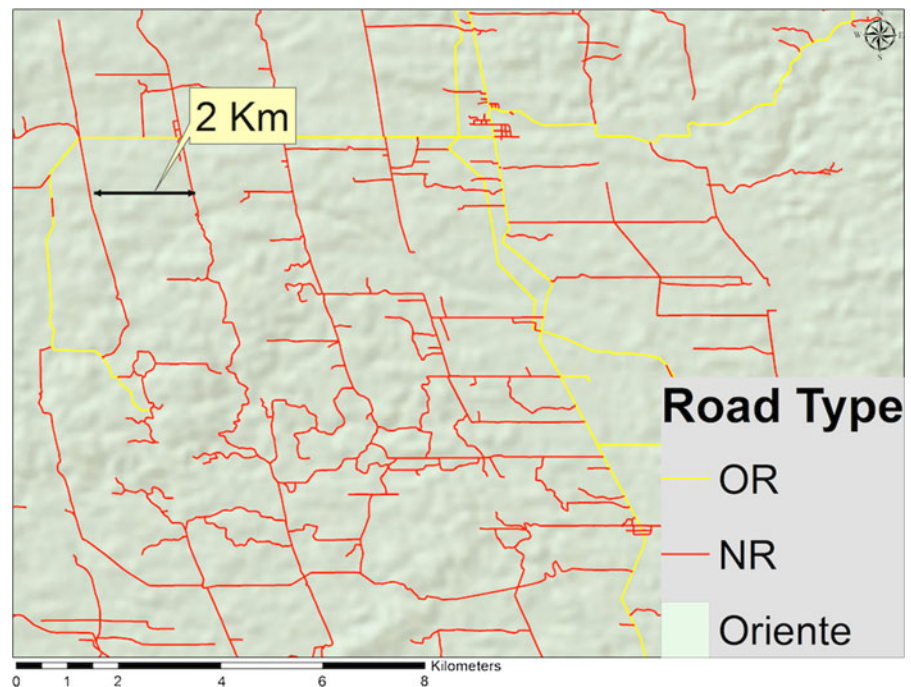
The study region is located in the moist tropical forests of northeastern Ecuador, where E&P have been important economic activities since the mid-1960s. We focused on four blocks: Block O, Block 10, Block 14 and Block 16, since they provided examples of the three types of E&P: public access, controlled and roadless. These blocks are located in the modern provinces of Sucumbios, Orellana and Pastaza.⁵

The first concession, which we named Block O for the Original block in the area, never received a number.⁶ Divided by the Napo River, the northern part was developed in the mid-1960s and the 1970s.

⁵ Previously, the Province of Napo occupied what is today Napo and Orellana.

⁶ Block O was at first a consortium comprised of the US companies Texaco and Gulf, who made large oil discoveries in the northeast Oriente in 1967 (Southgate et al. 2009; IDCH 1991). By 1971 a new hydrocarbons law was introduced followed by the creation of the Corporación Estatal Petrolera Ecuatoriana (CEPE), which led to renegotiations of oil contracts and state control of oil regions on the coast and in the Oriente (IHDC 1991). By 1974 CEPE owned 25 % of the Texaco-Gulf consortium and by 1976 Gulf withdrew from Ecuador, selling its shares to CEPE, who increased its ownership to 62.5 % (Southgate 2010; IHDC 1991). In 1990, Texaco transferred its operations to Petroecuador—formerly CEPE, and left Ecuador in 1992 (Southgate 2010).

Fig. 2 The common pattern of colonization zones set up in the Oriente. Note the settlement lines and *respaldos*



Under direction of the Ecuadorian government, private oil companies built roads to serve E&P activities, and by law these roads were required to be open to everyone (Southgate 2010; Wasserstrom 2010; Southgate et al. 2009). Consequently, by 1972 “the government declared that oil development would enable the northeast to become a target ‘area for migration and expansion’” (Wasserstrom 2010: 6). Additional highways, bridges and an airport followed (Wasserstrom 2010), forming the main infrastructure footprint, north of the Napo River.

In the 1980s a north–south highway, known as the Auca road, crossed the Napo River, extending to the southern part of Block O. As with the northern roads, this one was required by law to be a public-access road and was constructed without control points (Finer et al. 2009; Southgate et al. 2009). NRs were also established in this southern region, mainly parallel to the Aucua road, though the pattern was less dense than in the northern part of the concession. Blocks 14 and 16 were developed in the 1990s with one controlled-access road OR, while Block 10 was developed via “roadless” E&P (also in the 1990s), through the use of helicopters⁷—see Figs. 3, 4; Table 1).

⁷ Though its polygon-outline is no longer found in modern oil block maps of Ecuador, Block O is still an active E&P zone.

Methods

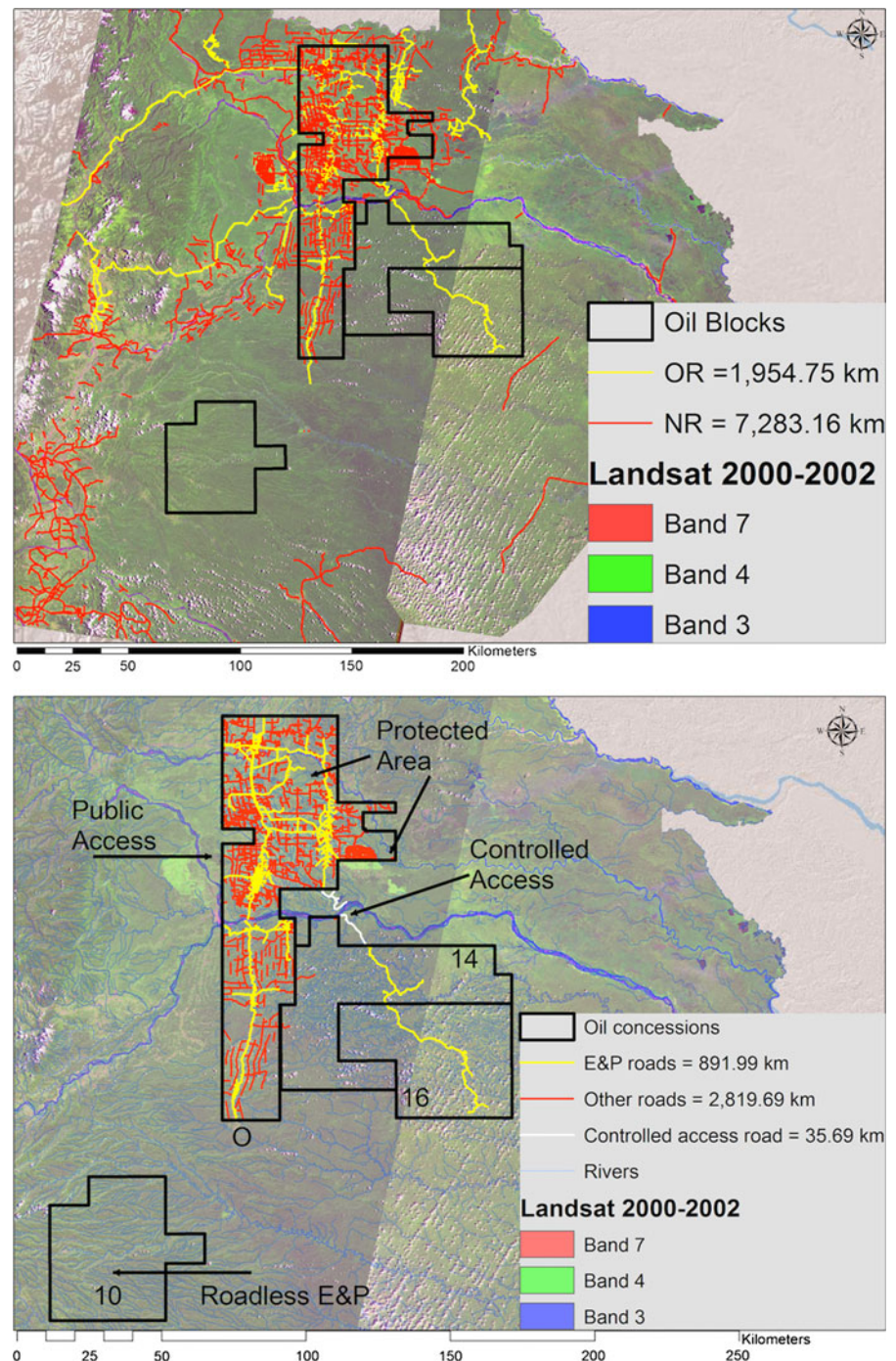
Data included two LULC classification maps for the year 2000, Oriente soils, road and river networks, indigenous lands and protected areas, oil fields, oil concessions and colonization zones. These spatial data sets were created by the following Ecuadorian government agencies⁸: Centro de Levantamientos Integrados de Recursos Naturales por Sensores Remotos (CLIRSEN); Instituto Geográfico Militar (IGM); Ministerio de Agricultura y Ganadería (MAG)—now MAGAP and its (former) subdivision PRONAREG; Sistema Integrado de Indicadores Sociales (SIISE), Dirección Nacional de Protección Ambiental (DINAPA) and Sociedad Ecuatoriana de la Ciencia del Suelo (SECS)—now SECO. The use of government data makes this type of analysis replicable, a central goal behind the LIF methodology.

Footnote 7 continued

Blocks 10, 14 and 16 appear on current maps, though operators and partner companies have changed numerous times. In 2000, the year analyzed in this study, Block O was operated by Petroecuador (a state-owned company); while Blocks 10, 14 and 16 were operated by the private companies ARCO, Repsol and Maxus, respectively.

⁸ Some of these agencies have changed names or been absorbed into other government agencies.

Figs. 3, 4 The distribution of oil roads (ORs) and non-oil roads (NRs) in the Oriente (3), as well as in the four oil blocks of the study area (4)



Additional non-government data included oil wells, a spectral classification LULC map we created specific to the four oil concessions for the years 2000–2002, a roads data set (based on time-series petroleum maps, IGM aerial photos, topographic maps, GPS data, and high-resolution IKONOS

satellite imagery) and colonization zones which were digitized from the JNPCE (1963) plan. Additionally, we digitized roads missing from the dataset that were observable in both medium and high-resolution imagery (following methods by Portillo-Quintero and Sánchez-Azofeifa 2010 and Baynard 2011) and

Table 1 Study area oil blocks: size and LULC

	Block O	Block 10	Block 14	Block 16
<i>SIZE</i>				
Hectares	442,976	200,108	234,872	197,743
Km ²	4,429.76	2,001.80	2,348.72	1,977.43
<i>CLIRSEN LULC 2000</i>				
Urban				
Hectares	1,794.27	0	4.20	0
% of block	0.41	0	0.001	0
Agriculture				
Hectares	237,996.98	2,603.10	3,920.23	2,760.48
% of block	53.73	1.30	1.40	1.40
Forest				
Hectares	195,737.37	197,081.97	228,413.69	194,470.47
% of block	44.19	98.49	97.25	98.35
Water				
Hectares	6,350.49	416.12	2,970.07	512.50
% of block	1.43	0.21	1.26	0.26
Other				
Hectares	1,097.05	6.50	194.27	0
% of block	0.25	0.003	0.08	0

separated ORs from NRs using existing data sets and expert knowledge. As Kumpula et al. (2011) confirmed, visual interpretation proved to be the most accurate way of identifying smaller roads.

Imagery

Four Landsat ETM+ scenes were downloaded from USGS 2011 Glovis (see Table 2). We processed and registered them to our base image (path 8 row 20) using ERDAS Imagine 10. Images were selected for their date availability and reduced cloud cover. We created a mosaic of the study area, subset images and a LULC map of the concessions. The subsets encompassed three different band combinations: 7,4,3; 4,3,2 (false color composite); and NDVI, or normalized difference vegetation index (Band 4 (NIR) – Band 3 (R)/Band 4 (NIR) + Band 3 (R)). Each combination provided advantages for identifying, visually checking and updating infrastructure features. The NDVI, for example, has been used in studies involving E&P and exurban-related LULC because of the contrast between infrastructure and healthy biomass (Janks et al. 1995; Kwarteng 1998, 1999; Musinsky et al. 1998; Baynard 2009; Shrestha and Conway 2011).

Table 2 Satellite imagery used in research

Satellite imagery	Acquired	Path/row	Resolution
Landsat ETM+	30 Aug 2000	8/60	30 m
Landsat ETM+	08 Jan 2002	8/61	30 m
Landsat ETM+	14 Oct 2002	9/60	30 m
Landsat ETM+	12 Sep 2002	9/61	30 m

Land-use land-cover, soils, colonization areas and protected zones

CLIRSEN LULC data covered the entire Oriente, allowing us to clip the four oil blocks and determine the amount of land in hectares (ha) and percentage of the concession dedicated to each of five categories: Forest; Agriculture (crops, cattle and pasture); Urban; Water and Other (*matorral*: shrubland, and exposed soils). Our LULC map covered most of the four concessions (part of Block 14 was not mapped) and resulted in six classes: Developed—which included urban and agriculture (crops and pastures), Forest, Water, Bare Soils, Clouds and Shadows.⁹

⁹ We used an unsupervised classification scheme and expert knowledge, based on Landsat 2000–2002 data.

We compared the hectares and percentages of the two LULC classifications, noting overlaps and differences in amount of land dedicated to each. Next, we mapped the soil regimes in the Oriente, paying particular attention to the location and amount of fertile soils and their spatial relationship to the oil blocks (Uquillas 1985; PRONAREG 1983).

We followed this with additional data sets: designated colonization zones (from the 1963 Plan), oil fields (geologic oil reservoirs), protected areas/indigenous zones, and roads. The above steps were accomplished through a series of geoprocessing techniques (using ArcGIS 10¹⁰) and iterations that resulted in a dataset containing all features located in the four oil blocks in terms of: fertile soils; protected areas/indigenous territory; colonization zones; oil-fields; water, forest, agriculture, urban and other (LULC).

Road effects

Non oil roads

Roads vary in terms of legal and functional constraints, surface cover, condition, the presence of rights-of-way and traffic volume. Yet “almost 70 % of all roads are local, and thus their function is primarily land access” (Forman et al. 2003: 41). We divided the road datasets into three categories: public-access oil roads; public-access non-oil roads and controlled-access oil roads. Next we sampled various roads in the study region to determine their width, using available air photos, high-resolution satellite imagery (in 2000) and contemporary high resolution Google Earth imagery. The widest ones ranged from 12 to 15 m, including verges. We chose the latter as the road width to represent the baseline width for direct effects of NRs, or amount of land cleared/taken up to accommodate these linear infrastructure features.

As a basis of comparison, we contrasted this width to edge effects, or transition zones from roads of open land to forest that exhibit abrupt or gradual edges, and where one or more ecological changes may be detected (EEA-FOEN 2011; Wuyts et al. 2009; Coffin 2007; Forman and Deblinger 2000). Keeping

in mind that the boundary for road ecosystem “changes over time due to succession and human activity” and therefore “is arbitrary and dynamic” (Lugo and Gucinski 2000: 252), the following edge effects created by roads are estimates provided by various researchers.

Avon et al. (2010: 1546), for example, studied the effect of forest roads on neighboring hardwood forest stands at five distances ranging from 5 m to 100 m and found that “the main road effect extended less than 5 m into the forest stand.” Mayaka (1994) and Mayaka et al. (1995) found that edge effects extended 10 m inside African whitewood plantations (Ayous) in Cameroon rain forests. Delgado et al. (2007) detected forest edge-effects from 6 to 10 m from road edges in pine and laurel forests, whereas Forman et al. (2003) found that the forest edge-effect averaged 15 m. Pohlman et al. (2009), examining microclimatic edge effects in tropical rainforests found they extended out to 25 m or less.

In a Western European-wide study of landscape fragmentation related to roads and urban expansion (EEA-FOEN 2011), the authors selected a series of buffers to calculate disturbance geometries associated with infrastructure features. The largest buffer was set at 30 m (15 m on each side of the road) for class 00 roads, or motorways. For Class 01 (major roads) it was 20 m; Class 02 (other major roads), 15 m; Class 03 (secondary roads), 10 m; Class 04 (local connecting roads), 5 m; and Railroads, 4 m (EEA-FOEN 2011).

Oil roads

Regarding road effects of oil and gas development, the US Bureau of Land Management (BLM) considers the average initial width disturbance of a road at 12.19 m (40 feet) (Porter 2009a, b; BLM 2010), with a minimal width for two-lane roads of 7.3 m (24 feet) (BLM 1985). Wilbert et al. (2008) used this road width for determining direct disturbance of oil and gas roads in Wyoming, while Wunder (2003) estimated average width cleared for primary oil roads in the Oriente at 20 m. However, if relying on oil roads to represent E&P infrastructure features, a buffer may be needed to compensate for wells, well pads, rights-of-way and pipelines that may not be observable in medium resolution satellite imagery (such as Landsat), or that are not available in the data sets.

¹⁰ This included techniques such as: clip, erase, merge, union and buffer.

Though it is difficult to measure individual road widths and detect infrastructure features with precision when using medium spatial resolution (15–30 m) satellite imagery¹¹ (e.g., CLIRSEN's Oriente land cover map—and our own Landsat imagery); it doesn't mean that roads are not observable. As de Wasseige and Defourny (2004) found, “On a 120 m regularised (sic) image recorded right after the logging, more than 95 % of the logging trail network was still visible.”

Weller et al. (2002), studying the Upper Green River Basin fields in Wyoming, used a 76.2 m (250 feet) buffer to measure direct effects. Back in the Oriente, WCS (2010) used a 100 m buffer along roads to determine direct effects of road construction and other human activities in the Yasuní National Park. The selection of this wide buffer in the WCS paper appears tied to the size of the 100 m vector grid, or fishnet cell size used to divide the study region. This buffer selection highlights the choice the GIS analyst must make when selecting a grid size: balancing the desire to use a smaller grid possessing a smoother visual display, against higher processing requirements needed for the smaller mesh (Wilbert et al. 2008; Baynard 2011).

In another Oriente study focused on the development of Block 14, Hutton and Skaggs (1995) observed that the entire OR width, including the right-of-way and (buried) pipeline was 25 m. Therefore in an effort to avoid underestimating the direct effects of oil infrastructure features, we doubled the Hutton and Skaggs (1995) 25 m width to 50 m. This width doubled the widest edge effect. Pohlman et al. (2009) observed in tropical regions; it more than tripled that for the sampled IRs (15 m) in the study region as well as initial oil roads identified by the BLM (2010) in the US and used by Wilbert et al. (2008) in Wyoming. It was 2.5 times wider than major roads (class 01) in Europe and primary oil roads in the Oriente (Wunder 2003) and five times

wider than the effects found in Cameroon by Mayaka and Mayaka (1994, 1995).

Finally, we separated all roads into three categories: public-access oil roads, controlled-access oil roads, and public-access non-oil roads. After buffering ORs centerlines to 50 m and NRs to 15 m, we calculated road length, density, amount and percentage of land occupied in each concession (direct effects). We mapped the results and calculated summary statistics (see Table 5).

Inferential statistical modeling

After examining summary statistics and the spatial relationship among roads and the above features, we wanted to uncover if these same findings were statistically significant by running an OLS linear regression model. We increased the number of observations by dividing the four-block study area into a fishnet (vector grid) of 1 km² blocks and clipped it to the study area blocks. This resulted in 516 observations. Through iterative geoprocessing steps we created one dataset that calculated the percentage of land inside each 1 km² block dedicated to: urban, agriculture, forest, water, other, colonization zones, protected areas/indigenous reserves, oil fields, public-access oil roads, public-access non oil roads and controlled access oil roads (Fig. 5). We also added the dummy variable “north of the Napo River” to test if location north of this region's major river was significant.

Since we wanted to understand which factors best explained the presence of agricultural land, we chose this LULC category to represent deforestation. Thus agriculture was our dependent variable. We further eliminated the “forest” category from the dependent variable list (since we were looking for deforestation), ran the model and then accounted for heteroskedasticity.

Results

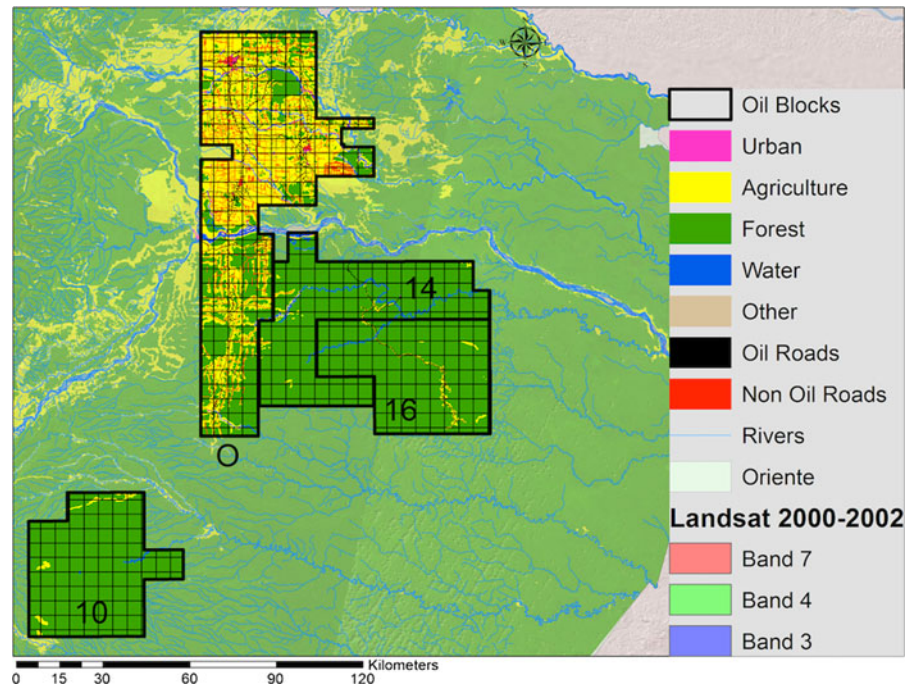
Spatial analysis

Soils

Amazonian soils, including those in Ecuador's Oriente, are characterized by poor mineral content, low

¹¹ Using high spatial resolution data allows to more easily distinguish between infrastructure and natural vegetation. However, high-resolution imagery “becomes prohibitively expensive and unmanageable large data volumes” (Shrestha and Conway 2011: 172). Thus the 15 m panchromatic band in Landsat ETM+ imagery can prove helpful; however, post March 2003 imagery is less useful due to missing data resulting from a sensor malfunction.

Fig. 5 The study area divided into a vector grid of 516 observations and geoprocessed to include all variables studied in one spatial file



fertility and elevated levels of mercury (Alfaia et al. 2004; Almeida et al. 2005; Mainville et al. 2006). The most fertile soils in the entire Oriente occupied a small area, about 4.0 %, and corresponded to the K1 and K2 soils regimes that have volcanic origins (CLIRSEN 2011; PRONAREG 1983; Uquillas 1985)—Table 4. The spatial relationship between fertile soils and (subsurface) oil fields showed that 20 % of oil fields—including the largest ones—happened to lie beneath the fertile soils zone. Thus two important economic activities, agriculture and E&P would likely be present in this area.

Mapping the location of oil wells—showed actual-versus-potential surface activities and indicated that 20 % of them were located in areas that had rich soils. This led us to ask: what LULC categories corresponded to the fertile soils? Based on CLIRSEN, almost half (47 %) was dedicated to agriculture (crops, livestock and pasture), while the other half (48 %) was forested. What about the relationship between areas chosen for colonization in the JNPCE 1963 plan and fertile soils?

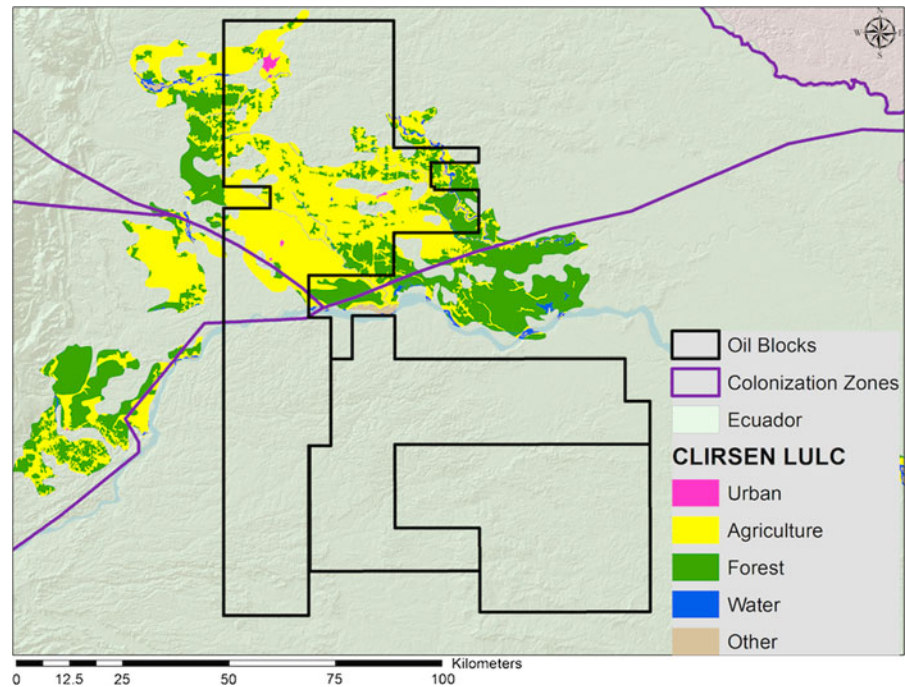
Here we calculated that 70 % of the most fertile soils in the entire Oriente were located north of the Napo River in the two northernmost colonization zones—the ones spanning Sucumbios and Orellana (previously Napo)—see Fig. 6. This area also

occupied the northern part of Block O, suggesting this region was selected as an area of agricultural colonization in tandem with oil production. In fact 33 % of the region's fertile soils were located inside Block O. Based on this analysis, it wasn't just oil that led this area to be opened up; the presence of good soils made colonization successful here—both planned and semi-directed (spontaneous).

LULC

Block O showed the highest levels of surface disturbance, particularly north of the Napo River, where most of the fertile soils were found. The lower part of the concession, which was developed later and located south of the Napo, exhibited less conversion. Table 1 shows the amount of CLIRSEN LULC occupying each block in terms of hectares and percentage of the concession. Agriculture (crops, livestock and pastures) accounted for 54 % of land use in Block O, while 44 % remained forested. Some pockets of forest remained mostly intact in the northeast, east and southeast where land had been deeded (by decree or legalized) to indigenous groups (Cofán, Secoya, Huaorani, Shuar, Achuar and Zapara) by the government and access controlled (SIISE 2000; Ministerio del Ambiente 2012). The

Fig. 6 Most of the fertile soils in the Oriente were located in the area surrounding the northern part of Block O, which was intersected by the two northernmost colonization zones



conservation of forest in these areas concurs with findings by de Espindola et al. (2012: 240) in Brazilian Amazonia whereby “Indigenous lands were significant in preventing deforestation in high-pressure areas.” Meanwhile, in Blocks 10, 14 and 16, 98 % of each concession remained forested (see Figs. 7, 8).

Our LULC map showed similar patterns to the CLIRSSEN map in terms of the location and type of land conversion in the concession areas (Table 3). However, the amount of land affected was not quite as extensive. Figure 9 shows side-by-side comparison of the CLIRSSEN map, the Landsat imagery and our map for a large-scale selection in Block O. In our map, about 37 % of land was developed (agriculture, cattle and urban), while 60 % remained forested. This 16 % difference in land conversion calculation suggests that CLIRSSEN used a buffer around roads and agricultural land (or a smoothing technique) when quantifying surface disturbance. After all, the CLIRSSEN map covered all of the Oriente; an effort likely requiring standardization, which included cloud and shadow removal.

Another example includes Block 10, where roadless E&P was pursued. Here, both LULC maps calculate forest around 98 %, but the agricultural patterns and amounts are different. The CLIRSSEN

map shows agricultural lands occupied 1.3 % and water 0.21 % of this block, while our maps showed about 0.01 % for agriculture and water at 0.97 %. These differences are small, but the distinct locations suggest that agriculture inside this roadless E&P zone was occurring along river banks.¹² The other two concessions, Blocks 14 and 16, remained largely forested in both LULC classifications,¹³ with developed areas occupying 1.0 % or less (Tables 3, 4).

Roads and access

Before oil roads were built, the first group of settlers was brought by plane to set up a coffee cooperative outside Lago Agrio “with their animals and seeds totally maladapted to the new medium they would discover” (Gondard and Mazurek 2001: 31; authors’ translation). Subsequently, referring to the JNPCE 1963 colonization plan proves insightful. Areas deemed as viable for settlement were those with

¹² As mentioned earlier, Mainville et al. (2006) note that some riverbanks in the lowland tropical forests of the Oriente tend to be intensely colonized.

¹³ Our LULC map covered most of the concessions, but areas with missing data match Landsat and CLIRSSEN data indicating this is a forested area.

Fig. 7 CLIRSEN LULC for all the features studied that intersected the four oil blocks: fertile soils, protected areas/indigenous zones, colonization areas and oil deposits

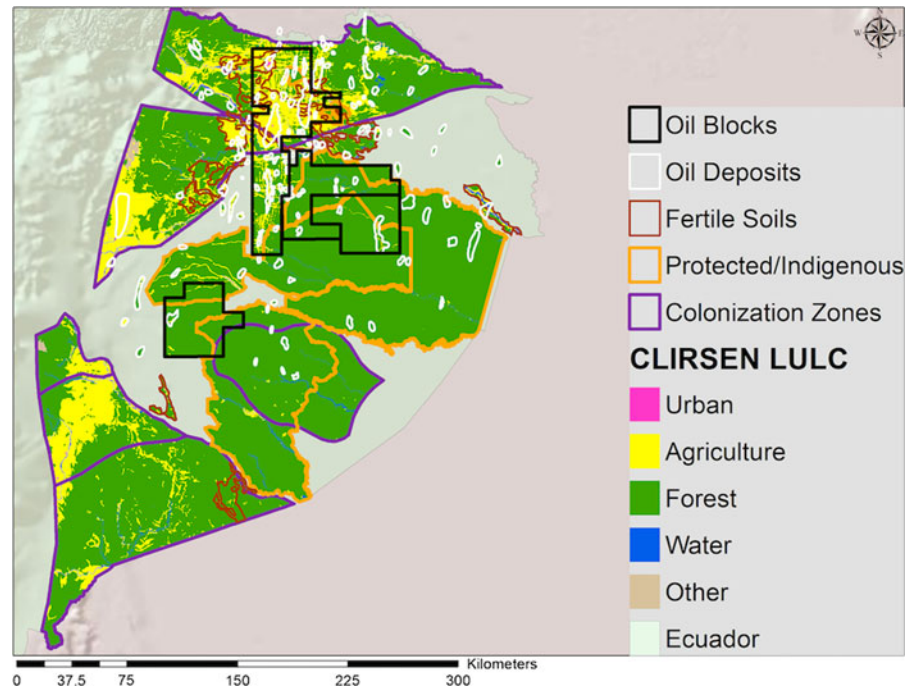
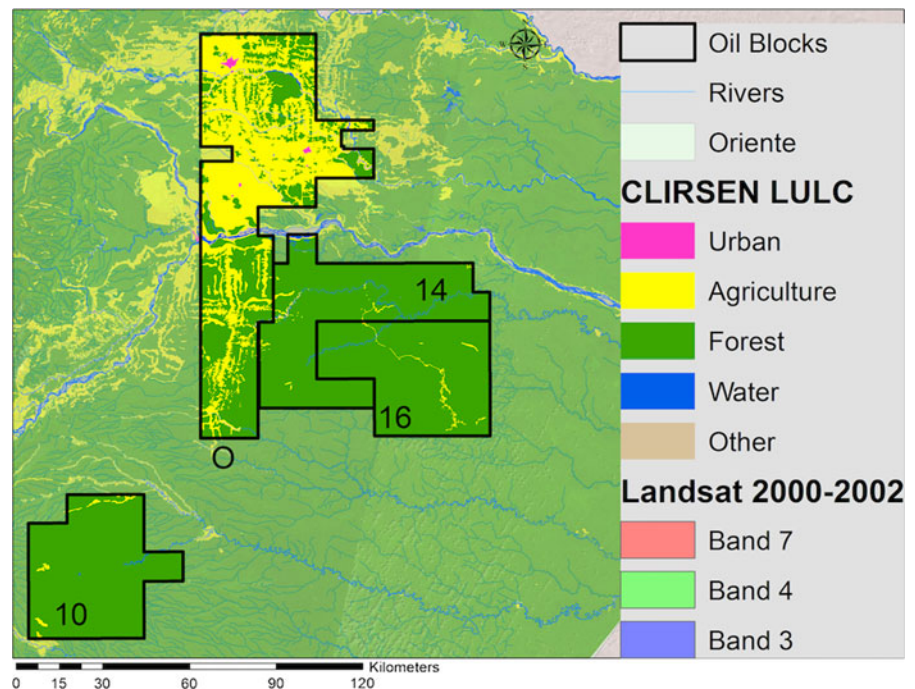


Fig. 8 CLIRSEN LULC categories for the four oil blocks in 2000. The land in Block had public access, whereas access was controlled in Blocks 14 and 16. Meanwhile, Block 10 had no access roads linking it with other regions. E&P development here was roadless



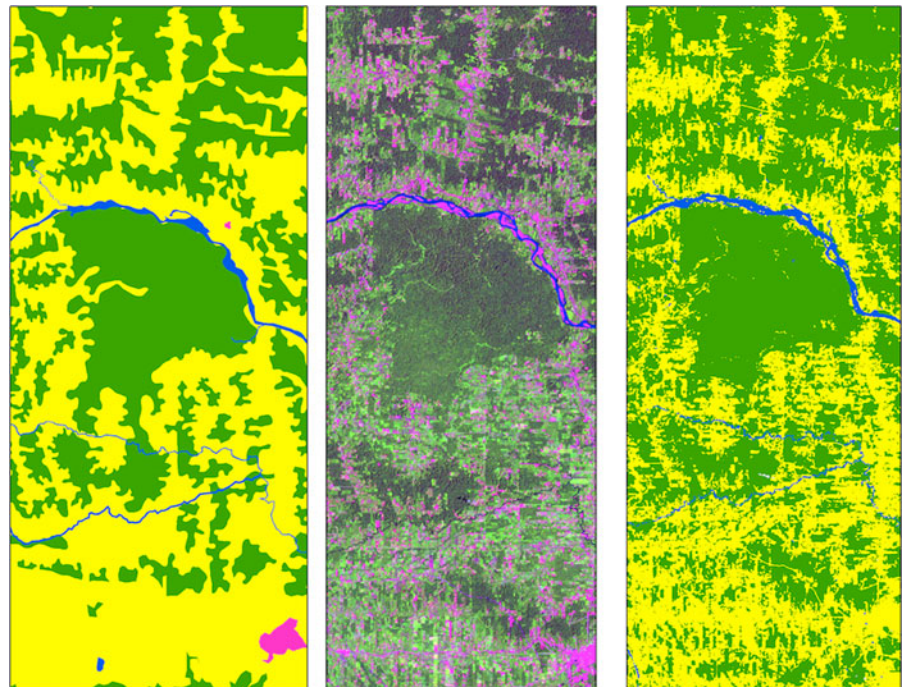
important oil deposits, fertile soils and located close to population centers in the Andes: the northern portion of Block O. We therefore expected to find higher disturbances in this area and uncover that a road network linked them.

Figures 3 and 4 show the pattern and distribution of ORs and NRs in the Oriente as well as that specific to the four oil blocks. ORs measured 1,954 km long; by contrast ORs had 7,283 km of roads, a 3.7 times denser network. Not surprisingly, both types of road

Table 3 Study area oil blocks, 2nd LULC classes

	2nd LULC 2000	Block O	Block 10	Block 14 (partial data)	Block 16
Developed					
Hectares		166,021.17	44.59	1,881.07	812.64
% of block		37.48	0.009	1.1	0.37
Forest					
Hectares		266,434.23	463,045.02	154,062.77	178,088.83
% of block		60.15	98.68	89.99	81.03
Water					
Hectares		7,215.93	4,556.85	2,182.09	1,309.51
% of block		1.63	0.97	1.27	0.60
Bare soils					
Hectares		0	124.44	0	0
% of block		0	0.02	0	0
Clouds					
Hectares		3,304.78	1,024	13,118.53	25,365.08
% of block		0.75	0.22	7.7	11.54
Shadows					
Hectares		0	428.54	0	14,191.80
% of block		0	0.09	0	6.46

Fig. 9 A comparison of land-use land-cover (LULC) methodologies in Block O. On the *left*, CLIRSEN's LULC map, Landsat ETM+ 2000 image in *center* (7, 4, 3 band combination as RGB) and our LULC on the *right*



features predominantly occupied designated colonization areas. In fact, 69 % of all Oriente roads (in our data set) were inside colonization zones (ORs = 63 %; NRs = 71 %), while 98 % were located within 50 km.

The fact that of NRs were located inside the designated colonization areas suggests that the settlement plan was successful in attracting people to this particular location. Given that this was also the

Table 4 Amount of land inside oil blocks dedicated to colonization zones, fertile soils, protected/areas indigenous zones—and underlain by oil deposits

	Block O	Block 10	Block 14	Block 16
Colonization zones				
% of block	65.12	3.68	0	0
Hectares	288,455.70	7,355.78	0	0
Fertile soils				
% of block	34.30	0	0	0
Hectares	159,915.56	0	0	0
Protected/Indigenous				
% of block	8.68	40.85	77.95	99.22
Hectares	38,457.39	81,646.30	183,078.10	196,200.40
Oil deposits (underlying)				
% of block	16.29	1.96	3.52	6.00
Hectares	72,167.73	3,925.84	8,257.26	11,848.06

Table 5 Road metrics for the study area oil blocks

	Block O	Block 10	Block 14	Block 16
Oil roads-public access				
Length: km	760.31	0	0	0
Density	0.17			
Direct effects (50 m width)				
Km ²	37.98			
% of block	0.86			
Oil roads-controlled access				
Length: km	0	0	48.94	82.74
Density			0.02	0.04
Direct effects (50 m road width)				
Km ²			2.44	4.13
% of block			0.10	0.21
Non oil roads-public access				
Length: km	2,805.51	0	14.18	0
Density	0.63		0.006	
Direct effects (15 m width)				
Km ²	42.90		0.21	
% of block	0.97		0.009	

fertile soils zone suggests this location was selectively chosen.

Moving to the oil concessions, Block O showed a pattern whereby ORs built in the 1960s and 1970s formed an infrastructure backbone. The central north–south road originally stopped at the Napo River, but later was extended southward. This southern segment, known as the Auca Road, was built in the 1980 s to connect southern oil fields. However, because access was not controlled, (indeed it was encouraged) settlements and agricultural

expansion occurred here too, though less so than in the north (Finer et al. 2010).

By comparison, the other concessions had a very limited road network (Table 5). Here, the policies surrounding road building were different. “In contrast to the Auca road,” in Block O, notes Finer et al. (2009: 9), “the Maxus road running through Blocks 14 and 16 was built with a control post at the entrance, which has successfully prevented non-indigenous colonists from entering the area.” Built into the Yasuní National Park, the Maxus road was so

named because of the company that assumed operator responsibilities in 1991 (Hutton and Skaggs 1995).

This company “agreed to pay the government and the Indians to set up a control system to exclude those that did not live or did not have permission to work in the Project area” (Hutton and Skaggs 1995). Also, rather than building a bridge to span the Napo River, crossing this body of water would be done by ferry in order to limit access (Hutton and Skaggs 1995; Finer et al. 2010). Furthermore, this road was designed to minimize environmental alterations by employing best practices such as hand clearing techniques, reducing the right of way width for the entire road and pipeline to 25 m and burying the pipeline (Hutton and Skaggs 1995).

The fact that a series of fishbone colonization roads had not developed along this main line (as occurred in Block O) is an indication that control points were working. This did not entirely prevent land cover change in Blocks 14 and 16, but the limited disturbances were due to actions by Huaorani (Waorani) and Kichwa indigenous communities living along the road (Finer et al. 2009).¹⁵

Meanwhile, Block 10 was an example of the Oriente’s first roadless E&P development. Using helicopters to reach this block, limited road building was allowed *inside* the concession (Marx 2011; Finer et al. 2008). Rather than utilizing an existing road network to reach this block and then overseeing accessibility into it, these roadless actions resulted in limited land-cover change (over 98 % remained forested) that is difficult to detect in Landsat imagery. In other concessions not examined in the paper, such as Block 15, a roadless pipeline and canopy bridges were also implemented, (Finer et al. 2008). Meanwhile in Block 31, a redesign without a major access road was required after E&P activities had begun, however, the project was eventually abandoned (Finer et al. 2008; 2010).

In summary, spatial analysis and the resulting summary statistics indicated that areas where fertile

soils, colonization areas and early E&P activity—with the concomitant public-access ORs and NRs, would be the area of greatest agricultural conversion (deforestation). This was Block O, particularly the northern section of the concession. At the same time, conservation areas such as indigenous zones in Blocks O, 14 and 16, remained mainly (98 %) forested, as did the roadless E&P Block 10. We tested these findings with statistical analysis.

Statistical analysis

The linear regression model (Table 6) indicated that the presence of public-access non-oil roads (PANRs) best explained deforestation, whereby a 1 % increase in these roads would result in a 22 % increase in agricultural conversion inside each 1 km² block. Meanwhile, a 1.0 % addition of public-access ORs (PAORs) would lead to a 6.0 % increase in deforestation. For controlled-access roads oil roads (CAORs), the increased deforestation figure was 3.0 %.

Surprisingly, the presence of fertile soils had a small effect on the increase of deforestation: 0.12 %. Regarding colonization zones, the result was the same; a 1 % increase of these areas would lead to 0.02 % increase in deforestation. Meanwhile, being located north of the Napo River meant that a 0.24 % increase in deforestation would result for each additional percentage of land developed in this area.

The presence of urban land (LULC) was negatively related to agricultural conversion, whereby a 1.0 % increase would yield a 6.0 % decrease in deforestation. However, this was an endogenous variable, since expanding urban areas by their very nature would reduce forest cover—not to agriculture, but it would result in landscape conversion. Protected areas, on the other hand, were negatively related to deforestation, indicating that this policy was working. Here, a 1.0 % increase in protected areas/indigenous reserves would yield a 0.04 % decrease in deforestation. Significance levels for all variables are shown in Table 6.

Conclusion

This paper has examined the role of oil roads and non-oil roads, both public-access and controlled, in helping explain agricultural conversion in eastern Ecuador’s Oriente for the year 2000. The aim was to

¹⁵ A different pressure, not associated with colonists, has been noted by Suárez et al. (2009), Finer et al. (2009) and WCS (2010) along the Maxus Road. It regards the increased hunting of wild animals by local Huaorani and Kichwa inhabitants in order to sell bush meat to nearby markets. The authors observe that the road provides an area of influence for hunting as well as a transportation corridor to get their poached wildlife to market (Suárez et al. 2009).

Table 6 OLS regression results for agricultural conversion—serving as a proxy for deforestation

Agriculture	Coefficient (robust std. err.)
Public oil roads	6.08573*** (1.624183)
Public non-oil roads	21.66785*** 2.525472
Controlled access roads	2.813089*** (.8560048)
Fertile soils	.1187259** (.0404181)
Urban	−6.077348*** (.6336984)
Water	.2311531 (.228185)
Other LULC	.466086 (.2965061)
Protected areas	−.0360973*** (.0068176)
Colonization zone	.0192222* (.0077379)
Oilfields	.049374 (.0438526)
North of Napo River	.2403066*** (.0352132)
Constant	.0083766 (.0013388)

Linear regression

Number of observations = 516

F (11, 504) = 181.26

Prob > F = 0.0000

R-squared = 0.8829

Root MSE = .02141

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

determine if the presence of oil roads begun in the 1970s necessarily lead to deforestation in remote regions, or if E&P activities, given their importance to the Ecuadorian economy, could be pursued with reduced surface disturbance.

A combination of spatial analysis and summary statistics was employed to determine the possible relationship between three types of roads and LULC, fertile soils, colonization areas and protected/indigenous zones. This was followed with statistical analysis, whereby the four study-area oil blocks were

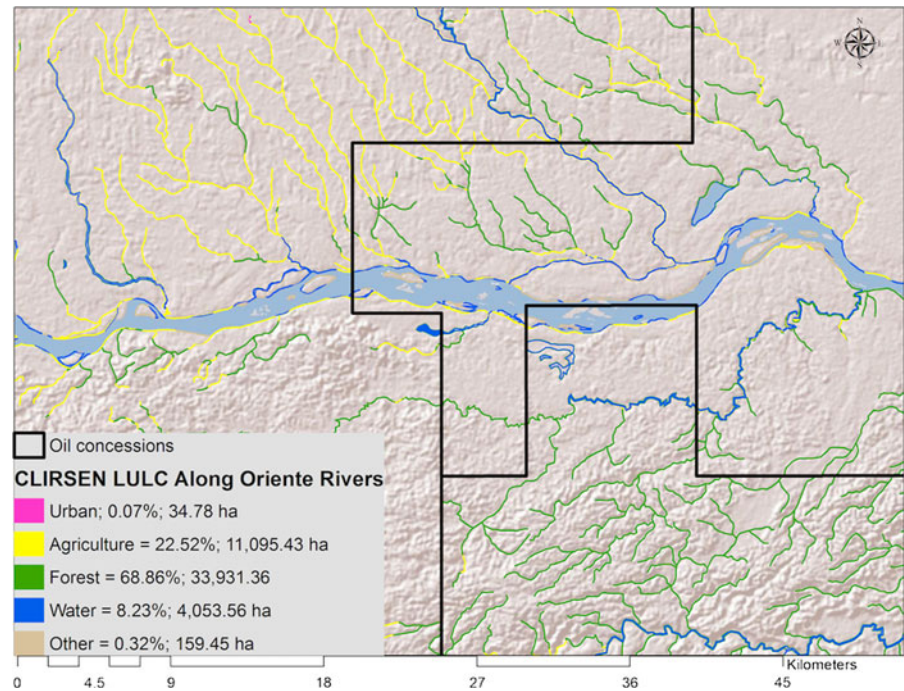
divided into 516 cells through a vector fishnet, followed by an OLS regression model that measured the relationship between agricultural conversion (deforestation) and the percentage of land occupied by each of the above categories inside each 1 km² block.

Spatial analysis showed that areas where fertile soils, colonization zones and public-access E&P development overlapped were most prone to deforestation in terms of agricultural conversion, primarily due to the 3.5 times denser network of public-access non-oil roads that developed over time. The northern area in Block O was the most affected. On the other hand, controlled-access E&P in Blocks 14 and 16 resulted in limited agricultural conversion relegated to the edges of the central E&P road running through both concessions and attributed to indigenous groups living in the area (Finer et al. 2009). Meanwhile no peripheral non-E&P roads were found branching off in the familiar fish-bone pattern found in frontier regions of Amazonia. In Block 10, where roadless E&P was undertaken, most of the concession remained forested and E&P roads were not detectable in Landsat imagery used in the analysis. The limited agricultural conversion was found along rivers. Mainville et al. (2006) note some riverbanks of lowland Oriente rivers are intensely colonized (see Fig. 10).

Interestingly, the three types of E&P development: public-access, controlled-access and roadless, mirror results Southworth et al. (2011) found in western Amazonia where Brazil, Peru and Bolivia meet. In this MAP region, so named for the meeting place of the tri-national frontier of Madre de Dios in Peru, Acre in Brazil and Pando in Bolivia, the authors found that three types of road building/paving: fully paved in Brazil, underway in Peru, and not initiated in Bolivia resulted in three patterns of forest cover. More forest was removed along Brazilian roads, less in Peru, and very little in Bolivia. Since unpaved roads in tropical forests “tend to become inaccessible during the wet season” (Laurance et al. 2009), this is akin to controlled/limited access roads, which help reduce land conversion related to newcomers and resource users.

The implications suggest that controlled-access and roadless E&P are viable options where E&P development and land conservation are priorities. In fact opponents of planned E&P projects in sensitive areas of the Oriente, such in the eastern Yasuní

Fig. 10 A close-up view of the LULC adjacent to rivers for Blocks O and 14, with *yellow rivers* representing agricultural conversion and *green rivers*, forest. The percentage and hectare calculations reflect values of rivers located inside all four study-area concessions. (Color figure online)



Reserve, have acknowledged that roadless E&P would be the best approach if the Ecuadorian government agrees to develop these resources (Marx 2011).

In either case, the use of the LIF methodology that utilizes geospatial data and techniques to understand, plan, monitor and expand the E&P footprint should be adopted by land managers (private and state-owned companies) where oil and gas development is occurring to minimize surface disturbances. This methodology would allow land managers to better understand potential and social environmental alterations, which can reduce legal exposure, increase customer loyalty, enhance likelihood of future contracts, attract investors and improve public perception. These factors are not only important to multinational oil companies, but also to developing countries where hydrocarbon production is crucial to their economic development.

Finally, a new threat to forests in Ecuador's Oriente comes from the introduction of coca, an illegal crop introduced via Colombia that brings its own environmental and social problems (UNODC 2009a, b, 2010, 2011). While neighboring Colombia, Peru and Bolivia have established areas with dense coca farming, only the northwest and northeastern parts of Ecuador are being monitored for coca cultivation (UNODC 2010). In parts of central Peru's tropical forests cattle

ranching, colonization and illicit coca cultivation are now the leading drivers of LUCC (UNODC 2011). This may pose the next big challenge to the region and will likely lead to a new research agenda (see Salisbury and Fagan 2011) particularly suited to geospatial analysis and monitoring.

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