1. Background. In November 2008 the Regional Government of Ucayali, Peru approved a budget for the building of a paved highway connecting the town of Puerto Esperanza, the provincial capital of the Province of Purús, to population centers of the Region of Madre de Dios. This highway will provide, for the first time, a terrestrial link to urban areas, and far more significantly it will connect this remote area to the Inter-Oceanic Highway that links Peru to the highway networks of Brazil and Bolivia, and thus to the Atlantic and the Pacific coasts of South America. The Inter-Oceanic Highway is a monumental undertaking that involves the renovation and construction of roughly 2,600 kilometers of road and 22 bridges and is scheduled for completion in 2009. The construction of the Purús road will commence within two years. The Ucayali Regional Government is set to commission impact statements and to take bids on highway construction. The Purús plan has aroused opposition as well as support from many quarters; there is virtually no doubt now that highway construction will commence sometime in 2010 (A. Ruiz, pers. comm.).

The imminent construction of a terrestrial link between one of the most remote areas of Amazonia with the rest of the South American continent offers an extraordinary opportunity to understand and monitor processes of change in communities of vectors of important diseases as land use and land cover changes dramatically, and human settlement and use patterns shift due to highway construction. The road connection is expected to bring better access to medical care, markets, and education. It will also result in extensive deforestation, and changes in agricultural production from biologically and spatially diverse household (smallholder)-based systems, and low human population densities to large-scale commercial monocropping and livestock production. Other changes are predicted, including the massive immigration of people from outside the region, who are expected to arrive with new and possibly ecologically inappropriate patterns of land use as well as with their domestic animals. While this opportunity is unique, the data, analyses, and model that will be generated by this project will inform a broad range of situations in Amazonia and beyond as large infrastructural projects transform environments and societies throughout the tropics.

1.1 Highways in Amazonia. Roads have linked the western Amazonian lowlands with areas outside the Amazon Basin since the late 1940s and 1950s when highways such as the Carretera Federico Basadre, which connects Pucallpa on the upper Ucayali to the Andes and the coast of Peru (Vivanco Pimentel 2004), and the roads from high-Andes Cusco and Puno to lowland Puerto Maldonado (Junquera-Rubio 2007, Dourojeanni 2006) were built. These largely unpaved roads were often hardly passable, but nevertheless brought many thousands of migrants into Amazonia, some settling along the roads, and many more swelling the Amazonian cities of Pucallpa and Puerto Maldonado. In Brazil, the most ambitious highway project, the TransAmazonica was begun in the late 1960s and inaugurated in 1972. Originally planned to span about 8,000 km and connect Brazil's Amazonian North and dry Northeast to Ecuador and Peru, it never achieved that goal and still remains only about 2,500 km long and mostly unpaved. Many more projects to build new roads or pave existing ones and to resettle populations in planned communities in Brazil, Peru, Bolivia, and Ecuador were designed and executed over the ensuing decades. Some gained worldwide notoriety such as the Polonoroeste project, which included the paving of BR-364, a highway through the Brazilian state of Rondonia. This project set in motion a massive migration from the South of Brazil to southwestern Amazonia and brought with it a great variety of environmental and social problems, such as deforestation and conflict between native and immigrant communities (Browder & Godfrey 1997, Mendoza et al 2007). Roads in Bolivia and Ecuador have also brought large numbers of *campesinos* from impoverished areas of the Andes seeking land and improved livelihoods in the lowlands (Rudel 1983, Rudel 1998, Steininger et al. 2001). It must be emphasized that there are multiple roadbuilding projects and various types of highway types in Amazonia (Perz et al 2007a). However the building -- and perhaps even more dramatically the paving -- of highways into and within Amazonia, despite promising development, improved livelihoods, and better services, has almost invariably resulted in profound and widespread social conflict and environmental degradation. These problems include: extensive deforestation and habitat fragmentation (Goodland and Irwin 1975, Soares-Filho et al. 2004, Kaimowitz and Angelsen 1998, Laurance et al. 2001, Nepstad et al. 2001, Perz et al.

2008, and many others), forest degradation, exotic invasive species (Trombulak and Frissell 2000), rapacious and illegal timber extraction, large destructive fires (Nepstad et al. 2001) massive immigration, unplanned, chaotic settlement, frequent land disputes and violence (Schmink and Wood 1994, Perz et al 2005, 2007), rapid urbanization overwhelming infrastructure and services and growth of shanty-towns, settlement of indigenous and other protected lands, increase in illegal activities including logging and coca production (Dourojeanni 2006, Nepstad et al. 2001, Bradley and Millington 2008), increase in small-scale mining operations that pollute rivers with mercury, and changes in the vectors of disease and human disease patterns (Vittor et al. 2006, Tadei et al. 1998). Rather than attempt to span the breadth of possible consequences of highway construction, in this project we focus on the links between changes in composition of human settlements and patterns of land use and land cover, and their relationships to vector community composition and rates of vector infection with malaria and leishmaniasis.

2.1 Highway construction and vectors of disease. Anthropogenic alterations of the environment are contributing drivers of emerging and re-emerging infectious diseases (Norris 2004, Keiser et al. 2005, Hunter et al. 1982, Patz et al. 2004). Development projects such as road building and improvements, dam construction, irrigation, changing crop production, mining, and industrialization have all been known to affect mosquito communities, increasing the proliferation and transmission of infectious diseases (Tadei et al.1998, Gratz 1999, Mäki et al.,2001, Singer and Castro 2001, Chaves et al 2008). A road transforms the physical conditions of the land it is constructed on, as well as the areas adjacent to it (Trombulak and Frissell, 2000). Hydrological disruption associated with road building increases the breeding sites available for some vector species, for example, populations of *Anopheles darlingi*, the major vector of malaria in the Amazon Basin, have increased following the construction of the Iquitos-Nauta road in the northern Peuvian Amazon (Conn et al., 2002). A further change introduced by road construction is the decrease in forest cover that has been linked to increased incidence of malaria in the lowland Peruvian Amazon (Dourojeanni 2006, Maki et al., 2001, Vittor et al. 2006). Deforestation first occurs as a direct result of road construction, but more extensive deforestation follows the completion of the road, as the road enables access and settlement of formerly remote areas.

Road development has the potential to change the vector community and the rates of infection within vector communities by combining features, such as deforestation, hydrological shifts, and new and enlarged human settlements (Wolfe et al., 2000; Patz et al., 2000). The increased facility and frequency of human population movements, including in Amazonia, has facilitated the introduction of disease vectors and infectious agents. Migrants can transport a disease endemic to their native locality into non-immune communities. Migrations of this sort have brought malaria to novel regions, and have also been known to move malaria back into regions where it was once eradicated (Martens and Hall, 2000). Diseases can also be harbored in communities that have acquired immunity. When migrants colonize and co-inhabit in an area, they are then susceptible to contracting endemic pathogens (Patz et al., 2000). Another way in which migration changes patterns of disease transmission is through the introduction of domestic animals brought from their regions of origin or acquired during transit; for instance when Andean migrants bring their dogs to Amazonia, they may introduce visceral leishmaniasis to the region (Llanos-Cuentas et al. 1999).

1.3 The Inter-Oceanic Highway. As part of a continent-wide initiative that has as its stated goal to promote the development of an integrated and more efficient infrastructure in 12 South American countries, the Initiative for the Integration of the Regional Infrastructure of South America (IIRSA), launched in 2000, has a planned portfolio of ten "axes of integration" each of which includes scores of infrastructural projects. Most projects focus on roads and waterways, but many are devoted to improving telecommunications and energy linkages (Killeeen 2007, Dourojeanni 2006). One of IIRSA's current major foci is the Inter-Oceanic Highway, an effort that encompasses several dozen projects including, as mentioned above, the paving and other improvements to roads and bridges that link Brazil with Peru. The Inter-Oceanic will connect a network of paved roads in the Brazilian State of Acre in the southwest of Amazonia with roads in the Peruvian Region of Madre de Dios. The improvement of these highway links and the building of multiple new bridges will greatly facilitate the movement of goods from Brazil to the Pacific coast of the continent and eventually to ports in Asia. It will also facilitate the circulation of people and goods within southwestern Amazonia, including Brazil, Bolivia, and Peru, as well as between Amazonia and the heavily populated Andean highlands and coastal cities of Peru. In Peru it is also expected to contribute to the development of a poor and little developed region of the Peruvian Amazon (Dourojeanni 2006). The road work in Peru consists of the upgrading, including paving of approximately 2,586 km of roadways and bridges between the town of Iñapari in Madre de Dios, on the border with Brazil, and the Pacific ports of Ilo, Matarani, and San Juan de Marcona (Fig. 1). The road will traverse the Regions of Madre de Dios, Cuzco and Puno, beginning from the Amazonian side at about 200 m above sea level, rising to more than 4,000 m. The number of people who will be affected by the newly paved highway is undoubtedly large. By one official estimate, six million people will be connected by the highway on the Peruvian side, or 20 per cent of the national population (MTC 2005 quoted in Mendoza et al. 2007). Counting the populations in Peru, Brazil and Bolivia, the number of people in the area of influence of the highway rises to 30 million (Brown et al. 2002, Mendoza et al. 2007).

Figure 1: Route of the Inter-Oceanic Highway in Peru. Puente Iñapari is the projected end of the road connecting Purús province to the Inter-Oceanic Highway.

Much of the Amazonian section of the Inter-Oceanic Highway will pass through some of the least disturbed forests in the Peruvian Amazon. Because of the broken topography and altitudinal range of the region, the forests of Madre de Dios are one of the planet's biodiversity hotspots with high levels of endemism, many threatened species, and a great diversity of ecosystems (Bates and Demos 2001, Dourojeanni 2006). The forests and rivers of Madre de Dios are also home to some of the last indigenous groups who choose to live away from contact with outside society. Purus is contiguous with Madre de Dios and similar in biological and cultural diversity, but has been orphaned from research and attention by its political division from Madre de Dios and geographic isolation from Ucayali. The upgrading and paving of the Inter-Oceanic Highway and the increased traffic in goods and populations that it will bring are expected to have profound, complex, and greatly varied impacts on the Amazonian regions through which the highway passes (Dourojeanni 2006, Mendoza et al. 2007, Perz et al. 2007), including: deforestation, forest fragmentation and degradation, leading to losses of wildlife and other biodiversity, higher incidence of both destructive forest fires and floods, a rise in illegal entries into and use of protected areas including indigenous reserves, and a rise in the general incidence of illegal resource uses such as logging, coca production, processing and trade, and illegal hunting and fishing activities.

Despite the multiplicity and seriousness of the conflict and change that can be expected as work on the Inter-Oceanic Highway progresses, researchers report that there is little apprehension among the general population about the near future of the affected area (Dourojeanni 2006). Most residents of the region seem unconcerned since the road itself is not strictly new, but rather an upgrading of existing links. Additionally, officials of the government have focused on the positive rather than the negative changes that the improved infrastructure is apt to bring (Lilleen 2007, Dourojeanni 2006). There are, however, some research and outreach organizations, notably the MAP Initiative that has been arranging meetings of representatives of local communities and grassroots organizations of the region to engage civil society and prepare communities for the changes that are about to take place (Mendoza et al.2007, Perz et al 2007).

1.4 An Ucayali Highway: The Carretera Federico Basadre. The entire Ucayali Region, with an area of more than 100,000 km^2, features a mere 339 km of official roadways. Two thirds of the total is the main trunk road, the Carretera Federico Basadre (CFB), which links the regional capital, Pucallpa, to the Andes and ultimately Lima (Vivanco Pimentel 2004). The CFB was built and improved largely in the 1940s, not only transforming the then small settlement of Pucallpa, but also substantially reconfiguring the geopolitics and commercial activity of the lowland Peruvian Amazon (Santos-Granero and Barclay 2000). The highway turned Pucallpa and the highway-connected parts of Ucayali Region into areas of rapid demographic growth, both through immigration from outside the region and concentration of local residents seeking better transport and communication facilities (Padoch et al. 2008). Between 1961 and 1993 the population of Pucallpa grew more than six-fold (Santos-Granero and Barclay 2000:286) and the population of the region.

The highway has also brought extensive changes in land use and land cover. While much of the landscape along the Region's many rivers, i.e., the traditional areas of settlement and agricultural production in lowland Amazonia continue to be dominated by mosaics of smallholder production characterized by small agricultural fields and pastures surrounded by large, if fragmented, secondary and mature forests, the areas along the CFB and its feeders are extensively deforested. Ongoing research by the PI and co-PI Christine Padoch shows a correlation between the presence of new immigrants from outside the region and greater levels of deforestation and landscape homogeneity, tending to eliminate all forest. The intrusion of large-scale, monocropping that is being actively promoted by the Regional government (www.agroucayali.gob.peis also fueling more complete deforestation. The area has also been subject in recent years to multiple escaped fires, resulting from extensive agriculture and environmentally inadequate practices (Gobierno Regional de Ucayali 2006, MPV and CP unpublished). The environmental repercussions of the road have been overwhelmingly negative, so that Soudre and colleagues cite the CFB as "an example of continued deforestation and land degradation" (2001:123).

1.5. The Province of Purús. Attention to the environmental and social effects of the paving of the Inter-Oceanic Highway in Peru has focused on the Region of Madre de Dios which will be traversed by the upgraded road itself. The neighboring province of Purús, a part of the Region of Ucayali, has rarely been considered, apart from concerns about the possible impacts on several indigenous groups living out of contact with broader society (Dourojeanni 2006). The potential effects on the relatively isolated and sparsely inhabited part of the Peruvian Amazon are, in fact, potentially devastating. The province is part of the Region of Ucayali, which as its name suggests is centered on the Ucayali River, the principal affluent of the upper Amazon. The Purús River, which drains the Province of Purus, flows into the Madeira River in Brazil far downriver from Peruvian territory. The very difficult terrain between Purús Province and the Ucayali regional capital, Pucallpa, has resulted in the Province's isolation from the Regional government, and from government activities altogether. The only direct link to Pucallpa at present is a twice-weekly flight in a small government-owned airplane. This relative absence of government authority and interest, and the province's very small population of approximately 4,200 persons in a territory of 17,847 km^2 exacerbates the vulnerability of the region and its communities (Vivanco Pimentel 2004). The province capital, Puerto Esperanza, is a small town that offers few services and remains unconnected — except by footpath — to any urban community. Apart from some residents of Puerto Esperanza, the population of the province is overwhelmingly indigenous, with peoples of the Pano linguistic group (Cashibo-Cacataibo, Sharanahua, Cashinahua, Yaminahua, Amahuaca, Nahua) and the Arawakan group (Piro and Culina) (Brack et al. 1997).

While the Inter-Oceanic Highway is not slated to pass through Purús, a feeder road will be built from Puerto Esperanza to the town of Iñapari in Madre de Dios located on the Highway (Fig. 2). A network of improved paths and logging roads periodically and temporarily passable by car (the hardly so), makeup much of the distance from Puerto Esperanza to the highway bridge at Iñapari. As in many frontier areas of the Brazilian Amazon, such "unofficial" roads are largely built by loggers to access valuable timbers (Perz et al 2007b, Perz et al 2008). According to officials of the Regional Government the proliferation of this unofficial infrastructure that facilitates rampant illegal activity, necessitates the construction of an "official" road governed by the State (A. Ruiz, pers. comm.). Opponents of the road

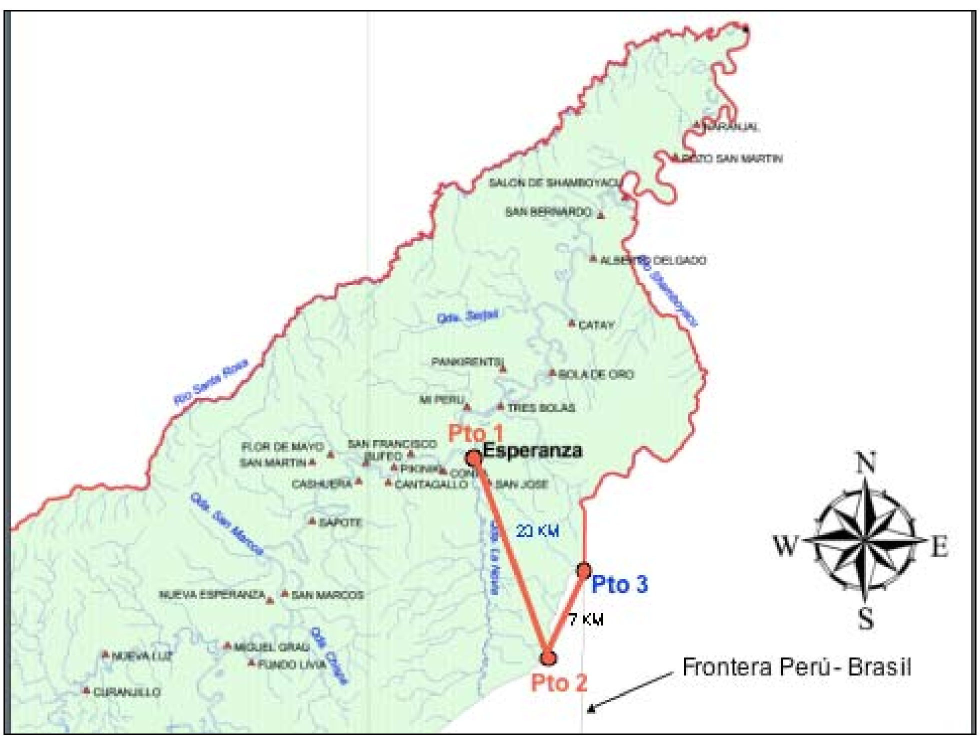

Figure 2: Proposed route of the Purus road.

cite the vulnerability of local environments and human communities as overwhelming reasons why the road should not be built; others emphasize the small population resident in the Province and the high cost of road building in arguing against the Puerto Esperanza- Iñapari link (Dourojeanni 2003).

Beyond doubt, the lack of effective State or non-governmental institutions in the area on the eve of great environmental and social change is very problematic, because local communities have no means of controlling the effects and repercussions of the road building project.

1.6 Phases of highway construction: research and monitoring. The project will make a unique contribution to understanding the effects of changes in land use, land cover and human settlement patterns due to road construction on vector communities. While a number of pioneering studies have looked at the impacts of road building and other large infrastructural projects, few have had the chance to establish a baseline of ecological and social variables prior to the project's start. Fewer studies still have had the chance to observe and monitor ecological and social changes as well as changes in vectors as they happened. The building of the Puerto Esperanza road offers the opportunity to observe a “natural experiment” on contemporaneous changes in landscape (vector habitats), migration, and disease vectors. We will study the process in its four phases:

- **Pre-Highway Baseline:** Although a footpath, partly passable by motor vehicles, already traverses the proposed highway route, the predominant cover over much of the area is still old-growth forest. Only within 2 km of Puerto Esperanza has considerable deforestation occurred, with agricultural fields and pastures predominating. Farther along the proposed track some local families have settled, with more reportedly now settling in anticipation of the building of the road. Between Pts 1 & 2 on figure 2, there are intermittent areas of small farming and fallow forests typical of land use in the region (Padoch and Pinedo-Vasquez 2001). Between Pts 2 & 3, the forest is virtually intact. At pts 2 & 3 there are very small clusters of houses.
- **Disruption by road building**: Substantial biophysical and social disruption are expected as road-building crews and heavy machinery begin work, starting from Puerto Esperanza in 2010. We expect to witness the onset of substantial human demographic change, of considerable deforestation, and major disruption of watercourses and formation of pools of water (Dourojeanni 2006), all leading to changes in vector communities.
- **Initial occupation**: During this phase we expect to quantify the most rapid changes in land cover as the result of massive migration by Andean farm households, investors, and land speculators. Also resulting in substantial alterations in the size and composition of human and vector communities, and abrupt changes in infection rates in the latter.
- **Stabilization of patterns**: While change will continue, following the initial phase of colonization, we anticipate a decrease in the rate of land cover change and consequent stabilization of the vector community structure and rate of infection. While this phase may not be reached soon along the Purús road, the Carretera Federico Basadre in Coronel Portillo Province described above, offers sites to study the ultimate demographic composition, land use patterns, and vector community ecology and rates of infection of a region where road construction took place decades before.

2. Statement of Problem, Objectives and Hypotheses

This project will describe and model changes in communities of vectors of malaria and leishmaniasis before, during, and after the construction, upgrading, and paving of a new highway in lowland Peruvian Amazon. Work on the new highway is slated to begin in 2010, giving a multi-disciplinary and experienced team the opportunity to observe at close hand the process of highway construction and changes in ecological, land use, social and demographic patterns as the highway is built and settled.

The project will:

1. establish a baseline for land cover and land use, composition and rates of infection of communities of insect vectors (focusing on malaria and leishmaniasis), and of the human communities that will be affected by the road in Purús province;

2. monitor changes in multiple ecological and human ecological variables and the communities of vectors as highway construction progresses through three distinct stages; and
3. collect comparative sets of data for selected sites in Coronel Portillo province that have long been linked to the urban centers of the rest of Peru by the Federico Basadre Highway to Lima.

The overarching objective of the multidisciplinary research team will be to answer the question:

How do communities of vectors change as the process of highway construction and settlement progresses?

To answer this question, the team will answer several interrelated questions and test associated hypotheses:

1. How does land cover change as the process of road-building and settlement progresses?

    1.1. Where forests exist, road building will result in a progressive net loss of forest cover, more fragmentation, and forest degradation.
    1.2. Where subsistence agriculture is practiced, road building will result in a progressive net loss of wooded areas and greater landscape homogeneity.
    1.3. Landscape homogeneity and loss of wooded areas will increase numbers of disease vectors and biting rates.

2. How will sociodemographic variables influence levels of deforestation and landscape change as the process unfolds?

    2.1. Areas settled by migrants from outside Amazonia will show greater net deforestation than those settled by Amazonians.
    2.2. The level of deforestation will be correlated with the types of agricultural production systems that are introduced, with household-based systems showing less deforestation than commercial.

3. How do communities of insect vectors change as landscapes along the road are altered?

    3.1 Populations of insect vectors will change (some increase, some decrease), as landscapes are progressively deforested, forests fragmented, and agricultural landscapes simplified with road-building and settlement.

3.2 The infection rate of malaria and leishmaniasis vectors will increase as the area progresses from Phase 2 through 4 of highway construction.Testing these hypotheses will allow us to model vector communities in Purus as a function of land cover, which will in turn be modeled as a function of: 1) the stage of highway construction, 2) The size of landholdings, 3) the density of users, and 4) the place of origin of local users. We will also quantify the relationship between these last two demographic variables and vector infection rates.

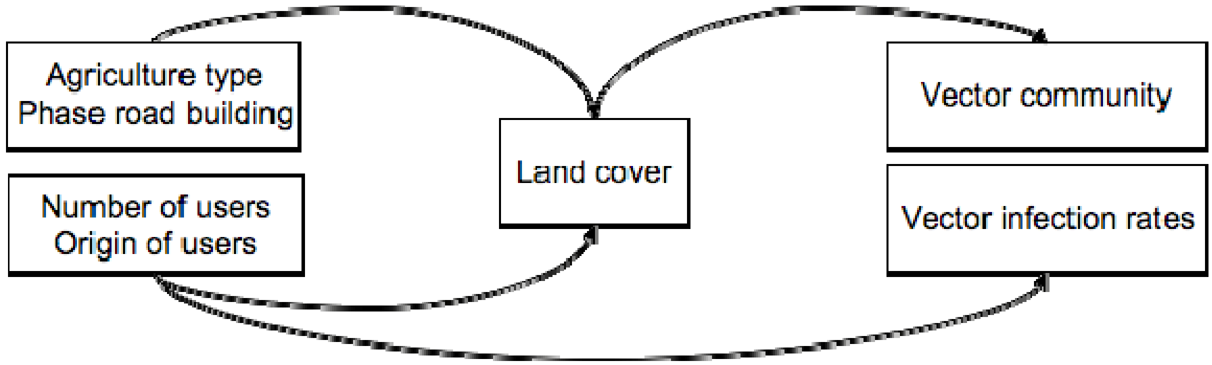

Figure 3: Conceptual model relating road building, size of landholdings, and immigration to changes in vector communities

These models take advantage of the unique opportunity to document changes with respect to a baseline of near-complete forest cover and traditional use. The observations collected and methods developed for this project will provide a general understanding of changes occurring as a result of infrastructure development throughout the tropics. These models will make it possible to examine likely responses of vector communities to future highway construction, and thus aid in formulating public health responses and policies. After developing the quantitative models using actual data from our field research, the independent variables will be adjusted to reflect potential scenarios of infrastructure, social, and demographic changes and run series of predictive simulations. The insights obtained from simulations will be used to help formulate appropriate and timely public health interventions, and inform infrastructure, land use and development policies.

3. Methods and Materials

Data for this project will be gathered and analyzed using remote sensing methods and techniques in entomology, ecology and social science, and will be used to set a baseline of human populations, land cover, vector communities, and rates of infection in vectors. We will develop a system for monitoring future change, and to construct models relating the different response and independent variable that will in turn form the basis of simulations of likely development and immigration scenarios for the region.

3.1. Study sites. The study will be conducted in Purus province along the track of the proposed new highway (Fig. 2), with comparative sites in Coronel Portillo province along the long-existing Carretera Federico Basadre highway (CFB). In order to test our hypotheses on the interactive effects of change in land cover, types of immigrants, and landholding size on populations of insect vectors of disease in Purus we will lay a grid over the 30 km track extending I km on either side of the road, and including one km around the road's starting point of Puerto Esperanza. This will give us an area of 62 km^2 or 6,200 ha. From this grid we will randomly select 200 one-hectare cells. Discarding the few cells where we might find it impossible to collect data, we will collect data on forest cover and on level of environmental heterogeneity in each of the remaining selected cells. We will also collect data on vector communities: species, relative abundance, and number infected with malaria and leishmaniasis. We will interview each member of all households with land holdings overlapping the selected cells. In addition to residents of particular cells or landholders, we will find and interview people who regularly spend significant amounts of time within each of the areas covered by the selected cells gathering, hunting, logging, fishing, or en route to other sites. We will identify these individuals through interviews and observation of residents of the area.

Highway building is expected to commence at Puerto Esperanza, and progress toward the border with Brazil (i.e., from Pto 1 through Pto.3 in Fig 2). We will start collecting baseline data at each of the sites before road building is expected to begin, and will continue collecting entomological, ecological, and social data as construction progresses through all the sites.   We expect to monitor Phases 1-3 at the Purus sites.

We will begin data collection at the CFB site at the same time and will continue throughout the four years of the project, although we expect little net change in land cover, land use, or disease vector variables. The CFB site will serve as an example of Phase 4 of highway construction and a proxy for what we expect to occur in Purus in the future. We will select a 10-km stretch of the highway to study located between km 30 (Campo Verde) and km 60 (Neshuya). This area is now characterized by substantial deforestation reflecting decades of settlement and exploitation. From ongoing research we know the communities in the area to be a mix of native Amazonians and migrants who have settled over the 50 years or so that the highway has been opened. There are considerable areas of commercial agriculture and pastures within this zone, although some household-based farming remains. Fifty one-hectare cells will be selected for study in this area.

3.2 Study variables. The project will collect data through remote sensing, ecological surveys, interviews and regular observation of local residents and users of the area, entomological field surveys, and laboratory analyses to detect malaria and leishmania parasites.

Phase of road building: each cell will be assigned to one of four categories (see Phases of Highway Construction) in year 1, and on each subsequent year hence, depending on the state of the road segment nearest to the cell. This categorical assignment will serve as an ordinal —because phases progress from 1 through 4— independent variable in analyses of land cover change. The expectation is that more advanced phases of road construction will increase the odds of a cell changing from forest to non forest.

Remote sensing data: Satellite images will be analyzed for the study region to monitor changes in forest cover and fragmentation as the road building moves forward. A historical baseline for the 1990s and 2000 will be constructed using data from the Landsat data base. All freely-available and low cost images from Landsat TM and ETM (Thematic Mapper and Enhanced TM), CBERS, and ASTER for the study region will be maintained in a project data base. We expect that cloud coverage will be a significant problem in this region. Data with daily coverage but coarser spatial resolution, e.g. MODIS, will supplement the database with higher spatial but lower temporal resolution to enable more frequent coverage.

The satellite images will be analyzed for changes in forest cover associated with the road construction. We expect to use classification and mixture model approaches to distinguish forest from cleared areas as has been successful with previous satellite analysis in this region of Peru and other regions of the Amazon (e.g., Achard et al., 2007; Hansen et al, 2008; Olivieria et al., 2007; Souza Jr. et al., 2005). Patterns of clearing (e.g., size of clearings, proximity to road, size and spatial arrangement of forest fragments) will be identified in each of the study areas and examined in conjunction with the ground-based survey data. The overlay of the survey and the satellite data will enable us to distinguish broad-scale habitat changes for disease vectors and fragmentation patterns associated with different immigrant communities. All remote sensing analysis will be done by students and post-doctoral researchers under the supervision of co-PI Ruth de Fries.

Features of each 1-ha cell will be categorized as forest, fields, fallows, water, and settlement. These characterizations will be ground-truthed through GPS-assisted field surveys. A simple metric of percent forest cover will be derived each year for each cell, and used to document the change from forest to non-forest cover. The change from forest to non-forest cover will be used as the dependent variable in logistic regressions (see below). The heterogeneity of land cover will be analyzed using FRAGSTATS (McGarigal et al. 2003). FRAGSTATS captures different aspects of landscape heterogeneity through metrics such as patch density, landscape shape index, several diversity indices, and spatial contagion. Comparisons in the performance of these different metrics as response variables with respect to socio-demographic measures, and as independent variables with respect to vector communities, will allows us to select the most appropriate for subsequent modeling.

Ground truthing: We will use standard landscape and community ecology methods to collect empirical data on changes in landscape configuration and forest cover as road-building progresses. We will run 10 m x 100 m transects at each of the selected sites (i.e. a 10 % sample of each of the 250 1 ha cells in Purus and Coronel Portillo). We will collect georeferenced data on forest type or other land use type, counting and measuring gaps, and locating and noting the condition of bodies of water. Each of the selected sites will be surveyed once per year.

Social and demographic variables: We will begin to collect baseline information at each site in the first year, expected to begin on September 2009. As described above, data on social variables will be conducted initially through semi-structured interviews. Data collected will include: place of origin of household heads or landowners, length of residence in the region, size of landholding, and plans for developing the property over the coming 5 years, especially plans to convert large areas to commercial agricultural production. At the FB site, longer histories of land use change will be collected through semi-structured interviews in the first year. Every selected household or landholding will be revisited and re-interviewed every six months to collect data on changes in land use and plans for the ensuing 5 years.

Interviews will focus on: 1) members of households with land holdings overlapping the selected cells, and 2) people who spend time gathering, hunting, logging, fishing, conducting other kinds of labor, or en route to other sites. The first category of users is relevant to managing and modifying the landscape, while the second category is expected to affect the infection rate of vectors (which depends on the continued presence or introduction of infected individuals and/or domestic animals). Users of each cell will be identified through interviews of residents and observation. Land use associated with each cell will be characterized as household-based (smallholder agriculture) or commercial (large-scale agriculture or cattle ranching), and users will be characterized as local or non-local (i.e., recent immigrant arriving as a result of road construction). The expectation is that household-based agriculture will be more closely linked to local people and tend to maintain some forest patches and heterogeneity, whereas immigrants from outside the region will practice commercial agriculture more frequently, leading to complete forest loss and landscape homogeneity. These expectations are based on on-going and as yet unpublished field research in the Ucayali region by Pinedo-Vasquez and Padoch. Household-based or commercial land use will be used as one categorical independent variable in models of land cover change from forest to non-forest. In cases where more than one type of agriculture is present in the cell, we will score the cell as corresponding to the highest percent of agriculture in the sample (for example if 30% of land use is commercial and 15% is non-commercial, the cell will be scored as commercial.) The total number of users and proportion of users (percent) of a cell will be used as independent variables to analyze both the change in land cover and the infection rate of vectors.

Entomological variables: The most important insect vectors that will be collected the leishmaniasis vectors *Lutzomyia spp*., and malaria vectors *Anopheles spp*. for each selected cell. Other biting insects, e.g., *Culex* spp., will be collected, quantified and stored, but not studied further. We expect to encounter higher relative abundance *Anopheles* close to houses and settlements along the road track, while *Lutzomiya* relative abundance will likely be higher in undisturbed natural areas and in agriculture-forest mosaics. Sampling localities in agriculture-forest boundaries and mosaics will be especially important because these areas are where many environmental modifications will occur as road-building advances.

The vector collections will be made using methods described by Perez et al. (1988) and Ogusuku & Perez (2002). These methods are currently being used by the vector surveillance system of the Peruvian Ministry of Health. J. Enrique Perez will lead collections in selected cells using the following methods:

- *Lutzomyia spp., Anopheles spp*, and other biting insects will be collected with Shannon traps with protected human bite between 6 pm and midnight. This type of collection will provide information on anthropophilic species and their abundance at each site.
- *Lutzomyia spp*., *Anopheles spp*. and other biting insects will also be collected with CDC light traps between the hours of 6 pm and 6 am. With this collection approach, we expect to collect both anthropophilic and non-anthropophilic species, including anthropophilic males.

Well-trained insect collectors working with the Ministry of Health in nearby Puerto Maldonado will collect insect vectors. These collectors will work with four young researchers who have recently completed theses on disease vectors of the region. The identification of the material will be made at the Entomology laboratory of *Instituto de Medicina Tropical* Alexander von Humboldt in Lima. The collections will also be preserved and deposited there. Vouchered identification of disease vectors will provide response variables for non-parametric comparisons between cells (e.g., at different phases of road construction), as well as models of insect communities as a function of landscape heterogeneity and forest cover. The presence of disease vectors, their biting rate, and abundance relative to total captures will be response variables in binary (for presence absence) and ordinal (for ranks of biting rates and relative abundances) logistic regressions.

PCR assays will be used to detect and identify both *Leishmania spp*. in *Lutzomyia* sandflies and *Plasmodium spp.* in *Anopheles* mosquitoes (Branch et al. 2005, Perez et al. 2008). Half the vectors collected at each sampling locality will be randomly selected for these assays. Pooled samples of 10 individuals will be used to extract DNA and amplify protein-coding genes of the relevant parasites with published primers (Branch et al. 2005, Perez et al. 2008). Pooling samples reduces cost, while enabling the detection of infection for each sampling locality. PCR assays will be verified by randomly selecting 10% of the positive bands for DNA sequencing. Sequences generated in this project will be deposited in GenBank. Malaria and leishmaniasis infection rates will be modeled as a function of the size and composition of the people using for each geographic cell. J. Enrique Perez will supervise all disease detection procedures at the molecular laboratory of the *Instituto de Medicina Tropica Alexander von Humboldt*.

4. Spatiotemporal modeling

We will develop spatially explicit data analyses using the R programming language (R Development Core Team 2005). The relationship between change in land cover and independent variables (phase of road building and sociodemographic characteristics) will be analyzed using logistic regressions. In logistic regression the response variable is binary —in this case change (1) and no change (0)— and the independent variables can be categorical, ordinal, or continuous. For example, the type of agricultural use —commercial or household-based— will be encoded as a categorical variable, whereas the phase of road construction closest to the sampling site will be encoded as ordinal categories. The relationship between the independent variables and the response variable (change in land cover) is not assumed to be linear, and there is no assumption of normality, both advantageous in a spatially explicit context (although the log odds of the dependent should be linear with respect to the predictor variables). Logistic regression applies maximum likelihood to estimate model coefficients, and the resulting log-likelihood reflects the odds that the observed values of the modeled variable can be predicted from the values of the independents. The performance of each model is reflected in its log-likelihood, with the best model having the highest log-likelihood. This enables straightforward comparisons between nested models, e.g., models with and without interaction terms, facilitating the exclusion of uninformative independent variables. We will first explore the effect of each independent variable on landscape change to exclude uninformative variables, and combine only those variables with the strongest effects in predicting land use change.

We will test models of land cover change by randomly selecting half the cells as testing data for a model constructed with the remaining half. Data will be available for three 1-year intervals, and we will also cross check models across time intervals. We will obtain remote sensing data for the entire 64 km^2 region in Purus, and because of the current human population density in the region, field surveys will provide detailed data on land use beyond the random sampling localities. The availability of data beyond target sites will enable model evaluation with land cover change observations across the region.

Logistic regressions will also be applied to model the presence of disease vectors and the presence of infection in sampled vectors as a function observed landscape features. We will fit ordinal-rank logit regressions to relative abundance data for vectors of each disease, malaria or leishmaniasis (e.g., Vittor et al. 2006), and for the frequency of infection observed in sampled vectors. These models will be evaluated using data sub-sampling.

The best-fit models with greatest predictive ability (as determined through sub-sampling) will be applied to simulations using likely scenarios of future change. For example, parameters of human population density and composition as observed in Pucallpa can be applied to the model coefficients obtained from functions in the Purus and projected to the entire region. The resulting patterns of land use will constitute the input in the best models of dependent entomological variables. These simulations will help inform public health and development policies in the region.

Our sampling strategy aims to a priori minimize spatial autocorrelation, but some clustering is expected as a result of human activities as the project continues. The spatial autocorrelation of independent variables (especially landscape features) will be evaluated using standard measures (e.g., Moran's I [Moran 1950]) at different distances. If significant autocorrelation is present at the relevant spatial scale, we will model using subsamples of cells at distances large enough to break autocorrelation or fit autoregressive parameters to the models (Dormann et al. 2007). While these methods have been frequently used at this geographic scale (e.g., Etter et al. 2006, Vittor et al. 2006), dynamic modeling of land cover is a rapidly growing field, and we will explore new methods, e.g., generalized additive models (Lehmann et al. 2003), or agent-based modeling (Parker et al. 2003), and adopt them if they outperform those considered here.

5. Linking Research to Education

The project will include multiple activities and produce a variety of products with an educational and training focus. The project will aim its educational activities at young scientists at the post-doctoral stage, at graduate students, at undergraduates from both the US and Peru, and at local decision-makers, technical personnel from both governmental and non-governmental agencies, and farmers. These activities will include:

- The project team will integrate two Ph.D. students at Columbia University in the research. These students will include project activities in their dissertation research. The project will also provide field research and analysis opportunities for two Peruvian graduate students supervised by consultant Dr. J. Enrique Perez.
- We will also provide field research and analysis training for graduate students at Columbia University through summer research opportunities in Y2, and Y3 in Peru. Funds for summer student training will be made available by Columbia University. We also expect to work with graduate students from US and Peru-based institutions doing longer-term thesis research in our focus sites.
- The project will also include four postdoctoral scientists who will work closely with senior personnel.
- We will coordinate student-focused field training activities with the administration of the Universidad Nacional Intercultural de la Amazonía (UNIA), a university in Pucallpa dedicated to educating the youth of indigenous and local communities. The PI has already begun talks with the Rector and Vice-Rector of UNIA about the possibilities of joint CU/UNIA student activities in the project.
- The project will feature briefing sessions for local decision-makers as well as technical personnel of regional and local governments and NGOs. The PI and other members of the team have multiple existing ties with local government and non-government institutions and leaders, and have already collaborated with them in training activities.

6. Dissemination of Results

In the course of this project we will produce a substantial number of scholarly articles, including some based on initial findings from our baseline field research and landscape analysis, results of the development of our model, results of model simulations of various scenarios of change, and, eventually policy implications with recommendations to global, national, and regional authorities.

In addition, we will produce English and translated summaries of our publications and relevant pieces of our project reports for the benefit of local authorities and organizations in the greater Amazonian region. These reports will be sent by email to a contact list that we have gathered through years of work in the Peruvian and Brazilian Amazon and also to new contacts, which we will seek in other Amazonian countries; they will be disseminated as well through a number of listserves. It is our expectation that our findings will be of use to decision makers and communities in all Amazonian countries.

We will establish a project website to be stored on the Columbia University server, which will provide greater access to our findings as well as to our data. This website will be publicized in the aforementioned materials whenever possible. Finally, as mentioned above, we will conduct training and workshops for local decision makers, technical personnel, and rural community members. Materials for these outreach activities will include brochures and posters in Spanish, and these will be made available as well on our website.

7. Results of Prior NSF support

PI Miguel Pinedo-Vasquez and Co-PI Christine Padoch participated as PI and co-PI, respectively, in an NSF-HSD (Agents of Change) project entitled: "Global Markets, Regional Landscapes and Household Decisions: Modeling the Transformation of the Amazon Estuary. This project examined the intrinsic and coupled connections between the role of external markets, the emergence of a forest economy, and the re-organization of households and rural-urban social networks in the Amazon estuary. The project which just ended a few months ago has generated many publications and conference presentations. A few of the prominent publications are:

- Pinedo-Vasquez, M., E. Brondizio, C. Padoch, and M. Ruffino. in press. Development and Conservation of the Amazonian Floodplains: the decade past and the decade ahead. Springer Publishers and The New York Botanical Garden Press, New York.

- Padoch, C., E. Brondizio, S. Costa, M. Pinedo-Vasquez, R. R. Sears, and A. Siqueira. 2008. Urban forest and rural cities: multi-sited households, consumption patterns, and forest resources in Amazonia. Ecology and Society 13: [online] URL: http://www.ecologyandsociety.org/vol13/iss2/art2/.

- Pinedo-Vasquez, M., and C. Padoch. in press. Urban, rural and in-between: multi-sited households, mobility and resource management in the Amazon floodplain in M. N. Alexiades, ed. Mobility and Migration in Indigenous Amazonia: Contemporary Ethnoecological Perspectives. Oxford, Berghahn

- Rerkasem K. and M. Pinedo-Vasquez. 2007. Diversity and innovation in smallholder systems in response to environmental and economic change. In: Jarvis D, Padoch C. and H. D. Cooper (eds.) Managing Biodiversity in Agricultural Ecosystems. Columbia University Press: New York

Educational Achievements of Prior NSF Research

The project's training component included the participation of three post-doctoral researchers, four graduate students, six undergraduate students, and six local interviewers. It also featured a workshop for farmers and leaders showing results of the project's household surveys. In the course of the project Pinedo-Vasquez and Padoch worked with undergraduate assistants at Columbia University to analyze and interpret initial household survey data from this project, conducted five two-week training courses for undergraduate students at the Universidade Estatual de Amapá (State University of Amapá) and two on rural development at the Nucleo de Altos Estudos Amazonicos (NAEA), Federal University of Pará. Approximately 90 Brazilian students attended these courses. Both will be offered and taught by two faculty members of the host institutions. Four graduate students were trained in the course of the project;

one (working with Padoch) has completed her Ph.D. three are still in progress. Two post-docs were trained, one each from Brazil and the US.

Broader Impacts of Prior NSF Research

Three one-week training courses on land and market surveys for rural extension agents from government and non-governmental agencies working in conservation and rural development projects in the estuarine region of the State of Amapá were conducted in the course of the project. Total participants included 32 rural agents working for the state rural agency and 14 agents working for two NGOs. Five two-week training courses: three on land-use and urban expansion for undergraduate students at the Universidade Estatual de Amapá (State University of Amapá) and two on rural development at the Nucleo de Altos Estudos Amazonicos (NAEA), Federal University of Pará were also held; approximately 90 Brazilian students attended these courses. Both will be offered and taught by two faculty members of the host institutions. During the last year of the project four two-day workshops for journalists and policy makers from the state of Amapá were conducted. Approximately forty journalists and eighty policy makers participated in the workshops. In 2007 Pinedo-Vasquez brought an American reporter from National Public Radio a field site; The story was broadcast in several segments of NPR's Morning Edition in February 2008.In addition to the HSD award, Pinedo-Vasquez supervised the following students who received Doctoral Dissertation Improvement Grants at Columbia University:

- Robin Sears who studied population ecology and regeneration dynamics of (Calycophyllum spruceanum) under (BCS 0203488) for her doctoral research on "Natural regeneration and management of agroecosystems in a seasonally flooded environment". Dr. Sears completed her Ph.D. in May 2003.
- Javier Arce-Nazario studied landscape history in Amazonia. His doctoral thesis "Reconstructing Amazonian ecological history: How humans and natural events influence the vegetation of structure in the Peruvian Amazonian varzea.
- Nancy Dammann is currently writing her dissertation entitled "Ecological analysis of the aquatic terrestrial interface in the Peruvian Amazon". She has submitted for publication three manuscripts and is currently finishing another three manuscripts.

Christine Padoch supervised the following students who received Doctoral Dissertation Improvement Grants at the City University of New York:

- Valerie Imbruce received her Ph.D. in Plant Sciences from City University of New York Graduate Center in October 2006.
- Angela Steward received her Ph.D. in Plant Sciences from City University of New York Graduate Center in June 2008.. She is currently teaching at Simmons College.
- Louis Putzel is a doctoral candidate in Plant Sciences at City University of New York Graduate Center, working in the Peruvian Amazon on his dissertation entitled The tree that held up the forest: Dipteryx spp. and the Chinese timber trade. He has published two articles based on his dissertation research.

8. Conclusion: Project Significance, Intellectual Merit and Broader Impacts

8.1. Project Significance. This project represents an extraordinary opportunity to study the impacts on insect vectors of transformative change in one of the most remote areas of Amazonia. Few, if any, research teams have had the chance to establish a baseline of ecological and social variables on the eve of such major change, and then to monitor the situation closely as it unfolds over four years of change. The research is urgent as the area in question is already changing in anticipation of the commencement of road-building. The issues that will be examined are of great and growing scientific importance and of overwhelming significance for the wellbeing of both human societies and environments in Amazonia and beyond. One of the great strengths of this research project is the multi-disciplinary research team ofhighly experienced, dedicated, and innovative scientists from the disciplines of ecology, geography, medical entomology, and anthropology, each of whom has already made important contributions to studies requiring interdisciplinary collaboration and original research approaches. The team is led by a PI with profound ties to the research area and an extraordinary and proven ability to translate research findings into local, regional, and national policy, as well as into other appropriate and effective ways of working with local society toward solutions to many important threats to the globally-important landscapes of western Amazonia.

8.2. Intellectual Merit. While valuable work has been done on the effects of highway construction on vectors and infectious disease transmission in Amazonia, this project will make a unique contribution by collecting baseline information on one of the most isolated areas of Peruvian Amazonia, by continually observing and monitoring the processes of change as the highway is built, and by constructing broadly applicable models and simulations of ecological and social change and their impacts on vector communities and rates of infection. Few studies of disease vectors have been done by a team with such breadth and depth of knowledge and experience in relevant areas of ecological, entomological and social change. The project explores a geographic area that is undergoing transformation economic, demographic and land use change, but has heretofore been largely neglected in research. The pattern of rapid change in western Amazonia also describes many, if not most other areas of the tropics and the models developed by the project will be usefully applied to other developing regions around the tropical world.

8.3. **Broader Impacts.** Project results will be used to put in place a monitoring system that will help alert local policy makers and health personnel to changing disease risks. It will also develop materials and conduct meetings for local policymakers and technical personnel. As described above (Linking Research to Education), the project will offer multiple opportunities to US-based and Peruvian students, including members of indigenous and local communities, to learn and use a variety of effective and innovative research approaches and tools. This project has the enthusiastic support of the Ucayali Regional Government and we expect that the results of the project will have considerable impact on future planning and policy, and monitoring in the Region.

9. Senior project personnel and functions in project. The senior members of the project team:

- P.I. Miguel Pinedo-Vasquez is a forest ecologist who has specializes in issues of land use change and forest management. He is a native of the Ucayali Region where the project will be carried out and has exceptional access to government authorities and many other local organizations. He will manage the project overall, especially contacts with Peruvian institutions, and will be in charge of ground-truthing and other ecological field activities.
- Co-PI Ruth DeFries is an environmental geographer who specializes in the use of remotely sensed satellite imagery to study land use and land cover. She has extensive experience working in many areas of the tropics, including Amazonia. She will be in charge of the remote sensing components of the project including the management of quantitative data generated by the research
- Co-PI Christine Padoch is an ecological anthropologist with extensive experience working on issues of agriculture and other resource uses in the humid tropics, particularly Amazonia. She will supervise the collection and analysis of social science data.
- Consultant J. Enrique Perez is a medical entomologist with much experience working on insect vectors especially Lutzomiya in Peru, including the Peruvian Amazon. He will be in charge of all collection, identification, and analysis of insect vectors as well as determination of infection rate for the project (see letter in Supplementary Documents).
- Unfunded collaborator Maria Uriarte is a quantitative ecologist who specializes in spatially-explicit modeling. She will help advise the project, especially the postdocs and students on modeling and other quantitative aspects of the project (see letter in Supplementary Documents).