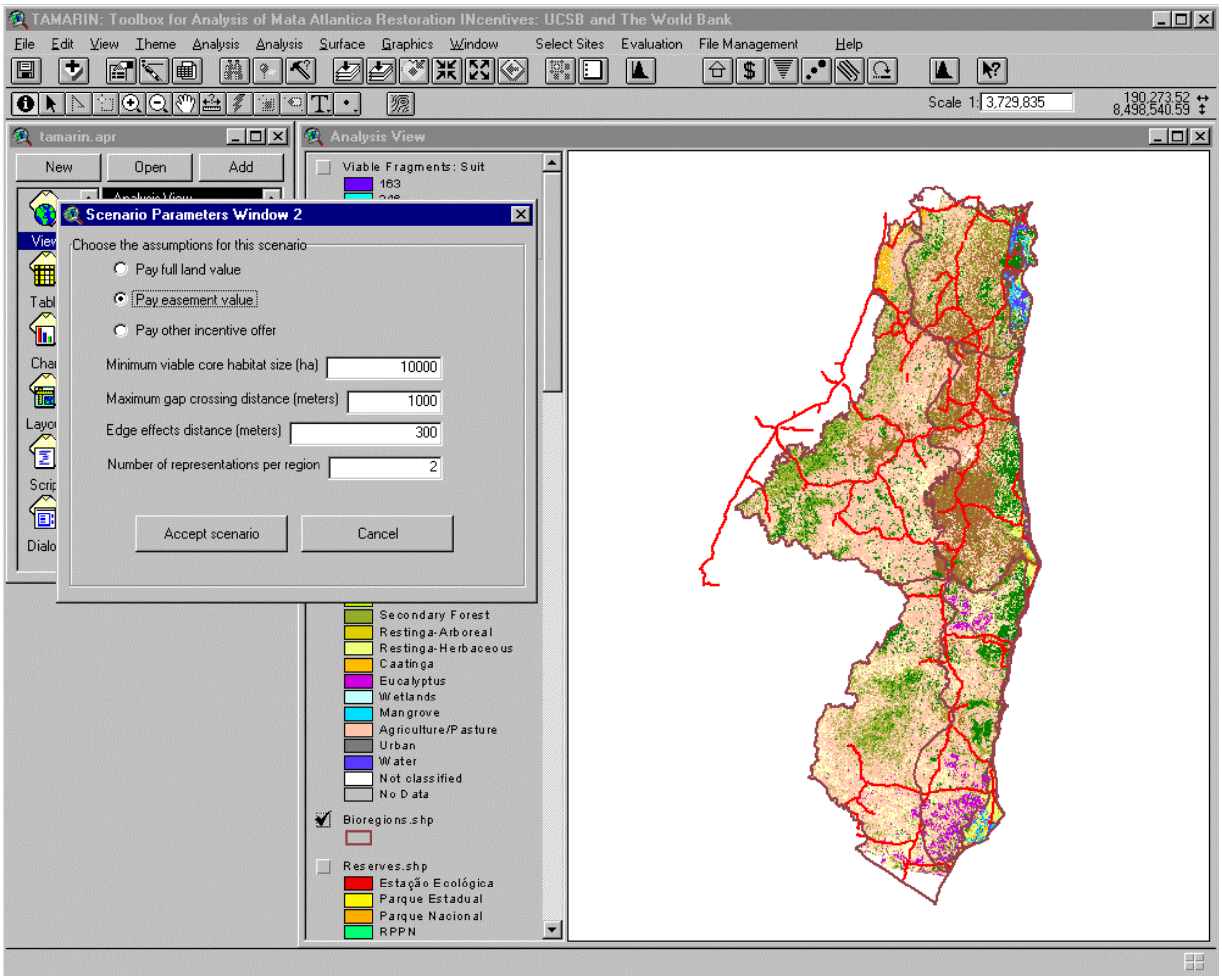
Economic Instruments for Habitat Conservation



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Executive Summary

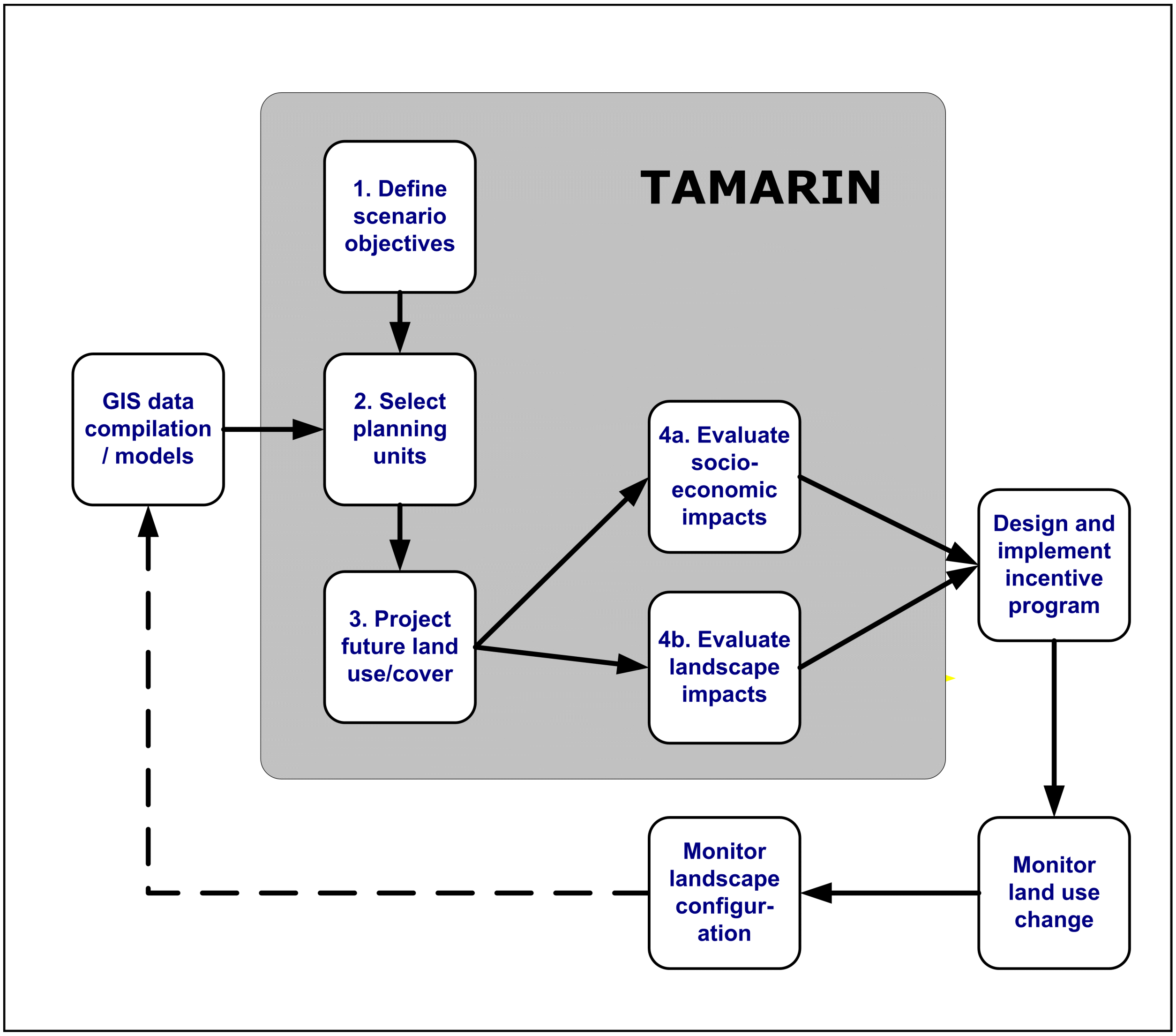
Introduction

Chomitz et al. (1999) recommended a framework to guide the application of incentive-based policies for encouraging the provision of environmental services – including biodiversity conservation – by landholders. This framework, they propose, would enable the simulation of alternative schemes that would "encourage clarity in the definition of goals and permit the development of simple, implementable strategies to reach those goals" (Chomitz et al. 1999, p. 168). Because land use, opportunity costs, and biodiversity value vary spatially, the framework was envisioned as a means to exploit that variation to craft simple, implementable policy options.

In this report we describe an implementation of an analytical framework based upon the suggestions in Chomitz et al. (1999). Specifically, we outline the framework and its basis in current conservation science and economic theory, which are used to define the desired landscape configuration for the conservation objectives. We then present a case study in the "Mata Atlântica," or Atlantic Forest, region of south Bahia state in Brazil to illustrate an application of the framework, named **TAMARIN** (Toolbox for Analysis of Mata Atlântica Restoration Incentives). We demonstrate **TAMARIN** by comparing a series of scenarios, including the present situation and the likely future trend. The results indicate the tradeoff between the suitability of sites for conservation with their value for other purposes.

TAMARIN performs two sets of GIS-based procedures, using a representation of the study area divided into 98.01 ha planning units (990 x 990 m). First, it assists planning teams to design scenarios and second to evaluate their economic and ecological consequences. Scenarios can be created by drawing on an electronic map, by defining rules for selection based on conservation and/or economic criteria, or by an external optimization model developed for the project. Scenarios can be constrained by a maximum budget limit or can be unconstrained with the total costs being calculated as a consequence of the plan. The framework can then calculate the effects of the scenario and create a series of GIS themes, tables, graphics, and reports that summarize the salient features for comparison with the present situation and other scenarios.

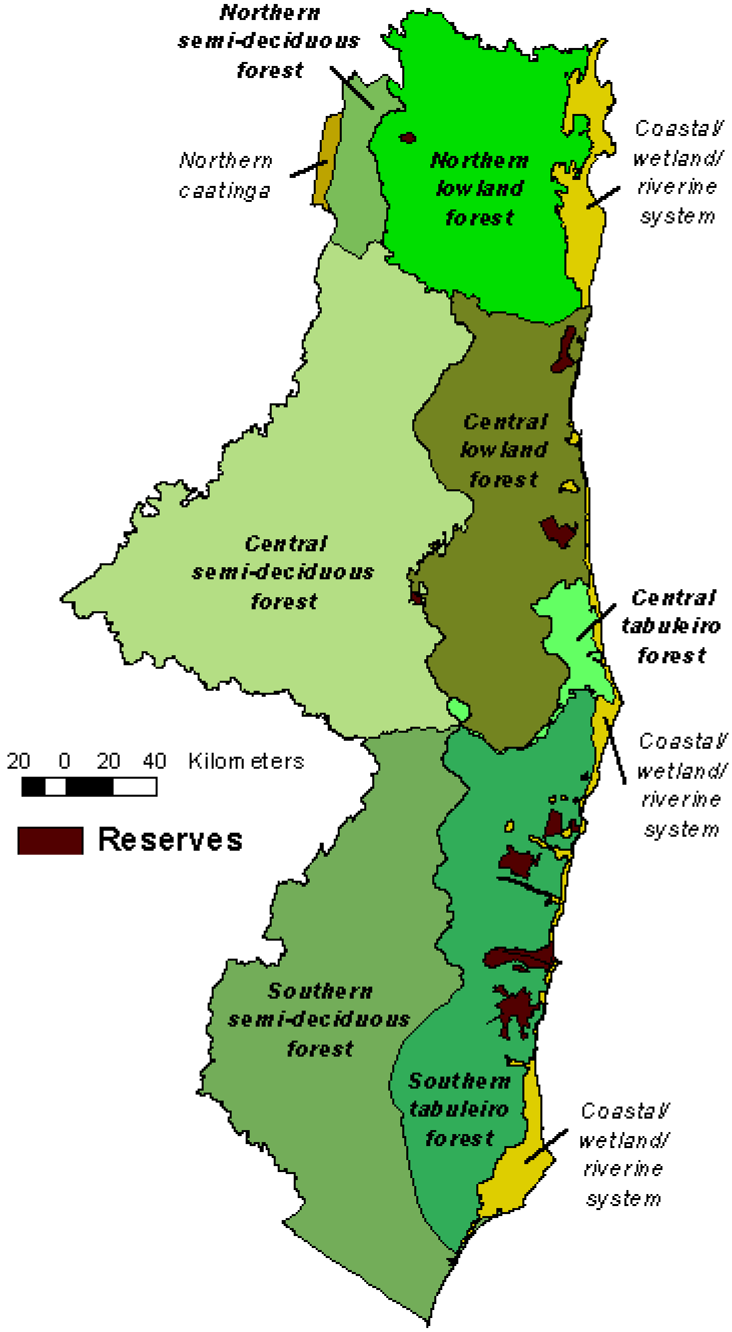
In addition to **TAMARIN**, the project developed an external optimizing land allocation model (Optimal Habitat Patch Selection or **OHPAS**) that selects the most cost efficient set of areas for conservation action that satisfies the desired future landscape configuration, if feasible within the budget constraint. The optimal solution is then evaluated in terms of the same socioeconomic and environmental factors as other scenarios inside **TAMARIN**. The optimal scenarios therefore set benchmarks against which scenarios for various policy instruments can be compared.



Central Atlantic Forest Corridor

The Atlantic Forest, Mata Atlântica, is by far the most threatened major ecosystem in Brazil, with less than 8% of its original area remaining. Conservation International places it third on its list of the 19 highest-priority habitats for conservation on the planet (based on the combination of threat and uniqueness). Within the Mata Atlântica, the area in southern Bahia is considered one of the highest priorities. In response to this global importance, the Programa Estadual para a Conservação da Biodiversidade (PROBIO) has funded a major biodiversity assessment and planning project for south Bahia. The project area is named the Central Atlantic Forest Corridor (hereafter referred to as the "Corridor") (see location map below). The dimensions of the Corridor are approximately 580 km (north-south) by 150-250 km (east-west).

Location map of Central Atlantic Forest Corridor.



Bioregions in Central Atlantic Forest Corridor.

Within a tropical area this large, there is naturally a significant variability of landscapes and land uses. Nine distinct bioregions are recognized in the Corridor. Along the immediate coast lies a narrow band of coastal, wetland, and riverine ecosystems. From east to west, the wetter bioregions support a tropical wet forest that grades into moist or semi-deciduous forest in the interior. Field surveys conducted by the PROBIO project have revealed a remarkable species replacement in both flora and fauna across the north-south gradient of the corridor. In particular, the

Rio de Contas and Rio Jequitinhonhia form biogeographic barriers that foster speciation. Consequently, the vegetation types and rivers divide the Corridor into nine bioregions.

Besides the biological differences between bioregions, there are related differences in land use and land tenure. The northern and central lowland forest bioregions are dominated by *cabruca*, a form of shade plantation for cocoa. Cabruca provides better habitat for forest canopy species than most other forms of agriculture but is not as suitable for understory birds as primary forest. Unfortunately, global market forces, government policies, and invasion of a devastating crop disease, are inducing farmers to convert cabruca to pasture. Farm size tends to be smallest and population density is greatest in this part of the Corridor. The southern tabuleiro forest bioregion retains some of the largest forest fragments in the corridor region. Farm size tends to be larger, and as a result, population density tends to be lower than in the northern bioregions. The interior semi-deciduous forest bioregions have been largely converted from forest to pasture, with only clusters of very small forest fragments remaining. Of the 74, 219 km^2 in the Corridor, only 8.8% remains as primary forest.

Principles

TAMARIN is based on conservation principles of representation, resilience, and redundancy. These are translated into the following specific criteria used in designing **TAMARIN**: 1) entire environmental/species gradients should be represented, 2) at the biogeographical scale, representation should only be counted if a forest fragment is larger than the area needed to maintain viable populations of focal species, 3) edge habitat is less suitable for interior forest species and should not count toward the representation goals, 4) several such forest fragments are necessary in each region as backups in case of catastrophic loss of any single fragment, and 5) restoration is most likely to be successful in close proximity to primary forest fragments.

From theoretical and empirical economics studies, we incorporated the following economic principles into **TAMARIN**: 1) opportunity costs vary spatially in response to relatively predictable biophysical and socioeconomic factors; 2) recognition of the variability may lead to more cost efficient conservation strategies; 3) economic incentives will more likely elicit the desired behavior from private landholders than command-and-control strategies; and 4) policy instruments derived from these principles must be based on a relatively simple set of rules that address the conservation objectives, yet are understandable and equitable to all stakeholders. Part of the challenge is that policies are directed towards changing land uses with the hope that those changes will produce the desired outcomes in landscape structure/function/composition.

Assumptions

We designed **TAMARIN** to be extremely flexible in allowing users to change many of the assumptions underlying it. Based on discussions with local experts, we made a number of basic baseline assumptions about future land use trends, the ability of the land to be restored to forest, the role of reserves, the minimum size forest patch needed to maintain viable populations for focal species, and other landscape ecological factors. We assumed that recent land use trends will continue over the next one or two decades if conservation interventions are not applied:

- Primary forest will no longer be converted to other uses because it primarily remains on marginal lands and has legal protection, but it will be degraded into secondary forest. Secondary forest will be permanently converted to pasture or agriculture except where adjacent to primary forest. Cabruca will be entirely replaced by other forms of agriculture. Pasture and agricultural lands and eucalyptus plantations will persist.

- Agricultural land and pasture that is abandoned will be recolonized by forest within a relatively short period (circa two decades). Cabruca, because it retains most of the native canopy trees, will recover more quickly.
- Primary forest in existing reserves will be protected from serious degradation, and disturbed sites in reserves will gradually recover.
- A conservation program for the corridor can either purchase land or purchase easements on the land. Purchase of the land will cost the market value of the property. We assume that to purchase a conservation easement, an owner must be paid an incentive at least equal to the foregone opportunity cost of the land in addition to the management costs.
- We defined the desired forest landscape configuration in terms of representation, redundancy, and resilience parameters. It was decided to require representation of at least two forest habitat units in all seven forest bioregions. A contiguous area of forest (primary and, if necessary, restored forest) had to be at least 10,000 ha, based on unpublished analysis of extinction probabilities for the *Cebus xanthosternos*, the yellow-breasted capuchin. A contiguous habitat unit of this size is expected to give 95% probability of survival for 100 years. Because *C. xanthosternos* can traverse nonforest habitats to reach other forest fragments, we relaxed the contiguity requirement by allowing fragments within 1000 m to be considered part of the same functional habitat unit. (Photo by Russell Mittermeier).

- Edge effects will degrade small forest fragments over time, rendering them of low biodiversity value. We assume a depth-of-edge-influence extending 300 meters from edges into forest fragments (Gascon et al. 2000). Core forest was defined for this study as primary or restored forest greater than 300 m from an edge of agriculture/pasture or urban area.

Application of TAMARIN

We used **TAMARIN** to design and evaluate five basic scenarios, including three stylized approaches that conservationists in the corridor had previously suggested. This provided an opportunity to demonstrate **TAMARIN** to a workshop in Salvador, Bahia, in June 2001, illustrating the tradeoffs inherent in corridor planning and the value of a formal framework for doing it. We also include one of the optimal scenarios here as a benchmark for comparison with other designs.

The scenarios were:

- Current—an evaluation of the present situation according to the landcover map, which was derived from 1997 satellite imagery. This defines a benchmark of how the landscape is currently configured.

- Business-as-usual—our assumption about the likely future if no conservation interventions were applied except for existing reserves.
- Cabruca—a restoration of cabruca (i.e., select all cells with greater than 50 ha of cabruca).
- Link reserves—linking the existing reserves with a series of connecting swaths of habitat of 1-2 km wide. The highest cumulative path of habitat suitability, analogous to a least cost path, determined linkages.
- Viable islands—manually selecting blocks of planning units to meet the conservation objectives in high suitability/low cost areas. This scenario was an attempt to manually emulate an optimization approach to show, to a first approximation, how efficiently the objectives might be met.
- Optimal benchmark—a least cost scenario (based on **OHPAS**) that ensures that at least two habitat blocks are protected per bioregion, and that the blocks are at least the minimum size and contain at least 1,000 ha of primary forest.

Scenarios were evaluated according to ecological and socioeconomic criteria. The ecological goals of representation, resilience, and redundancy were deemed met if each of seven distinct bioregions encompassed at least two protected 'viable habitat units' of 10,000 connected hectares each. Habitat in the viable habitat units could consist of primary forest or abandoned land (secondary forest, cabruca, or agriculture/pasture) assumed to regenerate into forest. Additional ecological criteria included area of primary forest placed under protection, the number of habitat units with at least 1,000 ha or primary forest as a source of propagules, and proportion of total forest exposed to edge effects. Socioeconomic criteria included affected population and opportunity cost of conservation. We considered two alternative assumptions about the opportunity cost of conservation. The high assumption used the full market value of the land; the low assumption assumed that landholders derived some benefits from the land even if agricultural uses were restricted, and hence that a conservation easement could be purchased for less than the full market value[1].

The following table summarizes key results for the six scenarios. There are several striking results worth noting in the table. First, in the current scenario the conservation objectives are met in six of the seven bioregions, but the majority of remaining forest consists of small patches (mostly edge forest) within the gap crossing distance. That is, very few of the fragments are large, relatively round blocks of core habitat. As a consequence of our business-as-usual assumptions, the percentage of primary forest significantly declines in the other four scenarios (from 8.8% to less than 2% in most cases). Much of this decline is in the loss of small, scattered fragments consisting of mostly edge forest (note that ¾ of remaining forest is in the edge zone in the Current scenario). This lack of remaining large fragments required the restoration of nearly half of the planning units selected in both the Viable islands and the optimal benchmark scenarios. In addition, the habitat-friendly cabruca land use disappears by assumption in all future scenarios, thus lowering the habitat quality of the matrix (the nonforest agricultural lands surrounding natural habitat). Maintaining cabruca as a strategy (while failing to conserve primary forest) entails very high loss of primary forest and extremely high financial cost, while still not achieving the conservation objectives in two bioregions where cabruca is not found. By focusing directly on the stated conservation objectives, a corridor can apparently be designed at a remarkably low financial cost, as low as $6 million US (R$12 Brazilian) for easements or envi-

[1] Easement_Value4 option was used for easement opportunity costs. See description of this assumption in the users manual in the appendix.

ronmental compensation, by our initial estimates for the optimal benchmark scenario. However, the optimal benchmark was unable to find a second planning patch or block in the Northern Semi-deciduous bioregion that was of minimum size and also contained enough primary forest.

	Baseline Scenarios					
	Present	**Business-as-usual**	**Restore cabruca**	**Link re-serves**	**Viable is-lands**	**Optimal benchmark**
# planning units selected	N/A	N/A	7,801	5,203	1,670	1,339
# regions with 2 habitat units > 10,000 ha	6	1	5	6	7	6
# viable habitat units with > 1000 ha of primary forest	12 of 12	4 of 4	5 of 19	10 of 12	13 of 15	13 of 13
% of corridor in forest	8.8	1.1	11.3	6.9	3.1	2.7
% of forest in depth-of-edge-influence zone	74	14	33	12	12	12
Total easement value of selected units (million reais)	N/A	N/A	140	96	14	12

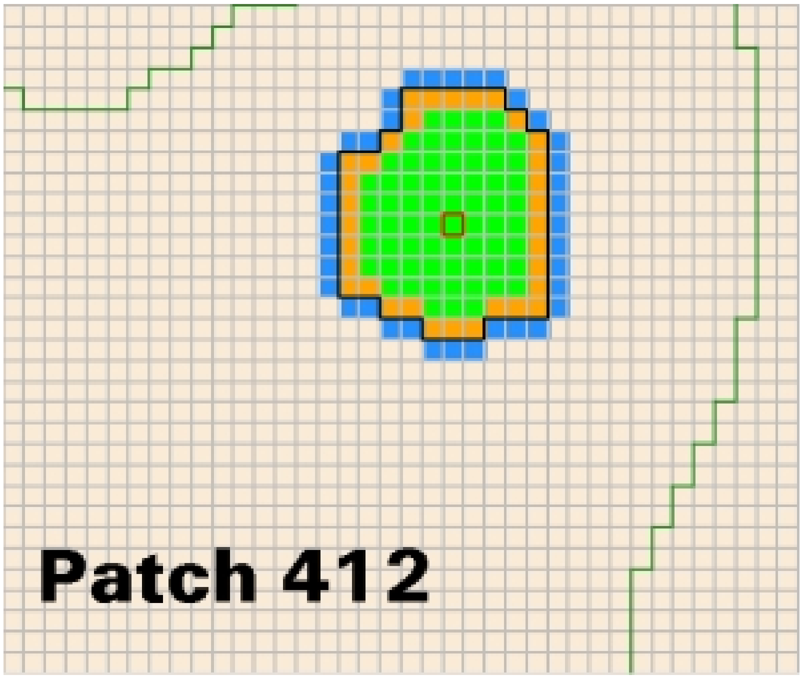
Optimization Model

TAMARIN assists users to craft conservation strategies and evaluate them but does not enforce the desired landscape configuration objectives. As such the process is essentially rule-based, where the rules are the criteria a planner thinks might create a plausible policy option. We also wanted to have a tool that would select planning units for conservation that did ensure that the landscape objectives were achieved and do so at least cost. Such optimal solutions may not always be feasible to implement for other reasons, but they provide a benchmark to measure how much more it will cost to select a suboptimal solution. The optimization reserve design process involves the following three steps:

1. Determine for each planning unit the environmental compensation costs and suitability in terms of amount of primary (and potentially restorable) forest. This was easily done through queries of **TAMARIN**'s database.

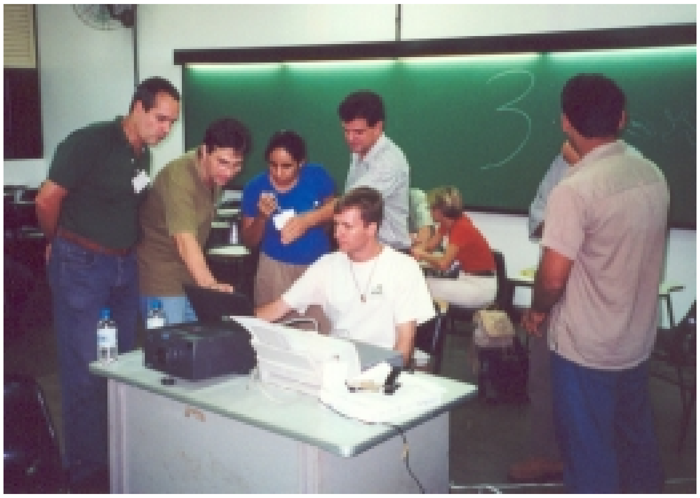
2. The size of the basic planning unit is small in regard to what would be minimally acceptable as a viable conservation area. A Planning Patch is defined as a set of connected planning units, which in concert meet the conditions of resilience. In this second step, we generate a large number of planning patches, from which to design a reserve system. This patch growing process (**PGP**) is based upon a computer algorithm that systematically generates possible patches for consideration that contain a minimum of

10,000 ha of primary and/or restored forest. Further, each Planning Patch must contain at least 1,000 ha of primary forest.



3. The third step involves a large-scale optimization model (**OHPAS**) that selects a set of Planning Patches that together optimize a set of objectives and constraints. The idea is that the set of possible planning patches spans the set of representative design alternatives. The selection of the optimal set involves minimizing cost as well as meeting all of the desired constraints. The selection of Planning Patches is also subject to the need to represent different bioregions. Regional distribution constraints maintain that at least a minimal set of Planning Patches is selected in each region.

Conclusions



TAMARIN was developed to facilitate the design and evaluation of alternative scenarios for application of economic incentives to identify priority sites within a large region for rainforest conservation or restoration. In particular, our goal was to integrate current principles in conservation biology with economic theory in a GIS framework that makes explicit the costs and benefits of each incentive option. Compensation of the opportunity costs of conservation is employed here as an incentive to modify behavior as an alternative to outright acquisition or command and control strategies such as agroecological zoning. Although we made many assumptions for our example scenario concerning the desired landscape configuration, opportunity costs, and trends in land use change, the framework is very flexible in allowing stakeholders and planners to substitute competing assumptions and objectives. These substitutions can be made as new GIS themes or simply as parameters to be entered when defining a scenario. We also discovered that users of the TAMARIN framework invented a mode of flexibility we had not foreseen. At a workshop held in Salvador, Brazil, in June, 2001, planning groups spontaneously began applying different economic incentives in different locations as they allocated a hypothetical budget.

The suite of models for optimization of the conservation and economic objectives constitute another significant contribution of the project. The patch growing process, **PGP**, used GIS data from **TAMARIN** to generate a set of sample planning patches that were guaranteed to satisfy the landscape criteria for minimum patch size and minimum amount of primary forest. Thus any patches selected automatically achieved the conservation objectives. The **OHPAS** optimization model then did the actual selection of the desired number of patches, controlled the amount of overlap allowed among them, and minimized the cost. This report presents only the initial application of this set of models for the corridor. We have only begun research on the implications of varying assumptions and objectives.

The real value of **TAMARIN** is not in assisting with making better decisions per se but in facilitating the planning process by interpreting spatial information to understand the tradeoffs between conservation and other social goals. Stakeholders and planners are forced to be explicit and quantitative in defining the desired future landscape configuration, to think not just about the current landscape but how it is likely to change, and to be creative in formulating equitable and affordable economic policies that can achieve the desired landscape with minimal disruption to the social fabric. The details of designing an incentive program, including the identification of exactly which parcels are eligible, would still need to be developed at a finer scale with more stakeholder involvement. Although **TAMARIN** was tailored to the planning issues and data sources of south Bahia, the ecological and economic underpinnings make it adaptable to many other locations.

There are many potential enhancements to **TAMARIN** that would increase its utility for regional conservation planning. Several that have immediate value include:

- Allow users to identify a nucleus of a forest block and have an option where the software would automatically expand each nucleus to a viable fragment, much like the planning patch program does.

- Developing a formal land use change model was beyond he scope of this project, but could be a valuable addition to **TAMARIN**.

- Add an option to design feasible alternative policy instruments for a range of environmental services (carbon sequestration and watershed services) and natural capital (biodiversity) and explore the tradeoffs between them.

This project focused on tool development rather than analysis. Thus there are many opportunities for additional analysis of alternative assumptions, trade-offs, and weights in both the **TAMARIN** framework and the optimization tools. We have not yet begun to formally study the implications of alternative policy options for economic incentives. The incorporation of other conservation benefits, such as carbon sequestration and watershed services, would make a richer research and planning environment for determining the relationship between biodiversity conservation and incentives for other conservation issues.

In the near future, **TAMARIN** will be made publicly accessible along with the GIS data from our project collaborators for use in conservation planning in south Bahia. Check our web site at http://www.biogeog.ucsb.edu/projects/wb/wb.html for updates on its status and applications.

Presentations of the results of this project have been made at two scientific conferences:

TAMARIN: A landscape framework for evaluating economic incentives to foster rainforest restoration. David Stoms. Presented at the 17th Annual Symposium of the International Association for Landscape Ecology, US Regional Association, Lincoln, Nebraska, April 2002.

Solving a large scale reserve design problem in Bahia, Brazil. Richard Church, Ross Gerrard, and David Stoms. To be presented at the INFORMS Annual Meeting, San Jose, California, November 2002.

References

Chomitz, K. M., E. Brenes and L. Constantino. 1999. Financing environmental services: The Costa Rican experience and its implications. *Science of the Total Environment* 240: 157-169.

Credits

Although staff of the University of California developed the **TAMARIN** software, Santa Barbara, many people and institutions contributed to its development and realization. The original concept is due to Kenneth Chomitz, who contributed to the design of the economic aspects of the framework. Gustavo Fonseca and Keith Alger (Conservation International (CI) /Center for Applied Biodiversity Science (CABS)) also made important contributions to the framework design and to its application to south Bahia. Crucial data components included: the land cover characterization undertaken by Charlotte Landau (Universidade Federal de Minas Gerais); the vegetation classification by Andre Carvalho (Centro de Pesquisas do Cacau) and Wayt Thomas (New York Botanical Garden); the land value survey data gathered by IESB under the supervision of Heloisa Orlando and interpolated by Timothy Thomas; the RADAMBRASIL land characteristics maps provided by the Instituto Brasileiro de Geografia e Estatística (IBGE). This project benefited greatly from additional contributions of data, expertise, and local knowledge of the ecological and cultural environments of south Bahia provided by participants in a sister project funded by Programa Estadual para a Conservação da Biodiversidade (PROBIO) and administered by IESB and CABS. We are grateful also to participants in three workshops (two in Ilheus and one in Salvador) who provided in-depth feedback on **TAMARIN** during its development. We regret any inadvertent omissions from this list of contributors.

This project was funded through a contract between The World Bank (Contract Manager Kenneth Chomitz, Development Research Group, World Bank) and the University of California at Santa Barbara (Principal Investigator, Frank Davis; Co-PI, David Stoms). Funding was provided by World Bank Research Support Board grant no. 683-42 and by the Rain Forest Trust. In-kind contributions were made by the PROBIO project. We also thank Kathy Scheidemen, John Sanchez and other staff at UCSB's Institute for Computational Earth System Science for contract accounting and administration. Mike Colee provided computing support at the UCSB Biogeography Lab. Doug Fischer of the UCSB Geography Department helped with some of the programming for the optimization-modeling component of the project. Thanks also to Peter Choi for help in testing the TAMARIN software and reviewing the users manual.

Table of Contents

1. INTRODUCTION

1.1 NEED FOR A CONSERVATION PLANNING FRAMEWORK IN MATA ATLÂNTICA

The extensive deforestation in many tropical regions has had a devastating array of impacts on biodiversity loss, release of carbon to the atmosphere, and degradation of other ecosystem services such as soil productivity and water purification. The most direct and widely used approach to habitat preservation has traditionally been the management of a network of protected areas. For the most part, the strategy has been to concentrate first on setting aside sites known to be extraordinarily ecologically rich or unique, and on remote sites without strong competing economic or political claims (Pressey et al. 2000). It is now widely recognized, however, that conservation needs both to expand the system of protected areas and to attend to the wider landscape outside existing protected areas. There are two reasons for this:

1. Existing conservation areas provide incomplete species and ecosystem representation. The ad hoc, opportunistic assembly of protected areas has resulted in networks in which some sets of species and habitats are over-represented while others are left unprotected.

2. Protected areas are often too small or provide too few replications to ensure viable populations. Inadequate habitat size results in species populations that are too small to maintain within-species genetic diversity and are susceptible to extinction from systemic stress. Too little redundancy of habitat patches makes the network susceptible to random catastrophic shocks. Hence species and ecosystem survival depends on what happens to contiguous habitats outside the protected areas.

The need to expand spatial coverage of conservation, however, can conflict with other legitimate social goals. To minimize this conflict, agroecological zoning techniques have been instituted to regulate land use over large areas. Zoning aims to direct development to areas of high agricultural potential and to restrict land use in ecologically significant and sensitive areas. A particularly important variant of this approach is the zoning of biodiversity management areas (Davis et al. 1996) that enhance the viability of the ecosystems involved.

The experience with zoning, however, has been disappointing. Zoning can only achieve its goals if enforced. Zoning enforcement has typically relied on a command and control approach rather than on economic incentives. In practice, enforcement has been problematic where zoning imposes potentially large costs on private actors and where political support is lacking. This points to a need for a deeper economic analysis of the basis of zoning, and of instruments and institutions that reconcile zoning objectives and landholder incentives.

Emerging market-based instruments for conservation finance may facilitate that reconciliation of landholder incentives with forest conservation. These include the potential sale of carbon emissions reductions under the Kyoto Protocol, payments for environmental service benefits (Chomitz et al. 1999) provided by forest habitats, and the potential to establish tradable development rights, whereby landholders in environmentally sensitive areas could sell development rights to those in non-sensitive areas. All these instruments could, in theory, mobilize substantial funds and induce the conservation of areas with high environmental value and low economic value.

The operational problem in tropical rainforest ecosystems is to deter further forest conversion and to induce abandonment of pasture in the interstices between forest fragments. This will result in forest regeneration, reconnecting fragments into viable habitats for all native species. Stakeholders often have "solutions" in mind of what lands to protect. The overall objectives are seldom formulated, however, and therefore the tradeoffs between conservation and other objectives are rarely examined.

The spatial variability of environmental and socioeconomic features is complex. The conservation value of a site is a function both of the site's attributes and its landscape context, which changes over time and in relation to other protected areas. Thus selecting a conservation strategy is far from easy and obvious. The challenge for planners is to help define the parameters of the desired future conditions and then identify affordable and enforceable policies that are likely to achieve them. Systematic integrated planning forces clarification and quantification of the conservation and other objectives and evaluation of alternative scenarios.

Chomitz et al. (1999) recommended a framework to guide price setting and prioritization of lands for financing environmental services, including conservation of biodiversity. This framework, they propose, would enable the simulation of alternative schemes that would "encourage clarity in the definition of goals and permit the development of simple, implementable strategies to reach those goals" (Chomitz et al. 1999, p. 168). Because land use, opportunity costs, and biodiversity value vary spatially, the framework was envisioned as a means to exploit that variation to craft simple, implementable policy options.

1.2 OBJECTIVES OF THE RESEARCH

In this report we describe an implementation of an analytical framework based upon Chomitz' suggestions. Specifically, we outline the framework and its basis in current conservation science and economic theory, which are used to define the desired landscape configuration for the conservation objectives. We then present a case study in the "Mata Atlântica," or Atlantic Forest, region of south Bahia state in Brazil to illustrate an application of the framework, named **TAMARIN** (Toolbox for Analysis of Mata Atlântica Restoration Incentives). We demonstrate **TAMARIN** by comparing a series of scenarios, including the present situation and the likely future trend. The results indicate the tradeoff between the suitability of sites for conservation with their value for other purposes.

TAMARIN is a planning support system to assist in regional conservation planning. It is a customized **ArcView** project file, with scripts written specifically for this application in south Bahia for the Central Atlantic Forest Corridor project. It has been tailored to the GIS data sets compiled by our collaborators for this project. It was designed as an exploratory tool for testing various strategies and assumptions about future land use in south Bahia against a set of descriptors of the desired forest landscape configuration that is believed adequate to meet biodiversity conservation objectives. The toolbox is NOT intended as a decision-making device to usurp the role of policy makers.

TAMARIN performs two sets of GIS-based procedures. First, it assists planning teams to design scenarios and second to evaluate their economic and ecological consequences. Scenarios can be created by drawing on an electronic map, by defining rules for selection based on conservation and/or economic criteria, or by an external optimization model developed for the project. Scenarios can be constrained by a maximum budget limit or can be unconstrained with the total costs being calculated as a consequence of the plan. The framework can then calculate the effects of the scenario and create a series of GIS themes, tables, graphics, and reports that summarize the salient features for comparison with the present situation and other scenarios.

In addition to **TAMARIN**, the project developed an external optimizing land allocation model that selects the most cost efficient set of areas for conservation action that satisfies the desired future landscape configuration, if feasible within the budget constraint. The output can be converted to an **ArcView** shapefile of the selected set of planning units, which is then evaluated in terms of the same socioeconomic and environmental factors as other scenarios inside **TAMARIN**. The optimal scenarios therefore set benchmarks against which scenarios for various policy instruments can be compared.

1.3 OUTLINE OF THE REPORT

The report is intended to describe the conservation and economic principles incorporated into the **TAMARIN** framework tool and to summarize its primary features, as these would be helpful to corridor planners. We begin in the next major section with an overview of the planning context and issues in the Central Atlantic Forest Corridor in south Bahia, Brazil. The third section summarizes the conservation and economic principles that underpin the framework. Section 4 describes the conservation objective for this particular corridor based on the principles in Section 3. We then outline the assumptions that we made or that were recommended by our collaborators, concerning the likely future land use of the corridor region in the absence of conservation interventions and about the ecology of forest restoration and edge effects. The framework is flexible enough to allow planners to test alternative assumptions. Section 5 outlines the basic procedures used to design a corridor, while Section 6 works through a sample exercise. Section 7 describes the development of the optimization model and companion software by Rick Church and colleagues to provide benchmark scenarios for **TAMARIN**. The report concludes with the significant findings of the project, including the results of a workshop in Brazil in June 2001, in which **TAMARIN** was introduced to and exercised by a diverse group of Brazilian biologists, conservationists, and agency staff. We also sketch out how **TAMARIN** would be modified to accommodate revisions in the database and more broadly the revisions needed to adapt it to other corridor projects. The appendix contains a detailed user manual for operating **TAMARIN**.

1.4 DEFINITIONS

Before describing the software and its use, here are definitions of key terms that are used throughout the report:

- bioregion—a subdivision of the planning region or corridor that distinguishes distinct biological composition. In south Bahia, bioregions were delineated by vegetation formations (east to west) and assemblages of endemic flora and fauna (north to south). Representation (see below) goals are set for each bioregion.
- business-as-usual scenario—a future land use pattern that is expected from current trends if no conservation intervention occurs. One such scenario is provided with **TAMARIN**, but the system allows users to substitute their own projections.
- cabruca—a traditional system of growing cocoa under the shade of native overstory trees, often with intervening patches of primary forest, and therefore considered important for the preservation of flagship primate species in the corridor (Alger and Caldas 1994).
- core forest—primary or restored forest (see below) that is beyond the influence of edge effects and thus provides habitat for forest interior-dwelling species.

- corridor—a planning region comprising a mosaic of land uses, including a network of parks, reserves and other areas of less intensive use whose management is integrated to ensure the survival of the largest possible spectrum of species unique to that region.
- depth-of-edge influence zone—the transition zone between the edge of agriculture, pasture, or urban land uses (see below) and core forest (see definition above) in which it is assumed that ecological processes such as fire regime and microclimate are altered. In **TAMARIN**, users can specify the distance of the depth-of-edge influence zone, although we provide a default value of 300 m based on Gascon et al. (2000).
- easement opportunity cost—this represents an estimate of the opportunity costs to the landowner if their land were included in the conservation corridor. Because the owner maintains title to the land and some opportunities to use it, this value is less than the land value (see below). Several estimates of easement value were made based on different assumptions of the opportunity costs for forest and cabruca land.
- edge forest—forest adjacent to agriculture, pasture, or urban land uses and therefore subject to conditions hostile to forest regeneration, which leads to a decline in its value as forest habitat for interior-dwelling species (in contrast to core forest) (Gascon et al. 2000).
- Environmental Benefits Index—we use this term that was coined for the USDA Conservation Reserve Program (described in Chomitz et al. 1999) as a measure of the desirability of restoring or protecting a planning unit, based on simple ecological and economic criteria. Several versions of an environmental benefits index are provided in **TAMARIN** based on different assumptions of the value for secondary forest and cabruca land.
- framework—we refer to **TAMARIN** as a framework because it structures the design and evaluation of alternative conservation strategies. We prefer this term to “model”, which implies an underlying ecological or social process.
- gap-crossing distance—the distance across non-forest habitat that a species is known or believed to be able to traverse to move between forest patches. Patches of forest separated by less than this distance are considered part of the same functional patch. In **TAMARIN**, we assume this distance to be 1km, based on expert opinion about the ecology of the yellow-breasted capuchin, although users have the option to modify this variable.
- incentive offer— a potential payment to a landowner in exchange for a modification in land use that will achieve desired conservation objectives, prescribed by a formula or schedule. Landholders accept or reject the offer depending on whether it is greater or less than the opportunity costs associated with the change in land use. In **TAMARIN**, we assume that incentive offers are equal across the entire corridor, although the user can specify the amount in a given scenario.
- land value—the market value of the land and improvements, as imputed from a survey of ~250 farms in the corridor. This represents the price of acquiring title to the land.
- matrix—the dominant land use or land cover of a region in which forest fragments are embedded. Some matrix types are more conducive to biodiversity conservation than others. For instance, a matrix of cabruca is more valuable to the maintenance of forest primates than a matrix of pasture.

- optimization—a model from operations research that selects planning patches that achieves the conservation objectives at the least possible cost.
- planning unit—the spatial unit used to analyze patterns of biotic diversity and land values in order to identify priority areas. For this project, we have chosen square cells of 990 meters on a side as the planning units. These units are large enough to compensate for uncertainty in the spatial data and to keep the size of the analysis manageable, yet small enough to allow flexible selection of alternative scenarios that respond to spatial variation in costs, restoration suitability, and existing land uses.
- planning patch—a set of connected planning units, which in concert, meet the required conditions of size, quality, compactness, and shape for the optimization model.
- redundancy—designating multiple sites for each element of biodiversity as backups to guard against catastrophic environmental or population fluctuations (Shaffer and Stein 2000).
- representation—maintain the full range of biodiversity, including species, habitats, environmental types, and genetic variation by designating a network of sites that saves some of everything (Shaffer and Stein 2000).
- reserves—lands legally protected for biodiversity conservation.
- resilience—designating sites of adequate size so that natural processes can operate at their characteristic spatial and temporal scales and increase the likelihood of maintaining species (Shaffer and Stein 2000).
- restored forest—forest that regenerates spontaneously (if near existing primary forest or cabruca) or through reforestation (if isolated from existing forest) if the current land use is abandoned, such as in response to an incentive payment to the landowner.
- scenario—an alternative strategic allocation of land uses guided by a set of assumptions and choice of planning units for conservation intervention.
- viable habitat unit—a patch, or functionally connected set of patches (within the gap-crossing distance—see above), that is at least as large as the specified minimum size to maintain a population of one of the flagship species of the corridor, the yellow-breasted capuchin. A viable habitat unit can include both core and edge forest, although scenarios are evaluated in part by the proportion of edge forest. In **TAMARIN**, we assume that this minimum area is 10,000 ha, based on a population viability analysis, although users can modify the size for a scenario.

2. CENTRAL ATLANTIC FOREST CORRIDOR

The Atlantic Forest, Mata Atlântica, is by far the most threatened major ecosystem in Brazil, with less than 8% of its original area remaining. Conservation International places it third on its list of the 19 highest-priority habitats for conservation on the planet (based on the combination of threat and uniqueness). Many have recognized this ecoregion as a global (Myers 1988, Mittermeier et al. 1998, Olson et al. 1998) or regional priority (Dinerstein et al. 1995). The environment is highly variable in its topography, soils, climate, and land use history. This environmental diversity has generated a unique biota with large numbers of endemic species adapted to living in small populations in semi-isolated habitats (Brown and Brown 1992).

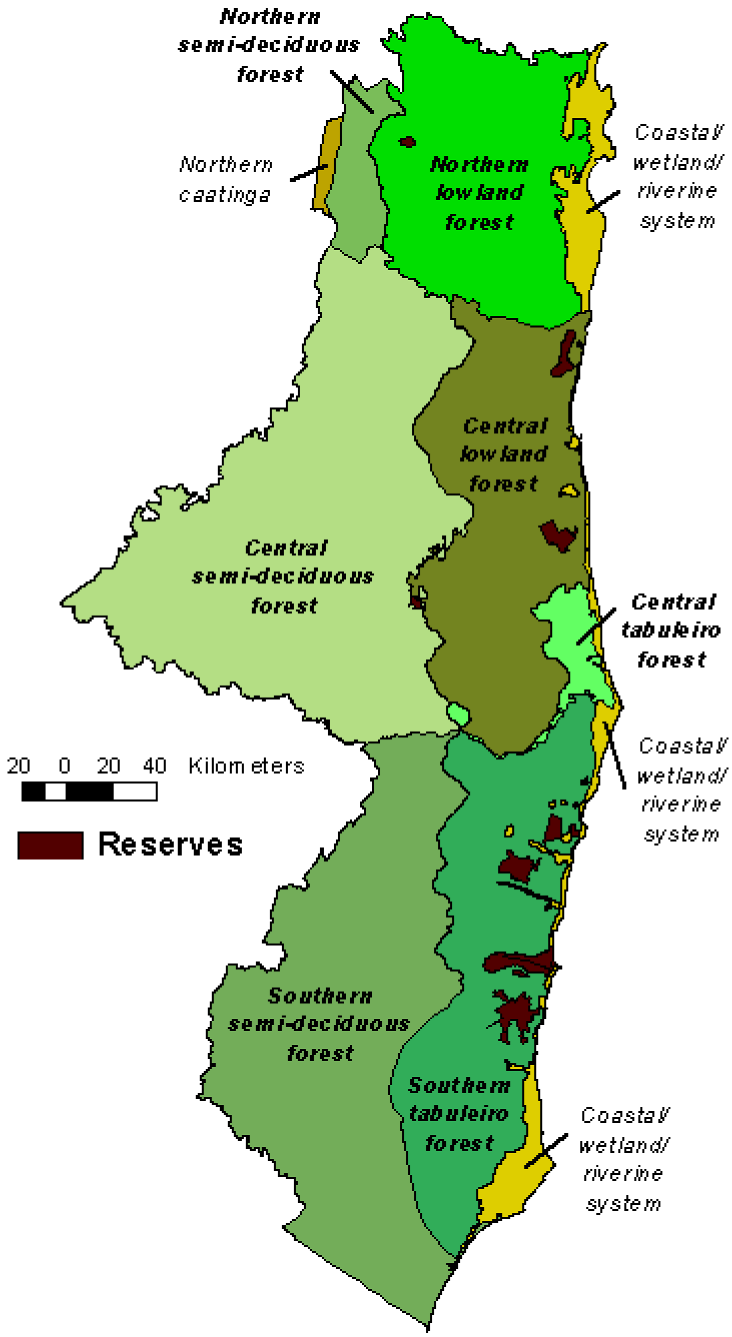
Within the Mata Atlântica, the area in southern Bahia is considered one of the highest priorities (Conservation International 1994). It is considered a significant center of endemism for several taxonomic groups (Thomas et al. 1998). In response to this global importance, the Pilot Program for the Brazilian Rain Forest (PPG-7) has funded a major biodiversity conservation project for south Bahia. The project area is named the Central Atlantic Forest Corridor (hereafter referred to as the "Corridor") (see location map below). The dimensions of the Corridor are approximately 580 km (north-south) by 150-250 km (east-west).

Within a tropical area this large, there is naturally a significant variability of landscapes and land uses. Nine distinct bioregions are recognized in the Corridor. Along the immediate coast lies a narrow band of coastal, wetland, and riverine ecosystems. From east to west, the wetter bioregions support a tropical wet forest that grades into moist or semi-deciduous forest in the interior (Fonseca 1985, and Thomas et al. 1998). In the far north, this semi-deciduous forest grades into scrubby, savanna-type vegetation known as *caatinga*. Field surveys conducted by the PROBIO project and others (Thomas et al. 1998) have revealed a remarkable species replacement in both flora and fauna across the north-south gradient of the corridor. In particular, the Rio de Contas and Rio Jequitinhonhia form biogeographic barriers that foster speciation. Consequently, they further divide the vegetation types into bioregions. Of the nine bioregions, seven originally had primary forest typical of the Mata Atlântica and will be used in Corridor planning for setting representation goals. The coastal/wetland/riverine and the Northern *caatinga* bioregions contain different forms of vegetation that would require different conservation strategies from those evaluated here.

Besides the biological differences between bioregions, there are related differences in land use and land tenure. The northern and central lowland forest bioregions are dominated by cabruca, a form of shade plantation for cocoa. Cabruca provides better habitat for forest canopy species than most other forms of agriculture but is not as suitable for understory birds as primary forest. Unfortunately, global market forces, government policies, and invasion of a devastating crop disease, are inducing farmers to convert cabruca to pasture (Alger and Caldas 1994). Farm size tends to be smallest and population density is greatest in this part of the Corridor. The southern tabuleiro forest bioregion retains some of the largest forest fragments in the corridor region (Fonseca 1985). Farm size tends to be larger, and as a result, population density tends to be lower than in the northern bioregions. The interior semi-deciduous forest bioregions have been largely converted from forest to pasture, with only clusters of very small forest fragments remaining. Eucalyptus plantations managed by large resource corporations to produce wood pulp are becoming a major land use in this bioregion. Of the 74, 219 km^2 in the Corridor, only 6,458 km^2 (645,800 hectares or 8.8%) remains as primary forest.

Location map of Central Atlantic Forest Corridor.

Despite the significant loss of forest habitat, there have been no unequivocal species extinctions in this ecoregion (Brown and Brown 1992). Brooks and Balmford (1996) predict, however, that extinctions will accelerate after a relaxation period if sufficient habitat is not restored promptly. This threat of mass extinction is further exacerbated by gloomy prospects that current trends in forest loss and fragmentation will abate. Preserving individual fragments will probably be insufficient to reverse these trends, as many fragments are too small to maintain viable populations of many species (i.e., low resilience). Current law and precedent are ineffective, if not counter-productive, to preserving and restoring forest ecosystems and their wealth of species. Without interventions to maintain, expand and link forest habitats, the forest ecosystems of the southern Bahian Atlantic Forest and much of its biodiversity appear to be doomed to extinction within the next ten years. Further, these interventions must be applied throughout the Corridor region, or many locally endemic species will be lost.



Bioregions in Central Atlantic Forest Corridor based on Thomas and Carvalho (2001).

Land reform is an important social issue in the Corridor. The government has transferred land in small tracts to groups of landless workers for them to settle and provide their livelihood. These often are lands with low value because they are marginal for agricultural production. Not coincidentally, these same lands frequently contain fragments of primary forest. Allocating such lands to a conservation scenario might conflict with the original goal of land reform. However, if forest land in these settlements were to be part of a conservation strategy, it would provide an opportunity for the settlement to receive incentive payments that may outweigh the potential income from farming.

3. CONSERVATION AND SOCIOECONOMIC PRINCIPLES IN THE FRAMEWORK

3.1 CONSERVATION PRINCIPLES (REPRESENTATION, REDUNDANCY AND RESILIENCE)

Conservation science has identified three fundamental principles for conservation of biodiversity: representation, resilience, and redundancy (Shaffer and Stein 2000). It is critical to maintain the full range of biodiversity, including species, habitats, environmental types, and genetic variation by *representing* this range in a network of sites managed primarily to ensure their persistence. Besides affirming the intrinsic value of biodiversity, representation is a hedge against the loss of species that play a crucial but undiscovered role in ecosystem functioning or that could be a source of new biotechnological material. Even with samples of all biodiversity elements represented in multiple sites, each site must be *resilient* or resistant to impacts from adjoining landscapes. The most basic solution to this is to protect or restore sites of adequate size so that natural processes can operate at their characteristic spatial and temporal scales. If only a single large, resilient sample of each species or habitat is preserved, catastrophic environmental or population fluctuations could still extirpate it. Therefore, the *redundancy* principle prescribes managing multiple sites for each element of biodiversity. This replication of sites also reinforces the representation goal by requiring samples across environmental gradients with the corresponding variation in genotypic and ecotypic responses. With limited resources, planners must choose between optimizing for resilience (larger but fewer reserves) and redundancy more but smaller reserves). Cost considerations may come into play here, as it may be more difficult and expensive to construct large reserves. Other things equal, Pelletier (2000) found that if species survivability is low in the matrix of surrounding land uses, then single large reserves are optimal over many small reserves. In other words, the minimal strategy to protect the whole ensemble of biodiversity in a region is to manage a system of relatively large sites that represents several viable populations of all species.

Many studies have reported on the degradation of forest fragments in a zone around their perimeter (e.g., Gascon et al. 2000). Adjacent land use practices such as burning modify the disturbance regime, which in turn can change the structure, composition, and function of the forest edge for hundreds of meters. Not only does this alteration reduce the resilience of the fragment, it is a dynamic process of attrition that in a harsh landscape matrix will continue to penetrate inward and reduce the size of the core habitat. In fact, fragments as large as 1000 hectares could be entirely within this altered edge zone (Gascon et al. 2000) and thus be poor representatives of primary forest habitat.

Conservation science has been more equivocal on the subject of connectivity and distance between (or proximity of) protected sites (Shafer 2001). As habitat becomes more fragmented, the individual patches tend to become more isolated from one another. What was once a large single population may become a metapopulation with periodic extinctions and recolonization of individual patches (Hanski 1994). With even further patch isolation, recolonization may become impossible and the entire metapopulation may be at risk. Having patches near each other, however, increases the risk of extinction from catastrophic events such as wildfire, disease, and extreme climate events. Habitat connectivity can be maintained with corridors or linkages (including “stepping stones”) between habitat patches. These linkages contain the same habitat as the patches or at least habitat that is adequately suitable for a species to traverse. The corridor literature is ambivalent about the pros and cons. Species differ in their behavioral response to corridors. Some species use them; some do not. The value of a corridor depends on its length and width, and thus a linkage of suitable habitat types is not automatically of benefit to a species. Long thin corridors by definition contain mostly edge habitat. For many species, this may increase their exposure to predators. Ecological theory also suggests that maintaining larger patches outweighs the negative effect of greater isolation for the same total area of habitat, particularly in cases where patches are already so isolated that there is no dispersal or colonization between them (Harrison and Fahrig 1995). At the biogeographic scale of the study area in south Bahia, we have not found adequate supporting information to justify the specification of linkages between forest patches as a requirement of the desired landscape configuration. Consequently, we have chosen to emphasize resilience (habitat block size) over connectivity in designing the Central Atlantic Forest Corridor.

If we assume there are two forest patches in a planning region, one larger and one smaller. There are at least five strategies, according to Possingham et al. (in press) regarding where to invest in a fixed amount of restoration, each of which increases representation equally in terms of hectares protected:

1. Make the existing large patch bigger (increase resilience);

2. Make the existing small patch bigger (increase resilience);

3. Link the two patches (increase connectivity with mixed effects on resilience, decrease redundancy);

4. Make one large patch (increase resilience, decrease redundancy);

5. Make many small, widely distributed patches across the region (increase redundancy).

Each strategy helps achieve some conservation objectives, such as representation across environmental gradients, connectivity, or viability through larger contiguous habitats. Yet each strategy alone cannot satisfy all objectives simultaneously. The implications of the strategies on their relative effectiveness are not always obvious. The implications of various strategies on other land uses, regional economics, etc. must also be considered. Thus planners must examine the trade-offs between strategies.

Surprisingly, most published studies of reserve siting models focus almost exclusively on the representation objective and give only tacit acknowledgment to the need for resilience and redundancy. Often representation is quantified as a single occurrence of a species or a habitat type (e.g., Kirkpatrick 1983, Margules et al. 1988, Church et al. 1996). Some projects have gone beyond this simple representation to achieving some quantitative level of representation such as setting areal objectives for each habitat type (Davis et al. 1999). Conservation planning for The Nature Conservancy in the United States has embraced the redundancy principle by aiming for representation of multiple occurrences in an ecoregion (Davis et al. 1999). We have seen few examples where resilience is directly addressed (e.g., Swetnam et al. 1998). It is indirectly considered in the areal representation goals (e.g., at least *x* hectares), but there is no guarantee that this will be achieved in patches of adequate size. At best, resilience is deferred to the reserve design stage of conservation planning by choosing boundaries that enclose adequate habitat (Kremen et al. 1999).

In summary, we extract the following conservation goals from these conservation principles—1) entire environmental/species gradients should be represented, 2) at the biogeographical scale, representation should only be counted if a forest fragment is larger than the area needed to maintain viable populations of focal species, 3) edge habitat is less suitable for interior forest species and should not count toward the representation goals, 4) several such forest fragments are necessary in each region as backups in case of catastrophic loss of any single fragment, and 5) restoration is most likely to be successful in close proximity to primary forest fragments. The **TAMARIN** framework was designed to evaluate and compare proposed landscape configurations in terms of these factors. It should be noted that whereas biological theory says representation, redundancy, resilience, and connectivity are all important, it cannot currently guide planners about the relative importance when choices must be made between them (Possingham et al. 1997). For instance, there are no clear guidelines between making a reserve larger (more resilient) versus adding more reserves (redundancy) of the same total area or cost.

The goal of virtually most biodiversity conservation programs is to maintain viable, self-sustaining populations of native species and ecosystem processes that sustain their habitats. At the same time, societies generally have other goals regarding issues such as economic production and growth, social equity, and land rights. Often the attempt to balance these potentially conflicting goals has resulted in a network of protected nature reserves in locations with the least competition with resource extraction. Thus these networks tend to be biased towards the least fertile and most rugged landscapes, which represent only part of a region's biodiversity (Pressey et al. 2000).

3.2 ECONOMIC PRINCIPLES (LEVEL OF SPECIES RISK, OPPORTUNITY COSTS, ECONOMIC INCENTIVES)

Shogren et al. (1999) identified three reasons why conservation planning should consider economics: 1) to determine the level of risk to species, 2) to account for opportunity costs of foregone resources, and 3) to formulate incentives that can effectively shape human behavior to achieve conservation objectives. We address the latter two aspects in relation to economic theory and the formulation of the **TAMARIN** framework.

Despite the view of some conservationists that preserving biodiversity is a fundamental ethic beyond consideration of economic value, the practical reality is that many decision-makers give prominent attention to the direct and indirect costs of conservation. Command-and-control strategies for conservation impose potentially large costs on private actors, and political support is often lacking. This points to a need for a deeper economic analysis and design of instruments and policies that reconcile conservation objectives and landholder incentives.

Habitat loss is the primary factor in species endangerment, and habitat conversion predominantly occurs on the highest valued, most productive land. Theoretical spatial models of rural land value and land use date back to the von Thünen model of 1826. The von Thünen model explains land values as a function of farmgate price, in turn dependent on distance to the market. The Ricardian tradition emphasizes the role of soil quality as the determinant of land value. The ability to estimate and implement such models empirically became feasible only with the advent of relatively inexpensive and accessible GIS (geographic information systems). These permit the creation of databases which link agroclimatic and geographical descriptors of large numbers of land plots. Using this approach, Mendelsohn *et al.* (1994) used a 'Ricardian' model to estimate county-level rural land values in the USA as a function of agroclimatic variables and used the model to predict spatial changes in land value as a function of climate change. In the context of tropical deforestation, Chomitz and Gray (1996) derived and estimated a reduced-form bid-rent model in which the value of a particular plot of land for a particular use depended on its agroclimatic suitability, accessibility to market, and tenure characteristics; land was assumed to go to its highest-valued use, or remain idle if no use had a value over some threshold. The model was estimated on sample points selected using a regular lattice across the landscape. This allowed continuous imputation of bid-rents or conversion probabilities across the landscape.

Among the indirect costs are opportunity costs, the economic value of land and resource use that is foregone by allocation of land to another use such as conservation (Shogren et al. 1999). Until recently, the reserve site selection literature did not include opportunity costs of protection. That is, all sites were implicitly assumed to have equal cost per unit area and only varied in their perceived biological value. The pioneering work of Magrath et al. (1995) was to stress the importance, and spatial variability, of opportunity costs. That paper attempted to impute both biodiversity values and economic opportunity costs over the landscape of West Kalimantan province, Indonesia. Economic opportunity costs were based on imputed farm profits, unadjusted for geographical variation in farmgate prices; timber values were not considered. Faith *et al.* (1996) examined tradeoffs between a biodiversity measure and opportunity costs of forestry production in southeast Australia.

Emerging market-based instruments for conservation finance may facilitate that reconciliation of landowner incentives with forest conservation. These include the potential sale of carbon emissions reductions under the Kyoto Protocol, payments for environmental service benefits (Chomitz et al. 1999) provided by forest habitats, and the potential to establish tradable development rights, whereby landholders in environmentally sensitive areas could sell development rights to those in non-sensitive areas. All these instruments could, in theory, mobilize substantial funds and induce the conservation of areas with high environmental value and low economic value.

Conserving biodiversity is a social goal that often exacts a cost on individual landholders. As mentioned above, enforcement can be problematic if these costs are high, which if imposed *ex post* might be construed as a legal "taking" or reduction in the utility value of an owner's land. Economic incentives are an alternative approach to elicit the desired behavior either by offering a payment (increase income) or financial relief (decrease costs). Such incentives have been more widely implemented in pollution reduction programs for air and water quality objectives, but there are examples in biodiversity conservation as well. In Scotland, the government pays farmers to restore woodland. The rate of payment is based on the costs of reforestation. Macmillan et al. (1998) used a cost-effectiveness analysis to evaluate the program by comparing the cost of restoration with the potential for restoration. They concluded that the most promising and least expensive restoration practices were natural regeneration near existing woodland, whereas the incentive program encouraged restoration far from woodland patches where the most labor intensive practices were required for success. Basing payments on landowner costs rather than conservation benefits may be appropriate when mandatory regulations are imposed but not for voluntary programs (Macmillan et al. 1998). Rather than excluding areas with low conservation value or high restoration costs a priori from consideration, they recommend employing a transparent system like bidding or points and let owners decide what is in their best interest. This recommendation is similar to the Conservation Reserve Program in the USA (cited in Chomitz et al. 1999), although eligibility is restricted to broad areas of conservation priority. Chomitz et al. (1999) also remark that a truly market-based approach cannot fully monetize the conservation value of individual properties. The level of biodiversity protection is an attribute of the entire landscape, so any single parcel's marginal contribution is dependent on the overall landscape configuration and complementarity with other conserved parcels and therefore is not predictable a priori. Some researchers have formulated the total benefits of reserve selection as the marginal ecological benefits summed over the selected set of planning units (Hyman and Leibowitz 2000), but we contend that the benefits are a global property of the whole region.

From these theoretical and empirical studies, we incorporated the following economic principles into **TAMARIN**: 1) opportunity costs vary spatially in response to relatively predictable biophysical and socioeconomic factors; 2) recognition of the variability may lead to more cost efficient conservation strategies; 3) economic incentives will more likely elicit the desired behavior from private landholders than command-and-control strategies; and 4) policy instruments derived from these principles must be based on a relatively simple set of rules that address the conservation objectives, yet are understandable and equitable to all stakeholders. Part of the challenge is that policies are directed towards changing land uses with the hope that those changes will produce the desired outcomes in landscape structure/function/composition (Oñate et al. 2000).

4. ASSUMPTIONS

We assumed that recent land use trends will continue over the next one or two decades if conservation interventions are not applied. Specifically, we assumed:

Land use trends under a Business-as-usual scenario

- Primary forest will no longer be converted to other uses because it primarily remains on marginal lands and has legal protection. However, it will continue to be degraded into secondary forest through firewood gathering and other resource extraction, hunting, and other human-related impacts. Secondary forest will be permanently converted to pasture or agriculture except where adjacent to primary forest. Because of the declining economics of cocoa production in the corridor, cabruca will be entirely replaced by other forms of agriculture including sun-grown cocoa, coffee, or crops or pasture. Pasture and agriculture and eucalyptus plantations will generally remain. Urban land uses and other habitat types (e.g., mangrove, wetlands, water bodies, etc.) cannot be converted into forest and are assumed to remain in their present condition. The modeling framework allows substitution of other future scenarios, but we limit our discussion here to this 'business-as-usual' scenario.
- Agricultural land and pasture that is abandoned (no longer actively kept free of trees) will be recolonized as secondary forest within a relatively short period (circa two decades). It may take many decades, however, before it becomes suitable habitat for interior forest-dwelling species (Sorensen and Fedigan 2000). We assume that these lands can eventually recover as forest if they are located within 1 km of primary forest that functions as a seed source. Otherwise, they tend to only partially recover as scrubby second growth known locally as '*capoeira*.' Cabruca, because it retains most of the native canopy trees, will recover more quickly. Beyond 1 km of forest, reforestation requires manual intervention for planting at a cost of $1000/ha.
- Primary forest in existing reserves will be protected from serious degradation, and disturbed sites in reserves will gradually recover (with only modest additional protection costs).

Opportunity costs and other conservation costs

- A conservation program for the corridor can either purchase land or purchase easements on the land. Purchase of the land will cost the market value of the property. Because use of forested land is already restricted, but forested land nonetheless has value, we assume that the cost of a conservation easement is less than the cost of outright purchase. In either case additional recurrent management costs are necessary.

Conservation goals

- Using a formal framework to design the Corridor forces conservation planners to be concrete about the specifications of a minimum acceptable landscape configuration that is necessary (to the best of our scientific understanding) to preserve and restore this section of the Mata Atlântica. We consulted with biologists working in the corridor area to develop these specifications, which we defined in terms of representation, redundancy, and resilience parameters. To conserve the full range of endemic species, and in the absence of comprehensive species data, it was decided to require representation of forest habitat in all seven forest bioregions delineated by Thomas and colleagues (unpublished data). Redundancy was evaluated by seeking at least two of these forest habitat units in each ecoregion. To count toward the representation and redundancy goals, a contiguous area of forest (primary and, if necessary, restored forest) had to be at least 10,000 ha. This figure was based on unpublished analysis of extinction probabilities for the *Cebus xanthosternos*, the yellow-breasted capuchin, (Adriano Pereira Paglia, unpublished data), a primate considered one of the range-demanding or "umbrella" species of the corridor. A contiguous habitat unit of this size is expected to give 95% probability of survival for 100 years. Because *C. xanthosternos* can traverse nonforest habitats to reach other forest fragments, we relaxed the contiguity requirement by allowing fragments within 1000 m to be considered part of the same habitat unit.

- Edge effects will degrade small forest fragments over time, rendering them of low biodiversity value. We assume a depth-of-edge-influence extending 300 meters from edges into forest fragments (Gascon et al. 2000). Core forest was defined for this study as primary or restored forest greater than 300 m from an edge of agriculture/pasture or urban area.

These were our working assumptions as a baseline for analysis. However, **TAMARIN** is configured such that most of these assumptions can be modified by a user, either by changing values in a text box in a dialog form or substituting a different spatial theme for our original one.

We readily acknowledge that additional conservation objectives, including connectivity, are important and that saving a handful of modest size forest fragments is insufficient to maintaining all biodiversity of the Central Atlantic Forest Corridor. Many species are endemic to a single watershed or hillside and are not likely to be represented in this admittedly sparse network of reserves. We emphasize, however, that our guideline from our collaborators was to design the first stage of a corridor program. They believed that it was critical to save the larger fragments first, since their fate was extremely precarious. Once they were lost, a viable corridor would not be possible.

5. TAMARIN OPERATION

TAMARIN performs two sets of GIS-based procedures. First, it assists planning teams to design scenarios and second to evaluate their economic and ecological consequences. Scenarios can be created by drawing on an electronic map, by defining rules for selection based on conservation and/or economic criteria, or by an external optimization model developed for the project. Scenarios can be constrained by a maximum budget limit or can be unconstrained with the total costs being calculated as a consequence of the plan. The framework can then calculate the effects of the scenario and create a series of GIS themes, tables, graphics, and reports that summarize the salient features for comparison with the present situation and other scenarios. The section that follows summarizes the procedures. They are described in detail in the user manual in the appendix.

5.1 PROCEDURES FOR CREATING A SCENARIO

The procedures for selecting are divided into three sequential steps. First the planner defines the parameters of a scenario in a form or dialog box. Next the planner selects planning units for the scenario by one of four methods as described below. The final step applies the budget constraint, if appropriate, to further refine the selection of planning units.

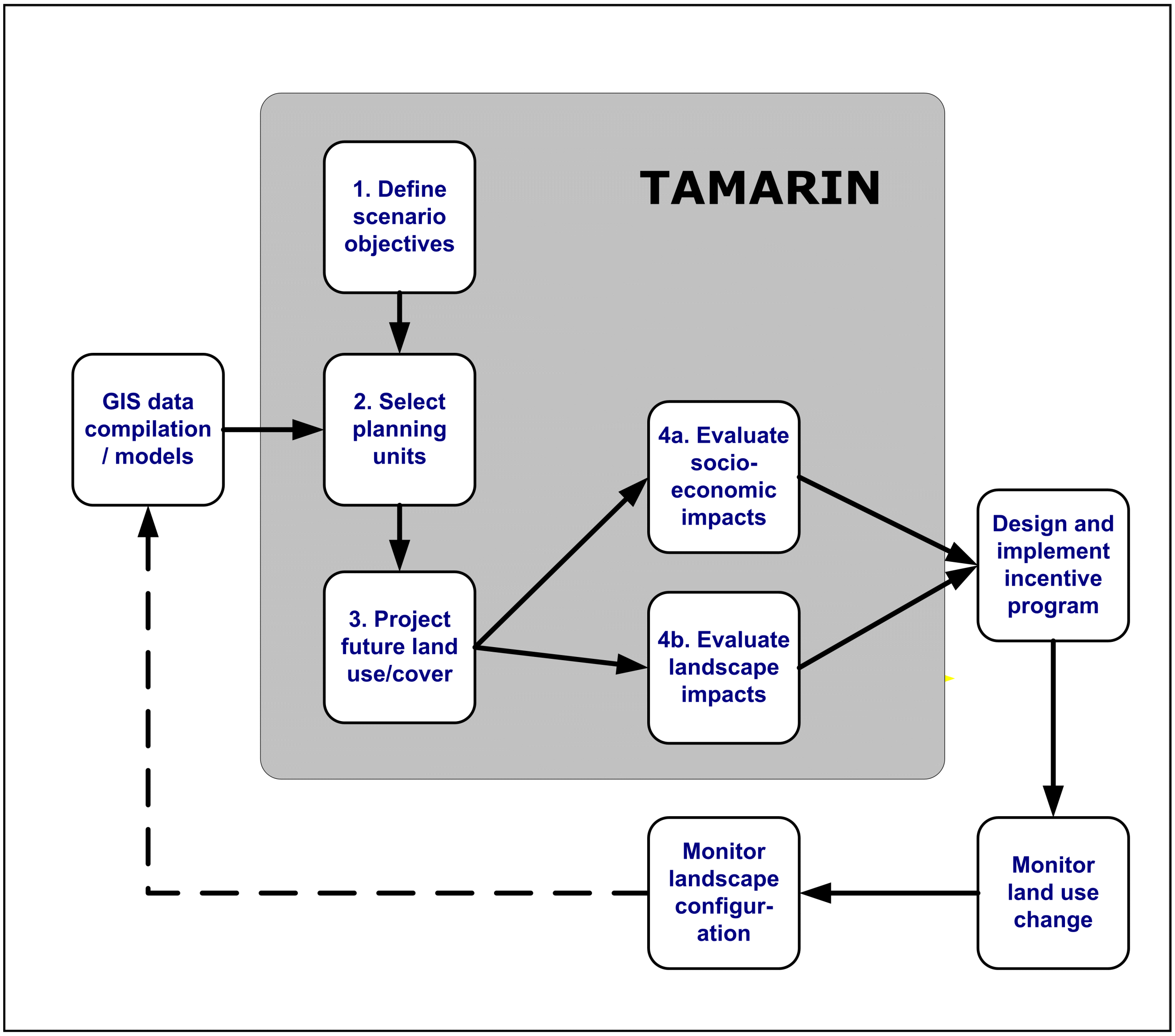
Each scenario will have different parameters. The first step is to define what those parameters will be, through a series of dialog boxes or forms, scrolling lists of files, and radio buttons. These represent factors such as the budget, payment method, desired landscape configuration, and assumptions.

A planner can select planning units through one of three methods. The first method is interactively using **ArcView**'s *selection tool*, either by clicking on planning units individually or clicking and dragging the cursor across a rectangular area. This works well when a planner has specific sites in mind for a scenario.

Alternatively, a planner may not know exactly <u>where</u> to restore forest but has a good understanding of the characteristics of the best locations. Then they can query the attributes of the planning unit coverage in terms of Boolean logic. For instance, a planner can query for units with attribute values =, >=, <= some value for land value or restoration suitability.

The planner or someone else may have created a shapefile (either previously or using the ArcView graphic tool and converting the graphic into a shapefile) that portrays a potential conservation corridor. By choosing the ‘Select by Theme’ option, this shapefile can be selected with the browser and have it select all planning units that occur within the boundary of its features. One example of the Select by Theme option is to evaluate an optimal scenario derived from the external optimization model (**OHPAS**) developed by Dr. Richard Church and colleagues for this project (see Section 7).

It is possible for the planner to select so many planning units that the initial scenario may exceed the budget specified in the scenario definition step. **TAMARIN** checks if a budget limit was set. If the planner did set a budget limit, the planning units are sorted either by their ‘Land_Value’ or ‘Easement_Value’ attribute in ascending order or the mean suitability attribute in descending order and sums the appropriate costs until the budget constraint is reached. The choice of which cost to use is based on the selection of whether to purchase land or easements in defining the scenario. Planning units below the constraint are then selected, while those beyond the constraint are deleted from the scenario. Thus the procedure selects either the least expensive units or those with the greatest relative suitability for restoration or conservation for the budget. After running this step, a new shapefile named after the scenario name will be created and added to the Analysis View.



5.2 Evaluating a Scenario

Once the scenario parameters have been defined and the set of planning units has been selected, the next group of procedures perform the evaluation of the scenario, including the forecast of future land cover/use; a summary of the economic and environmental effects; a series of landscape indices regarding the resulting landscape configuration relative to the conservation objectives; and preparing a summary report about the scenario.

The first evaluation step combines the data from the restoration option for selected planning units with the business-as-usual grid for the remaining lands to create a future land use forecast for the scenario. It is also necessary to derive some summary measures about it that can be compared to other scenarios, to the current situation, to the business-as-usual scenario, and to the conservation objectives. **TAMARIN** computes the summaries and prints them to a series of tables, including the future percentage of land cover/use types, the percentage of forest and cabruca types by each biophysical zone in the future land use scenario, and the total costs and restoration suitability for the selected planning units. The framework also derives a set of landscape measures on the size of fragments, the proportion of core vs. edge forest, and the number of fragments by bioregion the exceed the minimum habitat size and therefore contribute to the conservation objectives.

6. Application of TAMARIN

We used **TAMARIN** to design and evaluate five basic scenarios, including three that conservationists in the corridor had previously suggested. These are highly stylized scenarios for illustrative purposes, and are not intended to represent actual attempts at corridor design. This provided an opportunity to demonstrate **TAMARIN** to a workshop in Salvador, Bahia, in June, 2001, illustrating the tradeoffs inherent in corridor planning and the value of a formal framework for doing it. The results presented here differ slightly from those presented at the workshop because there have since been modifications in land values, planning units, and bioregions. We also include one of the optimal scenarios here as a benchmark for comparison with other designs.

The scenarios were:

- Current—an evaluation of the present situation according to the landcover map, which was derived from 1997 satellite imagery. This defines a benchmark of how the landscape is currently configured.
- Business-as-usual—our assumption about the likely future if no conservation interventions were applied except for existing reserves.
- Cabruca—regenerate forest from current cabruca areas(i.e., select all planning units with greater than 50 ha of cabruca).
- Link reserves—linking the existing reserves with a series of connecting swaths of habitat of 1-2 km wide. The highest cumulative path of habitat suitability, analogous to a least cost path, determined linkages.
- Viable islands—manually selecting blocks of planning units to meet the conservation objectives in high suitability/low cost areas. This scenario was an attempt to manually emulate an optimization approach to show, to a first approximation, how efficiently the objectives might be met.
- Optimal benchmark—a least cost scenario that ensures that at least two habitat blocks are protected per bioregion, and that the blocks are at least the minimum size and contain at least 1,000 ha of primary forest (see Section 7 for an explanation of the optimization model).

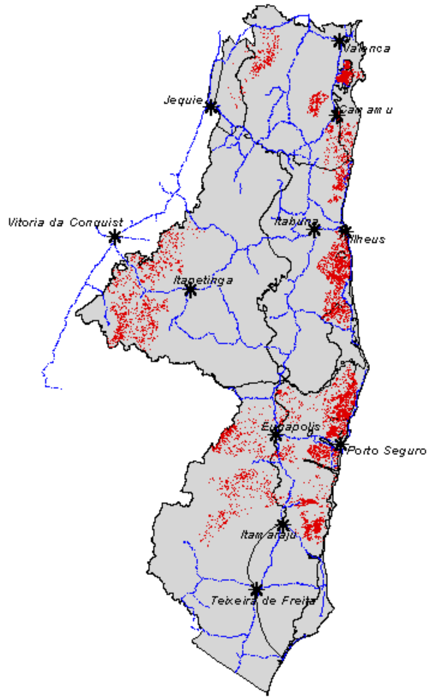
Scenarios were evaluated according to ecological and socioeconomic criteria. The ecological goals of representation, resilience, and redundancy were deemed met if each of seven distinct bioregions encompassed at least two protected ‘viable habitat units’ of 10,000 connected hectares each. Habitat in the viable habitat units could consist of primary forest or abandoned land (secondary forest, cabruca, or agriculture/pasture) assumed to regenerate into forest. Additional ecological criteria included area of primary forest placed under protection, the number of habitat units with at least 1,000 ha or primary forest as a source of propagules, and proportion of total forest exposed to edge effects. Socioeconomic criteria included affected population and opportunity cost of conservation. We considered two alternative assumptions about the opportunity cost of conservation. The high assumption used the full market value of the land; the low assumption assumed that landholders derived some benefits from the land even if agricultural uses were restricted, and hence that a conservation easement could be purchased for less than the full market value[2].

The following table summarizes key results for the six scenarios. There are several striking results worth noting in the table. First, in the current scenario the conservation objectives are met in six of the seven bioregions, but the majority of remaining forest consists of small patches (mostly edge forest) within the gap crossing distance. That is, very few of the fragments are large, relatively round blocks of core habitat. As a consequence of our business-as-usual assumptions, the percentage of primary forest significantly declines in the other four scenarios (from 8.8% to less than 2% in most cases). Much of this decline is in the loss of small, scattered fragments consisting of mostly edge forest (note that ¾ of remaining forest is in the edge zone in the Current scenario). This lack of remaining large fragments required the restoration of nearly half of the planning units selected in both the Viable islands and the optimal benchmark scenarios. In addition, the habitat-friendly cabruca land use disappears by assumption in all future scenarios, thus lowering the habitat quality of the matrix (the nonforest agricultural lands surrounding natural habitat). Maintaining cabruca as a strategy (while failing to conserve primary forest) entails very high loss of primary forest and extremely high financial cost, while still not achieving the conservation objectives in two bioregions where cabruca is not found. By focusing directly on the stated conservation objectives, a corridor can apparently be designed at a remarkably low financial cost, as low as $6 million US (R$12 Brazilian) for easements or environmental compensation, by our initial estimates for the optimal benchmark scenario. However, the optimal benchmark was unable to find a second planning patch or block in the Northern Semi-deciduous bioregion that was of minimum size and also contained enough primary forest.

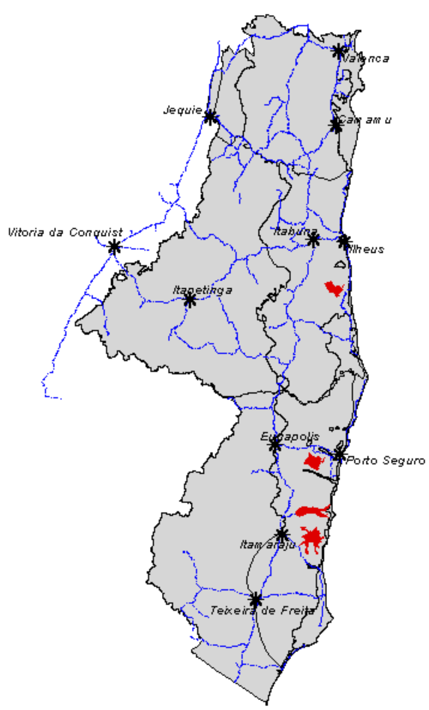
[2] Easement_Value4 option was used for easement opportunity costs. See description of this assumption in the users manual in the appendix.

	Baseline Scenarios					
	Present (Curr97)	**Business-as-usual (BAU)**	**Restore cabruca (Cabruc)**	**Link reserves (Link)**	**Viable islands (Island)**	**Optimal benchmark**
# planning units selected	N/A	N/A	7,801	5,203	1,670	1,339
# regions (of 7) with 2 habitat units > 10,000 ha	6	1	5	6	7	6
# viable habitat units with > 1000 ha of primary forest	12 of 12	4 of 4	5 of 19	10 of 12	13 of 15	13 of 13
% of corridor in primary (and restored) forest	8.8 (0.0)	0.7 (0.4)	0.7 (10.6)	2.1 (4.8)	1.5 (1.6)	1.4 (1.3)
% of forest in depth-of-edge-influence zone	74	14	33	12	12	12
Largest fragment (ha)	74,468	21,508	108,837	104,260	21,508	26,059
% of forest to be restored	N/A	34	91	67	49	46
Total land value of selected units (million reais)	N/A	N/A	373	199	41	33
Total easement value of selected units (million reais)	N/A	N/A	140	96	14	12
Total reestablishment costs of selected units (million reais)	N/A	N/A	0	2	0	0
Population in selected planning units (1000s)	N/A	N/A	264	130	23	14

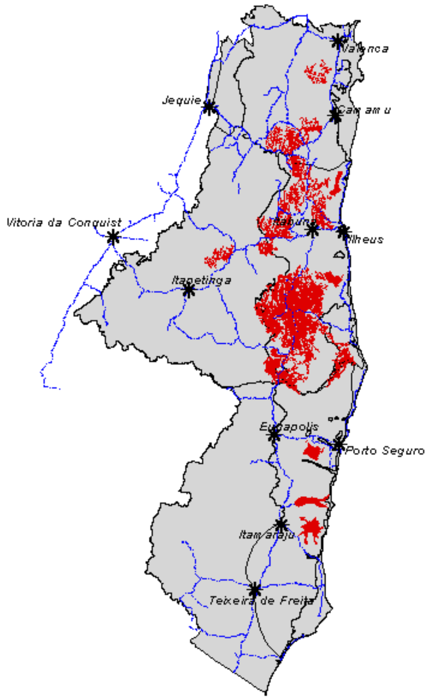
N/A – not applicable



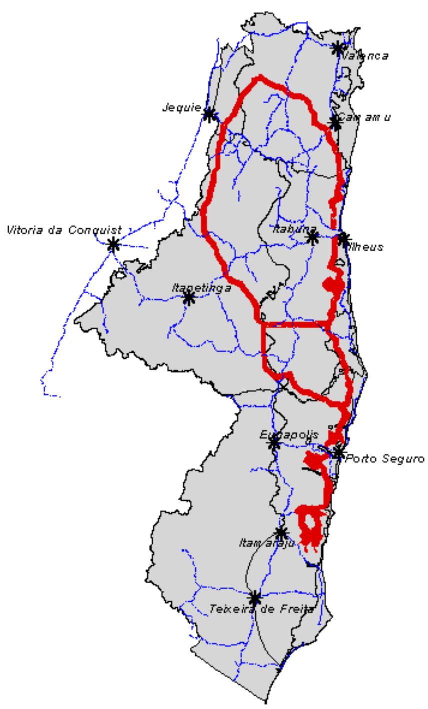
a) Viable fragments—present 1997 scenario



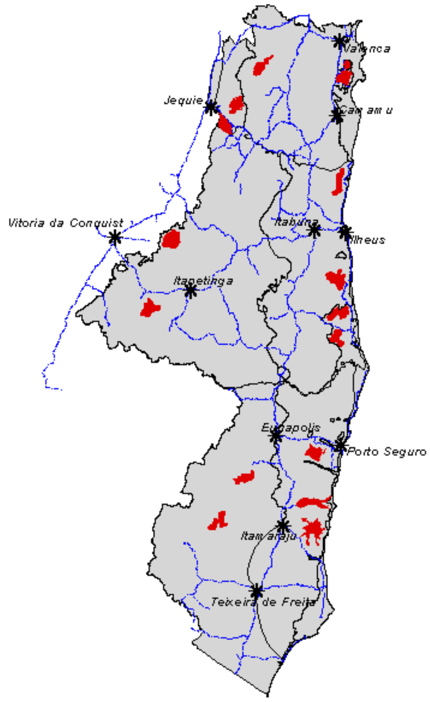
b) Viable fragments—business-as-usual scenario



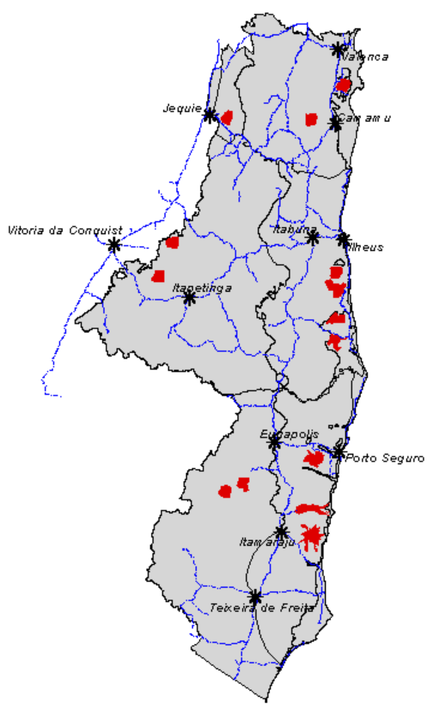
c) Viable fragments—restore cabruca scenario



d) Viable fragments—link reserves scenario



e) Viable fragments—viable islands scenario



f) Viable fragments—optimal scenario

7. THE OPTIMIZATION MODEL

7.1 BACKGROUND

TAMARIN assists users in crafting conservation strategies and evaluate them but does not enforce the desired landscape configuration objectives. As such the process is essentially rule-based, where the rules are the criteria a stakeholder or planner thinks might create a plausible policy option. We also wanted to have a tool that would select planning units for conservation that does ensure that the landscape objectives are achieved and at the least cost. Such optimal solutions may not always be feasible to implement for other reasons, but they provide a benchmark to measure how much more it will cost to select a suboptimal solution. Alternatively, an optimal solution could form the basis for crafting and implementing a policy option (Davis et al. 1999). To that end, we adapted and developed a suite of tools to support the selection of a least-cost set of forest patches that met all conservation objectives. These tools are not incorporated within **TAMARIN** itself, but are loosely coupled with it by exchanging GIS files.

Reserve design, at its best, is an ill-defined problem, that involves multiple and conflicting objectives and surrogate measures of goodness. Simply put, ecologists and biologists cannot state what exactly is needed for the preservation of most species. This is especially true for regions that contain a plethora of species not yet categorized or studied. Liebman (1976) would classify such public decision problems as wicked. Decision Support Systems are designed to help characterize such ill-defined problems, as well as attempt to generate alternatives that are top performers.

It is important in the design of Decision Support Systems to create the ability to manually craft solutions, track progress and performance, etc. If a set of different solutions is then crafted, then it is important to provide the capability to compare and contrast each solution as well as to test potential modifications of any one of those solutions. When design problems allow tremendous flexibility in decisions, involve multiple and conflicting objectives, and include structural constraints, then the problem is likely to be large and complex enough that manual methods of solution crafting will fail to identify the best solutions. To address this need, many DSS systems utilize optimization models and solution algorithms. In fact, the General Algebraic Modeling System (GAMS) was developed by World Bank Staff to meet the needs to quickly develop and apply an optimization model for project analysis. The size of the reserve design problem for the Bahia region is large enough that even tools like GAMS with a solver routine would be rendered ineffective by complexity and problem size. The focus of this section of the report is on the development of an optimization model and solution routine for selecting areas for conservation and habitat restoration.

A general modeling construct was selected that consists of three main models. This model set, when used together, can generate optimal plans for corridor design. The proposed modeling process is based upon an approach developed for protecting the San Joaquin Kit Fox in a two-county region of California (Gerrard et al. 2001, Church et al. 2002). Researchers at UCSB and UC San Diego developed the kit fox reserve design model with the support of the National Center for Ecological Analysis and Synthesis (Gilpin et al 1998). Subsequent work on this modeling process has been supported by the Western Ecological Research Center of the U.S. Geological Survey, supplemented here by the World Bank. The work presented here builds upon elements provided by the USGS project.

7.2 DEFINING THE CORRIDOR DESIGN OPTIMIZATION PROBLEM FOR BAHIA

The corridor design model involves the following three steps:

1. Characterize the suitability of planning units for conservation and/or restoration and their costs: Assume that we have collected appropriate spatial information for a region and have stored that information within a GIS. From this information, define a suitability score process, which when applied to the geographic data can be used to determine the suitability of each planning unit for use in a conservation reserve. *In the case of Bahia we used the planning units, approximately 1 square kilometer (98 ha). Admittedly, this is a relatively coarse grid, spatially, but is realistic in terms of the quality and variability of the data available. The suitability score for each planning unit is the area of remaining primary forest plus the area that could be reasonably restored as forest (i.e., not urban, water, eucalyptus plantations, and non-forest habitat types). Costs are the opportunity cost or environmental compensation payment for each planning unit, plus any costs to manually re-establish forest cover in sites far from any remaining forest fragments. Suitability and cost data were derived from attributes of the planning unit theme in* ***TAMARIN*** *and converted into raster cells the same size as the units.*

2. Aggregate cells into planning patches that meet the size requirement: It is assumed that the size of the basic planning unit (grid cell or polygon) is small in regard to what would be minimally acceptable as a stand-alone conservation area. Specifically, the planning units (grid cells) would never be chosen alone, but in groups of cells that meet some desired set of conditions, like a minimal combined size, standards on overall condition or quality, compactness and shape. A Planning Patch is defined as a set of connected units, which in concert meet these conditions, corresponding to what we have defined as resilience. In this second step, we generate a large number of planning patches, from which to design a corridor. This process is based upon a computer algorithm that systematically generates possible patches for consideration. The fundamental premise is that the basic decision making unit in the conservation and habitat reserve design problem will be the Planning Patch. Any set of connected units, isolated from other selected areas, but smaller than a Planning Patch, are assumed to be too small to be fully functional. Additionally, groups of connected units having at least the needed amount of combined area may not meet other conditions, like quality. The Planning Patch is designed so that it meets the standards of acceptance as a viable reserve unit (based upon the preset conditions). *For example, for Bahia it was proposed that the minimally acceptable stand-alone conservation unit would be 10,000 ha of primary and potentially restorable forest (or at least 103 planning units in size). Further, each Planning Patch must contain at least 1,000 ha of primary forest.* The process of building a possible patch given a starting unit is described in Section 7.3 in more detail.

3. Select a set of Planning Patches that meet the representation objectives at least cost: This step involves a large-scale optimization model that selects a set of Planning Patches that together optimize a set of objectives and constraints. The idea is that the set of possible planning patches spans the set of representative design alternatives. The selection of the optimal set involves minimizing cost as well as meeting all of the desired constraints, such as the need to represent different bioregions. Regional distribution constraints maintain that at least a minimal set of Planning Patches is selected in each bioregion. It is possible that two feasible Planning Patches may overlap. Such overlap may be too large and this should prevent choosing both patches for the same solution. On the other hand, a small level of overlap could be desirable in some conser-

vation planning problems, as it would represent the design of a larger-connected reserve. The optimization model is described in more detail in Section 7.4.

The rest of this section details the development of tools to support the above three-step process. Incorporating flexibility into the tools was a key design criterion, so that it would be possible to test variations in conservation objectives, assumptions about suitability (relative value of existing to restored forest), the patch-growing process parameters, and other parameters in the patch selection model.

7.3 PATCH GROWING PROCESS (PGP)

Various types of spatial units can be considered in natural reserve planning. These have included 7.5-minute quadrangle boundaries (in the United States, developed by the Geological Survey), watershed boundaries, or other regular units such as hexagons or the 98 ha square planning units employed in **TAMARIN**. An alternative and more innovative approach is to construct appropriate units based on environmental attributes as they vary across the landscape. The original idea of a "patch" as a conservation unit was associated with meeting the requirements of a single species, likely an "umbrella" species with relatively large spatial requirements. In a previous application, researchers constructed patches designed to meet the requirements of the San Joaquin Kit Fox in northern California (Gilpin et al. 1998, Gerrard et al. 2001, Church et al. 2002).

The **TAMARIN** database contained data from which conservation suitability could be derived. Brookes (1997) has observed, however, that suitability by itself may not be sufficient for designing a corridor reserve system because the highest ranked sites may not cluster into blocks of adequate size. Conversely, some contiguous clusters of highly ranked sites may contain many feasible sites that are not identified individually. Several researchers have developed algorithms to address this problem of growing or building sites from smaller building blocks (reviewed in Church et al. 2002). Others have designed optimization approaches to the problem, using objectives and constraints such as size and shape. These optimization approaches for patch growing are limited to the size of problem they can accommodate (Church et al. 2002). The Central Atlantic Forest Corridor contains tens of thousands of planning units to be grouped into patches on the order of 100 units each, far beyond the capacity of current optimization approaches. Consequently, a patch growing process (**PGP**) similar to that of Brookes (1997) was adopted. **PGP** is only summarized here (see Church et al. 2002 for additional details).

Spatial data on forest cover (primary and potentially restored) for the Bahia region was summarized for the approximately 77,000 planning units each of 98 ha in size and converted to a raster suitability map. Patches are built by starting at a single planning unit ("seed" unit) and building outward, adding planning units and enlarging the patch until a final patch that satisfies certain criteria is completed. These criteria are:

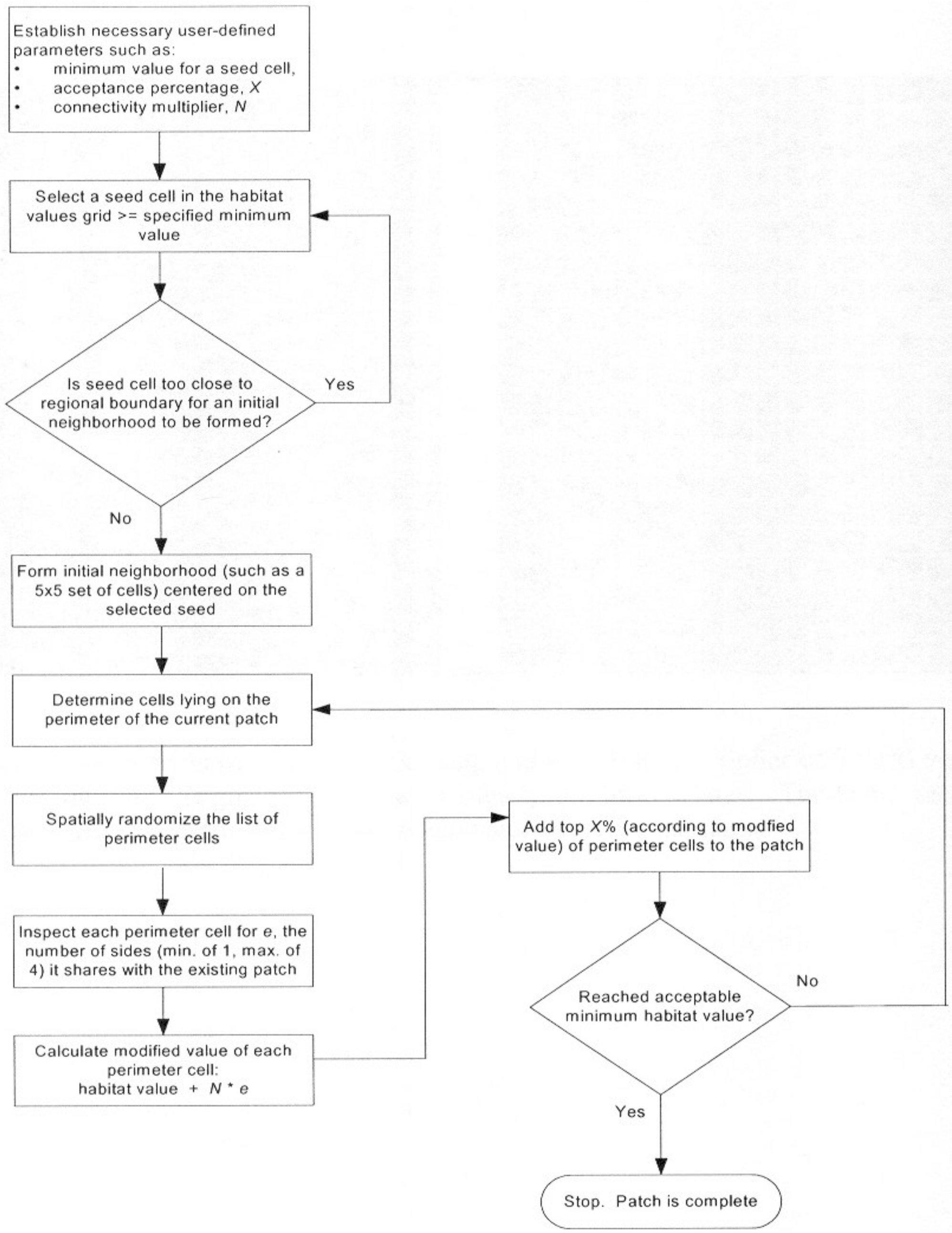
1. Primary and restorable forest are equally important for patch growing.

2. Patches need to contain 10,000 ha of restorable and/or primary forest.

3. A patch must contain at least 1,000 ha of primary forest.

The **PGP** is implemented through a significant programming effort. The patches are built out of the 98 ha units on the combined grid of primary and restorable forest. The combined grid was formed simply by summing the grids of the two forest types to yield units whose values are the number of hectares of both primary and restorable forest (we rounded off to integer values). This grid may be termed the landscape values (comparable to suitability) grid. Starting with a random seed unit, **PGP** constructs patches by adding units in successive iterations until the patch is large enough to contain the requisite amount of total landscape value (forest cover). An "iteration" involves considering units lying on the perimeter of the existing patch. The highest-value units are the most likely candidates for being added to the existing patch, creating a new, larger patch unit. The value of a unit for inclusion in the patch is the amount of primary + restorable forest in the unit, plus a term reflecting its connectivity to the existing patch. The more of its sides that a unit shares with a patch, the higher its connectivity value (which is multiplied by a user-selected coefficient that allows one to vary the desirability of favoring highly connected units). In each iteration, the perimeter units are considered in terms of their total value, and then a percentage of the top-valued units (typically 20%) is added to the patch. After some number of iterations, the patch will be large enough in area and composed of the right units to reach the requirement of 10,000 ha of landscape value (primary + restorable forest). At this point, patch accretion is terminated (see flowchart below).

The process just described would be sufficient, except for a secondary requirement unique to the Bahia application. This is requirement (3) above, requiring that at least 1,000 ha (or about 10%) of a patch be composed of primary forest. This requirement exerts a strong control over where in Bahia valid patches may be created, since primary forest is not present everywhere. Once a patch has been finished, having reached the 10,000 ha condition, our program checks to see if 1,000 ha of primary forest exist in the patch. If so, we make a final acceptance of the patch as valid for consideration in the selection heuristic. If not, the patch is rejected and not considered further. In order to promote the generation of patches that can meet the 1,000 ha condition on primary forest, our code tries to start patches in promising areas. This is accomplished by considering the 3x3 unit neighborhood surrounding a chosen seed unit. If these nine units contain at least 10% primary forest, patch development is continued from this 3x3 "starter." If not, another seed unit is chosen and its 3x3 neighborhood considered. Also, no seed unit containing less than 90 ha of forest cover is considered. This leaves over 90% of all units in Bahia as potential seed units.



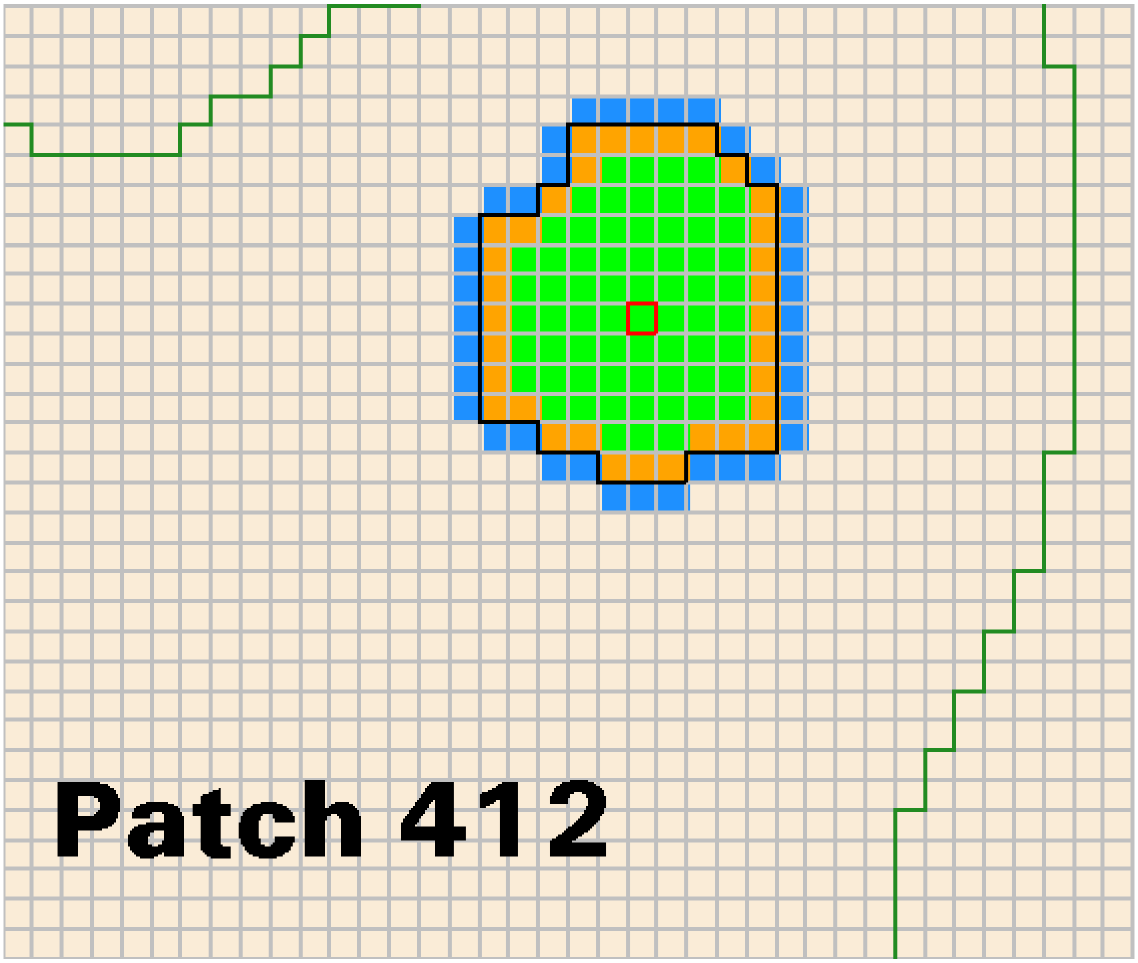
Flowchart of the Patch Growing Process (from Church et al. 2002).

We ran **PGP** as a batch process to generate 100 patches in each bioregion, starting from randomly selected seed units on the landscape values grid. We considered 100 patches adequate to cover the conservation options in this corridor. (Note that in two small bioregions, only 50 patches were generated). The vast majority of patches contain ~103 units. This is not surprising as most of the landscape is composed of units that have close to 98 ha of forest cover (primary + restorable). In order to achieve 100 valid patches, additional patches were actually generated, with some dropped because they failed to meet the 1,000 ha criterion on primary forest. The "wastage" rate of approximately 15% is not considered overly large. Other factors that control how patches are grown, such as the initial seed patch size, the connectivity multiplier, and percentage of best cells to accrete to the patch at each iteration, are described in Church et al. (2002).

Upon termination of the batch process, we have 100 candidate patches per bioregion that are passed to the patch selection heuristic for consideration. One hundred is a sufficiently large number that there is likely overlap among patches. Two different seed units, close to each other, would likely spawn a very similar patch or even the exact same patch. Every patch created by the **PGP** is stored in the form of an ESRI grid so that it may be easily viewed if desired. In addition, a file containing metadata about each patch is generated. Another file contained data on the cost of each cell in any planning patch. Note that cost was not used in patch growing, only in patch selection. Finally, a single file is generated that stores all 100 patches in a compact format specially designed for passage to heuristic. Two sample patches are illustrated in figures below.

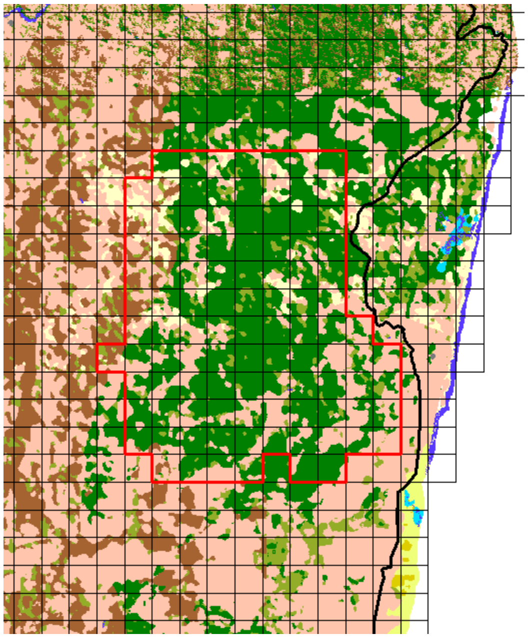
For the corridor project, there are two additional factors in growing and selecting patches. First, the conservation objectives seek redundancy of representation within each bioregion. Second, paved roads were treated as barriers to resilient habitat patches. That is, a patch could not cross a paved road. We addressed the first factor by growing planning patches and solving the patch selection optimization separately for each bioregion. Thus we avoided the problem of having a candidate patch spanning a regional boundary, with each portion being too small to meet the conservation objectives for its respective region (Note that **TAMARIN** does not check for this problem). We elected not to exclude planning units crossed by paved roads from being included in a planning patch, but chose instead to make the cost of such a unit prohibitively high so that it would never be selected. Other options would overly constrain the patch growing process.

The patch generation code produces a compact, but readable output format of the patches that are generated. This output format is a specially defined and abbreviated form of the export grid format of ESRI. This format codes grid cells in a patch as core, edge, or just outside on the edge. We have developed a program that can read this file and compute for each potential pair of patches, the total number of units that occupy both patches (total overlap), the number of edge units in a patch that share an edge with the other patch, and the amount of core unit overlap. This patch analysis code has now been written and tested and is now operational as a stand-alone program as an MS windows console application. The output of this program is a data file that will be read into the optimization/patch selection routine and used to prevent the selection of adjacent patches that have too much overlap (as defined by the user). A second version of this code was written in order to add the capability of generating for each potential pair of patches, a list of units involved in the overlap (or shared by each patch). In a test data set of 100 patches, there were only 645 pairs out of a possible 4,950 that had overlap, or an average of 6.5 nearby overlapping patches per patch. These shared unit lists will be used in the optimization routine, to efficiently account for costs and habitat protection without double counting any units in terms of costs or habitat values.

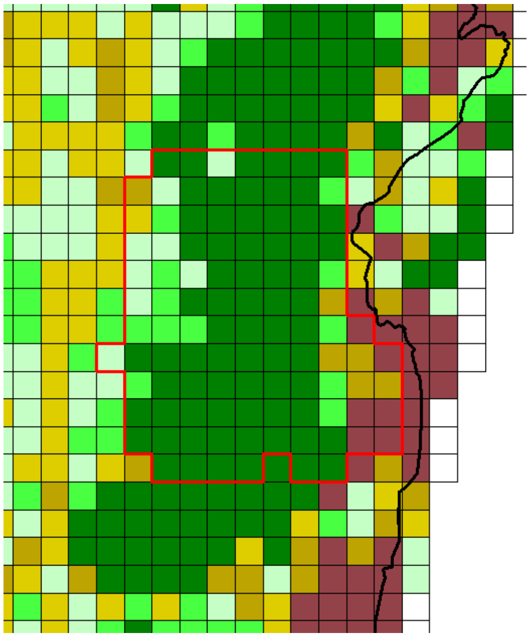


In the close-up of Patch 412, the red box is the seed unit, the blue are the perimeter units of the final patch, the orange are 'near-perimeter' units which are members of the patch which border perimeter units, and the green are interior units. This information can be used in assessing the amount and type of overlap between patches in the patch selection routine.

Conceivably, millions of possible Planning Patches exist, although many of these would be small variations of one another. We realize that such a large potential number do exist, but we are interested in those that are both viable and generally representative of options, rather than representing all of the potential small nuances. Consequently, our process for generating patches is based upon starting at a given "unit" with good habitat values and asking the following type of question: "If this unit is part of feasible planning patch, just what surrounding units would be included in such a patch?"



Sample patch on the rainforest data of Bahia, Brazil. The patch is composed of 103 planning units. The background layer shows the remnant primary forest (dark green); tan areas are agriculture and pasture; dark brown is cabruca.



Same sample patch on the cost data of Bahia, Brazil. The background layer shows the easement value from lowest (dark green); medium (light colors), to high (brown). Cost was only used for patch selection, not in patch growing.

7.4 OPTIMIZATION MODEL FOR PATCH SELECTION

The main reason for generating patches is to select a number of them to constitute a reserve system or corridor. By expending the effort to build the patches carefully, we can have a degree of confidence that when we select one for a reserve, there is reason to believe that it is viable for our selected umbrella species (i.e., *Cebus xanthosternos*). As part of our research, an integer programming optimization model was developed that selects patches according to multiple criteria. The model is called **OHPAS** (Optimal Habitat Patch Selection model). **OHPAS** seeks to minimize the "cost" and maximize the biological value of selected patches. For any specified number of patches, different objective weights can be used to put a different amount of emphasis on cost versus biological value. It also includes a routine for controlling the amount of spatial overlap allowed for the patches in a solution, in case overlap is desired or acceptable.

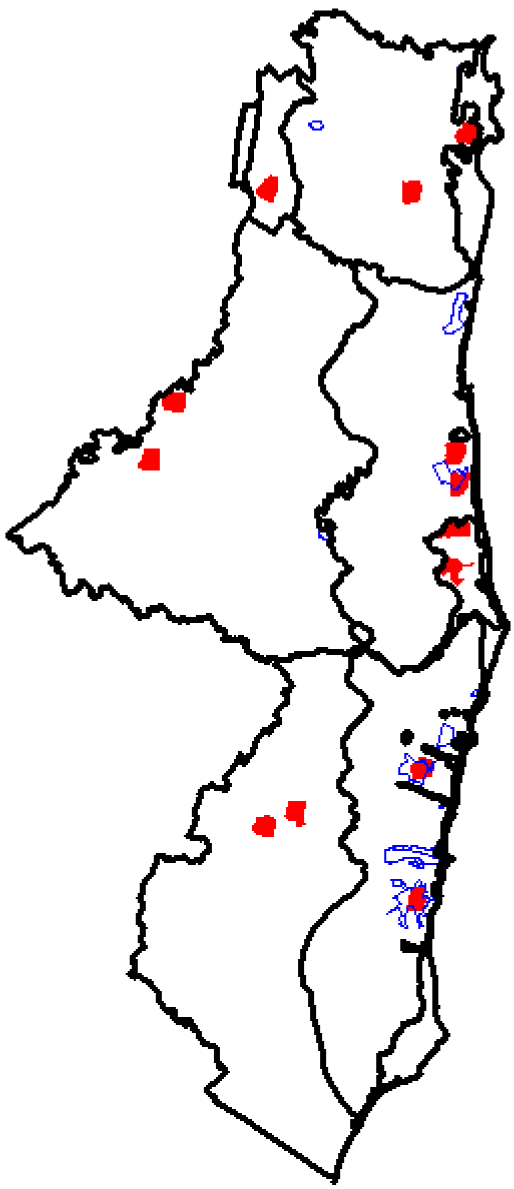
Although this report does not give a formal mathematical construct of that model, we have developed a formulation for this problem that will be documented in a future paper. We used this formal mathematical model as the basis for an application using a general-purpose software code for a very small planning problem. Because, the Bahia planning example is relatively large, we have concentrated our efforts at developing a special heuristic algorithm for solving this problem. **OHPAS** was solved by **the Patch Selection Heuristic (PSH1)** program, written by Rick Church in Visual Fortran. The general structure of the **PSH1** is based upon a defined "search neighborhood" about a trial solution with the desired number of planning patches. This "search neighborhood" allows several possible heuristic solution strategies to be implemented (including Tabu search and simulated annealing). The code was developed using a Lambda-Opt approach as originally developed by Lin and Kernighan for the traveling salesman problem. Constraints on overlap from no overlap to maximum allowable amounts of overlap will also be easy to set.

OHPAS is designed as a general-purpose model. Not all its features were utilized for this corridor design project. For instance, **OHPAS** has features for controlling the amount of overlap between selected planning patches, which may be appropriate in conservation problems where connectivity or creating reserves larger than a planning patch are important. Because the specified objectives here only involved selecting two planning patches, overlap was not desirable. Another feature in **OHPAS** is a control on the compactness of selected planning patches, which can be traded-off against cost. This is particularly useful when a planning patch consists of a large number of planning units or cells that may form a highly irregular patch. For the Bahia data, planning patches were relatively small, roughly 100 cells each, and these tended to be very compact. We determined that it was unnecessary to add compactness (perimeter/area ratio) to the objective function, since adequate compactness was automatically achieved at no additional cost.

7.5 THE OPTIMAL BENCHMARK SCENARIO

Only one scenario was generated for this study as a benchmark for comparison with the other scenarios described in Section 6. Therefore, we applied the same conservation objectives as before (two viable habitat units greater than or equal to 10,000 ha per bioregion, with at least 1,000 ha of primary forest in each selected planning patch). For the optimization scenario, the objective function is to minimize the cost of meeting these conservation objectives (or constraints). The **PGP** generated the set of candidate planning patches, with 100 in each bioregion except for the two smallest regions where only 50 were generated. The **PGP** ensured that the planning patches were of adequate size and contained sufficient primary forest.

PSH1 was run with patch and cost data for each bioregion independently. The program, which executed in seconds, identified the two planning patches that cost the least. The selected patches from all bioregions were used to select their planning units in **TAMARIN**. Then a scenario was run in **TAMARIN** as with other scenarios to evaluate future land use and the landscape metrics. **PSH1** and **TAMARIN** are only loosely coupled. Files are shared but the planning patch files must be integrated into **TAMARIN** through GIS operations and is not currently automated.



Planning patches selected by the PSH1 program (in red). Blue lines indicate outlines of existing reserves. Black lines are the bioregion boundaries.

As expected, **PSH1** tended to select planning patches associated with existing reserves where possible, because these were assigned zero cost. One planning patch was associated in the Una Biological Reserve, and two were associated with reserves in the Southern Tabuleiro bioregion (Parque Nacional de Pau Brasil and Parque Nacional de Descobrimento). Another planning patch was selected just north of Una Reserve, presumably because the sandy soils led to a low cost. This apparently made it more attractive than expanding the Conduru State Park, which is surrounded by relatively expensive land near roads and the coast. The other planning patches were selected in locations of remaining forest fragments and relatively low cost. Therefore this initial solution appears to have selected planning patches that are quite reasonable in terms of the data and the objectives and constraints. The details of the evaluation of this scenario were presented in Section 6 with the other scenarios.

Interestingly, there was no feasible solution for the Northern Semi-deciduous bioregion. This region is relatively small and contains very little primary forest with which to generate a planning patch. As a result, all candidate patches significantly overlapped, and thus did not meet the redundancy objective. For the **TAMARIN** evaluation, we selected one planning patch to represent this region.

Caveats: Although we called this scenario an optimal benchmark, readers should realize that this represents one solution from a family of solutions that are nearly as good. Further, this solution was based on a sample of potential planning patches. It is possible, therefore, that there are other potential planning patches that would yield a (slightly) less expensive solution. Also, cost was not a factor in growing planning patches, so there may be other potential patches that would include more of the existing reserves (no cost) and require fewer cells adjacent to reserves. Readers should not conclude that the scenario presented in this report should necessarily be implemented. Our purpose was only to illustrate the utility of an optimization model, in conjunction with the patch growing process, in decision support for the design of a conservation corridor.

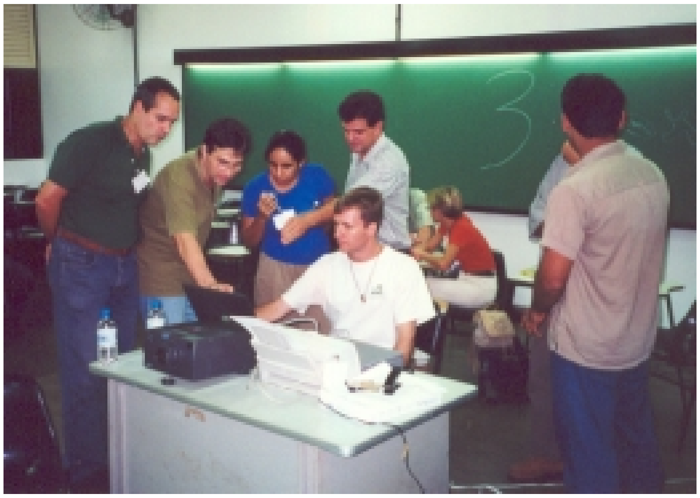
8. CONCLUSIONS

8.1 SUMMARY OF SIGNIFICANT FINDINGS

TAMARIN was developed to facilitate the design and evaluation of alternative scenarios for application of economic incentives to identify priority sites within a large region for rainforest conservation or restoration. In particular, our goal was to integrate current principles in conservation biology with economic theory in a GIS framework that makes explicit the costs and benefits of each incentive option. Compensation of the opportunity costs of conservation is employed here as an incentive to modify behavior as an alternative to outright acquisition or command and control strategies such as agroecological zoning. Although we made many assumptions for our example scenario concerning the desired landscape configuration, opportunity costs, and trends in land use change, the framework is very flexible in allowing stakeholders and planners to substitute competing assumptions and objectives. These substitutions can be made as new GIS themes or simply as parameters to be entered when defining a scenario. We also discovered that users of the **TAMARIN** framework invented a mode of flexibility we had not foreseen. At a workshop held in Salvador, Brazil, in June, 2001, planning groups spontaneously began applying different economic incentives in different locations as they allocated a hypothetical budget.

The real value of **TAMARIN** is not in assisting with making better decisions per se but in facilitating the planning process by interpreting spatial information to understand the tradeoffs between conservation and other social goals. Stakeholders and planners are forced to be explicit and quantitative in defining the desired future landscape configuration, to think not just about the current landscape but how it is likely to change, and to be creative in formulating equitable and affordable economic policies that can achieve the desired landscape with minimal disruption to the social fabric. The details of designing an incentive program, including the identification of exactly which parcels are eligible, would still need to be developed at a finer scale with more stakeholder involvement. Although **TAMARIN** was tailored to the planning issues and data sources of south Bahia, the ecological and economic underpinnings make it adaptable to many other locations.

In June, 2001, a workshop was held in Salvador, Bahia, for biologists, conservationists, agency staff, and the directors of the program to design a biosphere reserve for south Bahia. The purpose of the workshop was to present the results of the PROBIO project to date and the **TAMARIN** model. The attendees were randomly divided into three working groups of about 15 people each and asked to develop a conservation scenario for the Central lowland forest bioregion. All three groups were asked to select and evaluate their best set of planning units, either through purchase or environmental compensation, subject to a R$2 million budget. Each group was assigned a facilitator who was familiar with the bioregion and with **TAMARIN**, and a GIS operator to do the actual processing (Photo below of one of the working groups, led by Paolo Cordero and assisted by Karl Morrison of CI). The intent was not to generate a real conservation plan but to give firsthand experience with **TAMARIN** to a group of potential users. Our hope was both to get potential users excited about the software for exploring and discussing options and to get feedback on it for any final revisions.



The workshop exceeded our expectations. The groups appeared to grasp the concepts relatively quickly and began to test different policy instruments and different approaches to selecting sites. Some groups even tried splitting their budget, spending part on land purchases and part on easements. The manual or graphic selection method appeared to be more popular than the query method, because participants knew the bioregion's biodiversity patterns and the landowners. The feedback was generally positive, with many people wanting to know when **TAMARIN** and the related GIS data would be available.

The development of **TAMARIN** at UCSB was part of a wider collaboration of researchers. The GIS data needed to run the software was compiled by these collaborators and thus is not ours to distribute. The intent is to work with these collaborators to assemble a single package on CDROM with the **TAMARIN** software (excluding the optimization model set), the GIS data layers, and appropriate documentation that can be freely distributed by summer, 2002. Toward this end, we have prepared a 'Proprietary Rights and Disclaimer' statement (see the user manual in the appendix) that clarifies the rights and responsibilities assumed by the University of California, Santa Barbara, and places the software in the public domain.

The suite of models for optimization of the conservation and economic objectives constitute another significant contribution of the project. The patch growing process, **PGP**, used GIS data from **TAMARIN** to generate a set of sample planning patches that were guaranteed to satisfy the landscape criteria for minimum patch size and minimum amount of primary forest. Thus any patches selected automatically achieved the conservation objectives. The **OHPAS** optimization model then did the actual selection of the desired number of patches, controlled the amount of overlap allowed among them, and minimized the cost. These tools were already under development for a research study involving the San Joaquin kit fox (Gerrard et al. 2001, Church et al. 2002). The Central Atlantic Forest Corridor project provided an opportunity for further development of these tools and to begin testing their application. This report presents only the initial application of this set of models for the corridor. We have only begun research on the implications of varying assumptions and objectives. Some ideas for future research in this area are discussed in section 8.4.

In addition to the workshop in Bahia, presentations of the results of this project have been made at two scientific conferences:

TAMARIN: A landscape framework for evaluating economic incentives to foster rainforest restoration. David Stoms. Presented at the 17th Annual Symposium of the International Association for Landscape Ecology, US Regional Association, Lincoln, Nebraska, April 2002.

Solving a large scale reserve design problem in Bahia, Brazil. Richard Church, Ross Gerrard, and David Stoms. To be presented at the INFORMS Annual Meeting, San Jose, California, November 2002.

8.2 UPDATING THE DATABASE

TAMARIN was developed with the GIS database that existed at the time. Some of the data layers were draft versions or need some fine-tuning before final analysis. At least four types of revisions may be involved: substitution of a newer version of a theme (e.g., a final land cover theme that fills in cover types where clouds obscured the ground in the initial version), substitution of a new value for an attribute (e.g., revised model results for predicted land value), replacement of derived GIS themes as a result of revision in the primary data layer (e.g., updating the business-as-usual scenario which is derived from the landcover theme), and creating new themes as alternatives (e.g., creating your own business-as-usual scenario based on different assumptions about the future). Refer to the user manual in the appendix for details on these updating procedures.

8.3 WIDER APPLICABILITY OF TAMARIN TO OTHER CORRIDORS

Conservation International has expressed interest in adapting the basic **TAMARIN** framework to other conservation corridors, such as the Philippines and eastern Madagascar (Keith Alger, personal communication). This section briefly summarizes what would be involved in such an adaptation.

Conservation planning for the Central Atlantic Forest Corridor was based primarily on meeting broad conservation objectives (i.e., representation, redundancy, and resilience) in the most economically efficient manner possible. The Corridor has been severely deforested, with only about 9% on the region remaining in primary forest, mostly in small fragments. The focus in this project was to decide on the best combination of protecting remaining fragments and restoring forest to expand, connect, or complement those fragments. **TAMARIN** may not be particularly useful in planning efforts where the conservation issues are significantly different than those in Bahia. For instance, **TAMARIN** would not be useful where the objective was to represent many different habitat types to some specified level.

The GIS themes used in the analysis procedures in **TAMARIN** must be included for projects for other corridors as well. In addition, they are generally referenced by their name in the View table of contents, so they must be given the same names in other applications. Furthermore, the attributes of the themes, particularly for the planning units theme, must exactly match those in the Bahia project, both in attribute name and its definition (e.g. width, type, decimal places). It is recommended that the themes be placed in the same folders as their counterparts in the Bahia project.

The other issue in adapting **TAMARIN** to other areas is that much of the scripting was hard-coded for the Bahia database. A prime example is where processing is based on specific cover class values in the Landcover theme. A user in a new corridor has two choices: either reclassify the landcover theme to match the existing script or modify the script to match the new classification. Ideally, the scripts would be modified so that they were more generic and adapted to whatever the inputs in a particular region were rather than forcing the data to match a preconceived classification. This is particularly important since classifications will rarely be identical between two regions.

Other examples of hard coding are in the summary analyses and reporting functions. For instance, in the Central Atlantic Forest Corridor, evaluating the impacts of conservation scenarios prime farmlands was an issue. Other corridors will have different issues and corresponding GIS layers. Ideally, there would be some setup procedure to customize **TAMARIN** for a particular region and that would only be run once at the beginning of the planning process (not for each scenario). Perhaps this could take the form of having the planner select the set of themes for which land cover summaries are to be made and automatically revise the summarization script to treat each theme. The user manual in the appendix lists the scripts under each section of the software to help programmers identify where changes should be made.

Thus, the best use of **TAMARIN** in other corridors may be as an exemplar of a planning support framework that structures the process of setting conservation objectives, designing scenarios, and evaluating them in terms of the objectives and other socioeconomic and environmental criteria. The basic framework could be reproduced even though the details of implementation might vary significantly.

8.4 FUTURE RESEARCH OPPORTUNITIES

Having **TAMARIN** as a planning framework opens several avenues for further development and research. These avenues can be categorized as enhancements to the basic framework itself to make it more useful and flexible, additional analyses to test the sensitivity of research assumptions and tradeoffs between objectives, utilizing the framework to develop and test alternative policy options for payment of conservation incentives, and integration of additional objectives for ecosystem services.

The current version of **TAMARIN** is flexible in scenario design, but it does not automatically generate potential blocks that contain the minimum viable area. One possible enhancement would be to have users identify a nucleus of a forest block and have the software expand each nucleus to a viable fragment, much like the planning patch-building program does.

Assumptions about future land use ends have a major impact on corridor design. Here we used a simple forecast of land use change in the absence of conservation intervention, based on what we were told by individuals who are familiar with the corridor. Developing a formal land use change model was beyond he scope of this project, but could be a valuable addition to **TAMARIN**.

This version of **TARMARIN** evaluates scenarios in terms of a number of measures of representation, resiliency, redundancy, and cost, but it stops there. There is currently no decision support mechanism to assist a user in weighing the competing conservation and economic objectives and then determine which scenario best meets them. As mentioned in the section of the report that presented the underlying conservation principles, scientific theory offers little guidance in the relative importance of the conservation principles or objectives. This portion of decision analysis moves into the realm of policy and opinion. Techniques such as the Simple Multiattribute Ranking Technique, or SMART, could be implemented as an enhancement for ranking and comparing scenarios (Rothley 1999). SMART also allows planners to examine the sensitivity of the ranking to the weights chosen, as a means of determining how robust a choice of scenario is.

The second category of future research ideas includes a number of analyses and further exploration of the patch growing and patch selection models that were not performed during this project. For instance, in this report we have only considered one set of criteria for patch growing and one set of objectives for representation and redundancy in patch selection. We only considered one option for calculating suitability for patch growing, namely that primary and restored forest had the same weight or value. Other possibilities include giving higher weight to primary forest, because it has higher habitat value immediately, and to give higher weight between current land use types for their restorability. For instance, cabruca would regenerate (and provide higher quality habitat) faster than pasture. It would be instructive to consider a range of redundancy objectives from one to many planning patches per bioregion in patch selection to determine the marginal rate of increase in cost. That is, what is the cost of additional increments of conservation? Likewise one could explore the tradeoffs between objectives such as the relative differences in cost and habitat value with changes in size of planning patch, number of patches selected, connectivity or patch overlap, and bioregional representation. As an example, would it be cheaper to select four 5,000 ha planning patches per bioregion than the original objectives of two patches of 10,000 ha (i.e., resiliency vs. redundancy). We constrained the initial set of candidate planning patches to contain 1,000 ha of primary forest as a source of propagules for natural regeneration. Did this force the process to build patches with higher easement values than unconstrained patches? And if so, would the savings in environmental compensation to land owners be offset by the additional cost that manually assisted regeneration incurred? This constraint automatically precluded patch generation in many locations in the corridor where no forest, or only tiny fragments, remain. We did not test the feature in **OHPAS** that also attempts to maximize patch compactness by minimizing the perimeter/area ratio. What would be the tradeoffs between compactness, with the benefit of a higher proportion of core forest, and cost?

The **TAMARIN** framework was developed to support the exploration of alternative policy options for economic incentives to achieve conservation objectives. The framework has been developed in this project, but the actual research on policy options is yet to come. For instance, Parkhurst et al. (2002) have demonstrated how, at least in an experimental setting, bonuses can be used to encourage collaboration among neighbors to create large contiguous reserves voluntarily.

Other conservation goals are also likely to mobilize significant financial resources as compensation for environmental services such as carbon sequestration and watershed services (Chomitz et al. 1999). Policy instruments designed for these services may also benefit biodiversity, but research is lacking that would suggest the degree to which the two policies are mutually beneficial (Balvanera et al 2001). For instance, a carbon sequestration incentive program might focus on the most productive soils, which would ignore biodiversity found in other landscape types and thus fail to achieve representation goals. A useful enhancement to **TAMARIN**, therefore, would be option to design feasible alternative policy instruments for a range of environmental services and natural capital (biodiversity) and explore the tradeoffs between them. An ideal planning support system would facilitate both the design of such instruments, including the amount of incentives, and the evaluation of such collective conservation proposals.

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10. APPENDIX: TAMARIN USER'S MANUAL