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Current Opinion in Environmental Sustainability

Land system science and the social–environmental system: the case of Southern Yucatán Peninsular Region (SYPR) project

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Land system science axiomatically addresses social–environmental systems by integrating the dynamics of land uses (social) and land covers (environment), invariably including the use of remote sensing data and often, spatially explicit models of land change. This kind of research is illustrated through the Southern Yucatán Peninsular Region project (1997–2008) aimed at understanding, predicting, and projecting spatially explicit land change in a region with juxtaposed land uses-agriculture and a biosphere reserve. The successes of the project, its contributions to contemporary land system science, and the organizational mechanisms that fostered the research are identified as well as various corrections, which if applied, may have refined and extended the project's goals. Overall, the project demonstrates the kind of integrated research required to advance understanding of a social-environment system and the team-based methods used in the process.

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Current Opinion in Environmental Sustainability 2016, **19**:18–29
This review comes from a themed issue on **Sustainability science**
Edited by **Hal Mooney**

Received 3 July 2015; Accepted 25 August 2015

http://dx.doi.org/10.1016/j.cosust.2015.08.014
1877-3435/Published by Elsevier Ltd.

Integrated research linked to sustainability

Sustainability science addresses human–environment relationships as signified by the base phenomenon of study, the social–environmental system (SES) [1]. Analytically, this phenomenon is typically treated as two subsystems requiring specialists from the social and natural sciences to team together to understand the interactions between the subsystems and their consequences for the SES as a whole. This approach is necessitated because (1) the complexity of SESs requires a range of knowledge that few, if any, researcher can master alone, and (2) reflexive agents (humans) make the social subsystem analytically distinct from ambient environmental processes. As a result, funding and research programs increasingly champion integrated, team-based approaches to SES problem solving (e.g., the Coupled Natural-Human System program of the National Science Foundation [U.S.] or the emerging international program of Future Earth).

With roots extending back to Alexander von Humboldt and the subsequent German *Landschaft* (landscape) tradition [2], if not earlier, various research approaches have treated land (or landscape) systems as SESs [3–7]. Global environmental change and sustainability research frame SESs explicitly through the lens of science, with attention to understanding the processes at play within SESs, modeling their interactions, and projecting the implications of their change. This framing dominated the SESs research advanced by the International Geosphere-Biosphere Program (IGBP), especially its ecology components, and in partnership with the International Human Dimensions of Global Environmental Change Program (IHDP) sponsored the development of an international effort on Land Use and Cover Change (LUCC) in 1991, formally launching a research project by that name in 1994. Focused on land systems, it was reorganized as the Global Land Project (IGBP-IHDP) in 2005 and remains on-going. Paralleling this effort, DIVERSITAS, established in 1991, increasingly adopted an SES framing for much of its biodiversity research, especially that on ecoSERVICES established in 2014 and intended to fuse into Future Earth.

These origins strongly shaped the research efforts of, and SES approaches applied within, land system science [8] and complementary research on the resilience of SESs [9]. Global change research communities required attention to the observation and projection of the kind, amount, and location of land changes. Land system science was challenged to improve observations through advances in the remote sensing data of land cover and model-based assessments of land-cover change, especially in regard to spatio-temporal resolution. Remote sensing science and modeling joined the natural and social sciences as the four legs of SES research on land systems [10–12]. Integrated research teams emerged composed of environmental, social, and remote sensing, and in many cases, modeling specialists, especially in regard to the integration of social and environmental subsystems.

Unlike its complementary environmental research programs, land system science found it difficult to establish research objectives based on standard sets of theories and hypotheses about the operation of SESs. This lacuna followed from the distinctions in the operations of the two subsystems, from the different perspectives in the social sciences regarding the value of addressing proximate (e.g., population pressures) or distal (e.g., political economy) drivers of land change [3,11], and from the complexity of land systems. Rather, its international goals have been defined in terms of measuring, modeling, and understanding land-based SESs (aka coupled human–environment systems), commonly involving exploratory research of the environmental and socio-political-economic factors at play, although individual projects may address specific theories and hypotheses relevant to either subsystem. The critical point is that rather than focusing on a set of a priori theses and theories, land system science tends to engage case studies of the connections between land-use and land-cover, revealing the intricacies of the phenomena and processes of the SESs that might be missed in deductive approaches. The complexity of SESs fosters attention to model projections as much as predictions of land change, and plays to the interests of the social sciences in theory of middle range [13], usually concerning some component of the SES, as opposed to, for example, systems theory's search for patterns and principles about the system itself as exemplified in resilience research [14]. This same complexity promotes place-based studies, consistent with that proposed for sustainability science [15]. Once important linkages in the SES are revealed, hypotheses may be tested, frequently through natural experiments in which variance in the system is not controlled. It is noteworthy that no formal criteria have been established to determine the boundaries of a place (area or region), but land system science tends to link some dimension of land cover (e.g., tropical forest or savanna) and use (e.g., slash-and-burn cultivation or livestock herding), often within one governance jurisdiction (i.e., rarely crossing major governance boundaries).

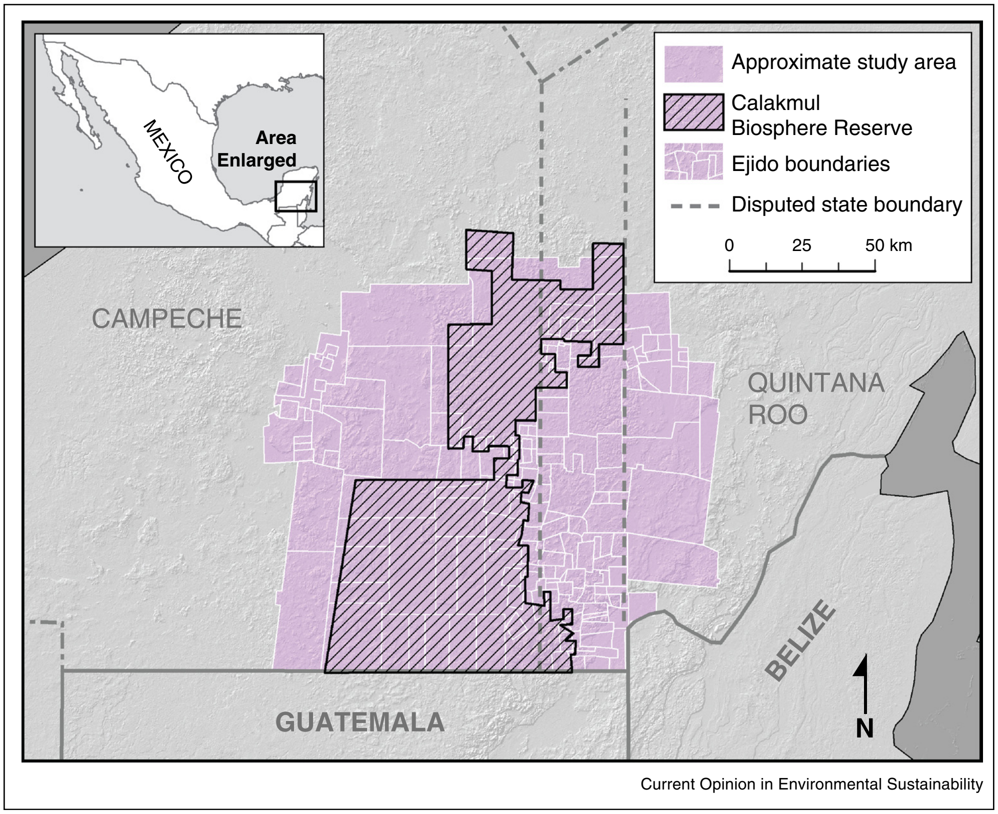
Various reviews of the contributions of land system science exist [7,9,10,11] and need not be reiterated here. Rather, we draw on one of the original projects linked to LUCC and GLP to illustrate integrated, team-based SES research of this kind, the various challenges confronted and the understanding gained in this effort, and on reflection, changes in the design and operation of the project that may have improved its performance and science contributions.

Southern Yucatán Peninsular Region project: an integrated effort to address a SES

The Southern Yucatán Peninsular Region project (SYPR), operating from 1997 to 2008, sought to observe, understand, and model changes in land-use and land-cover in the forests of southern Quintana Roo and Campeche, Mexico (Figure 1). The study region was selected for several strategic reasons. First, it contains biodiverse, seasonal tropical to evergreen forests that were affected by ancient Maya land uses but remained minimally disturbed for nearly a millennium after Maya abandonment about C.E. 950 [16]. Second, agricultural settlements (*ejidos*) and cattle operations proliferated with the late 1960s construction of a highway crossing the peninsula, generating a regional 'hotspot' of tropical deforestation, a large portion of which was designated as the Calakmul Biosphere Reserve in 1989, part of the MesoAmerican Biological Corridor [17]. Third, a small, precursor project helped to identify the base research problem and establish initial links to El Colegio de la Frontera Sur (ECOSUR)-Unidad Chetumal, a Mexican research institution in the region. And fourth, the principal investigator of the SYPR project had undertaken extensive research on ancient Maya land uses in the region, providing insights about longer-term SES dynamics.

The SYPR project addressed a major problem throughout the tropical world: maintaining older growth forest landscapes in the context of pressures for economic development. This issue was particularly acute in the region

Figure 1



The Southern Yucatán Peninsular Region of Quintana Roo and Campeche, Mexico.

because of attempts to create eco-archaeo-tourism in a landscape interspersed with farm-land and reserve-land. Despite its implications for various government and NGO programs present in southern Quintana Roo and Campeche, the SYPR project was not designed to inform these programs per se (but see below). Rather, consistent with land system science promoted by the LUCC agenda and NASA's complementary Land-Cover and Land-Use Change program, the SYPR project explored land dynamics, foremost the identifications of the drivers and major consequences of deforestation, while making advances in observations of land-cover changes with Landsat data and in spatially explicit models of land-cover and land-use changes. Consistent with case-study approaches, the project was not orchestrated around a priori theory or hypotheses to test, but rather permitted a talented research team to uncover various dimensions of SES dynamics relevant to the broader problem, from which hypotheses and specific needs in advancing methods emerged.

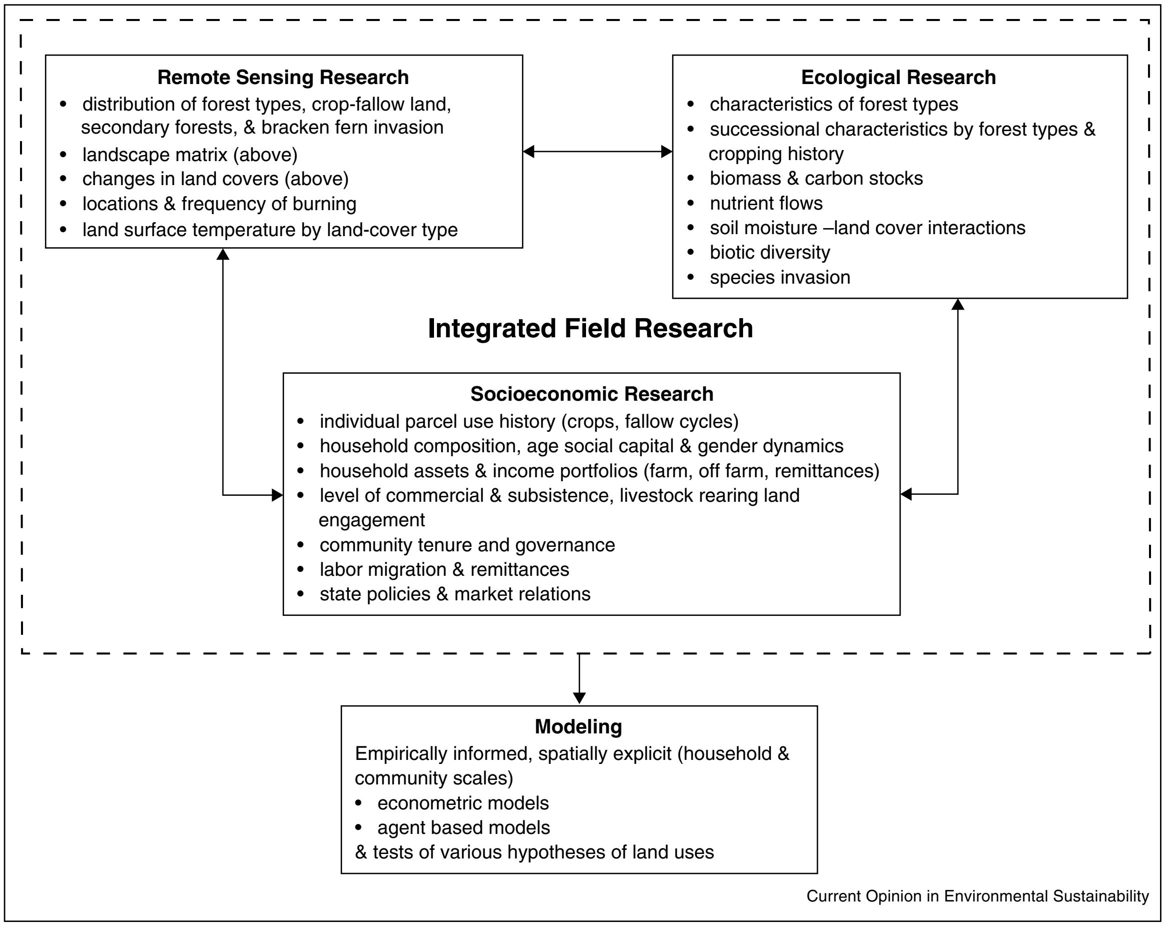
Selected topics, questions, hypotheses and advances: gains from integration

Exploration of its base research problems (Box 1) engaged the project in a large number of topics, examples of which are listed in Figure 2. These dealt with implications of swidden (slash-and-burn) and intensive chili cultivation on forest recovery, species invasion, biodiversity, and nutrient cycling for the environmental subsystem, and household characteristics and land-use decisions, labor migration and remittances, governance structures, and policy impacts for the social subsystem. Many of these topics became questions addressed explicitly or implicitly as hypotheses, which are too numerous to review in full. A

Box 1 Research goals of the project

1. Identify the drivers of changes in land covers and the consequences of these changes for the SES at large but with an emphasis on households and forests.
2. Document changes underway in the land covers of the region, foremost changes in amount and kind of older growth forests, using Landsat data.
3. Generate robust models explaining and projecting the location and amount of changes in land uses and covers over a decadal period and under different socioeconomic and climate conditions.
4. Understand the land system consequences of placing a tropical biosphere reserve within a region of existing agricultural communities.

Figure 2



Range of Research Topics undertaken in the Four Parts of the SYPR Project (see Box 1 for the overarching research questions).

selection embedded within or crossing the two subsystems is provided in Table 1 (the specific question, state of understanding, hypothesis or quasi-hypothesis, understanding gained and key references). Addressing the broader goals of the project also required advances in remote sensing and modeling methods listed in Table 2 (question/task, state of the art, advance made and key references). Given this detail, the information in the tables is not reiterated here. Rather, the selections are clustered and discussed in terms of the project integration, information and the outcomes gained by the integration (Figure 3).

The questions posed about the environmental subsystem required field study, informed by the location (from remote sensing) of the field site relative to other land covers within the landscape matrix, and the kind, timing, and frequency of past land uses (e.g., crop-fallow cycles on parcels with secondary vegetation; from household surveys) on, or in proximity to, the field site (Figure 3). Integrating these data improved understanding of forest recovery from human uses, including carbon stocks and the capacity of land cover to capture phosphorus (P), a key nutrient in the forest ecosystem and agriculture (Table 1 #1, 2 and 4). Beyond this, integration helped to explain various environmental conditions. For example, loss of male head-of-households due to labor migration, tended to reduce cultivation, lowering biomass and crop yields, a relationship discovered that improved modeling results. Remote sensing identified the range of the invasive species, *Pteridium aquilinum* or bracken fern, and the characteristics of affected and non-affected parcels, whereas household surveys provided information on timing of invasion relative to crop-fallow cycles and the decisions about invaded parcel use or abandonment (Table 1 #3).

The questions that addressed the social subsystem treated household conditions (e.g., size, age, ethnicity, social capital) and dynamics (e.g., subsistence or mixed subsistence-commercial behavior), informed by the land-cover conditions of individual household parcels and adjacent

Table 1

Example questions, hypotheses, and understanding gained about the SES (# in [ ] are references)

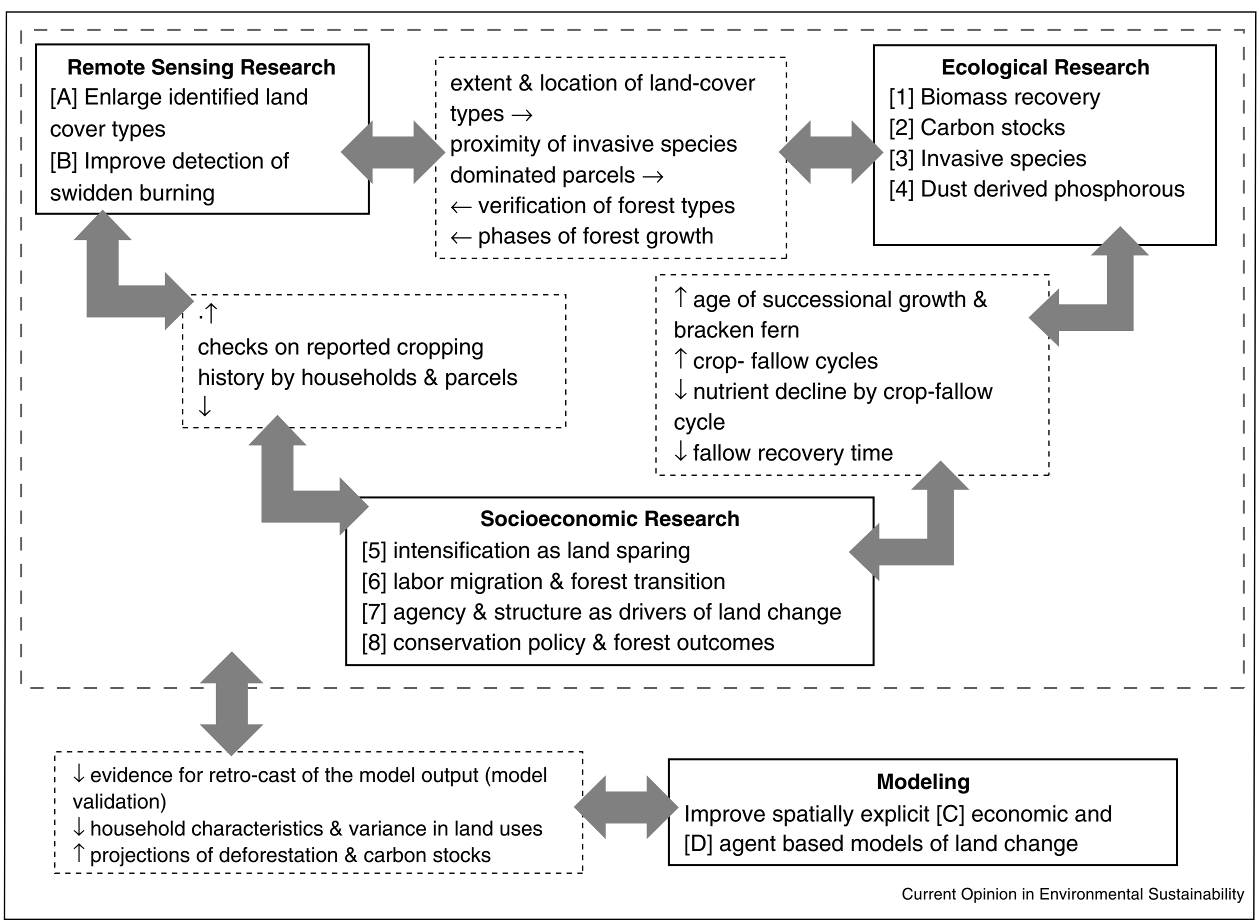
Question	State of understanding	Implicit/explicit hypothesis	Understanding gained
Environmental subsystem			
1. Effect of swidden on forest recovery time	About 50 years is required to achieve mature forest biomass in seasonal tropical forests	Biomass recovers in 50 years	Biomass requires 55–95 years to reach parity with mature forests, 60–120 years to reach a pre-logged state [18••,19,20,21].
2. Effect of swidden on carbon stocks	Estimates typically failed to account for the history of crop-fallow cycles on parcels recovering to forest	No decline in carbon stocks occurs if crop:fallow ratio is low (long fallow). Decline in carbon stocks occurs if crop:fallow ratio is high (short fallow).	Significant above-ground C is lost from the first to the third crop-fallow cycle; soil C declines after one cycle and then stabilizes. Changes to P cycling are likely to result in further declines with subsequent crop-fallow cycles [18••,22,23].
3. Presence of invasive bracken fern and effect on deforestation	Plant invasions occurred in degraded lands impeding forest succession & leading to deforestation.	Increased crop-fallow cycles & soil degradation increases presence of invasive.	Increase in parcel size & proximity to invaded parcels positively relates to invasion and parcel take-over; invasive is too costly to combat, leading to deforestation for new parcel [24,25,26,27•].
4. Source of key nutrient, P	Internal recycling occurs at the plot and landscape scale through litterfall and fire	Inputs of Saharan dust are critical to maintaining P levels & forest function	Saharan dust balances leach in mature forest but reduced canopy trapping in secondary forest leads to net losses of P from the system [28••,29,30••].
Social subsystem			
5. Effect of agricultural intensification on deforestation	Land sparing, consistent with conservation needs, could be met by high value, intensive agriculture supplanting extensive cultivation. Farm income increases would reduce the need to use marginal lands, retained in or returned to forest.	Increases in commercial chili cultivation decreases area of swidden cultivation (hence forest cutting).	Owing to constraints on chili farm-to-market system, environmental vagaries of the chili market and nature (yields), and shifting household economics, increases in commercial chili were not matched by decreases in swidden. The total area of cultivation increased with market engagement [31,32].
6. Effect of male labor migration on forest land uses	Contested views existed that this migration leads to increases in cattle & pasture or to a forest transition owing to labor losses and remittance gained.	Male labor migration leads to a forest transition.	Increases in migration were linked to slight decrease in overall deforestation, but some households withdraw from agriculture while others invest in pasture & cattle. This variance was associated with which member migrates & various household conditions [33•,34,35••].
7. Effects of agency (household decision making) and structure (i.e., societal rules, power relations) on deforestation and forest conservation	Contested views existed that agency or structure constitutes the most robust entry point for understanding land use decisions.	Agency (or structure) is the primary driver of land use decisions.	Considered independently, agency = slightly greater explained variance in land use but combined, agency & structure = greatest explained variance. Interactions exist such that structure (e.g., policies) have unintended or uneven impacts due to varying agency (land users). This allowed identification of empirically derived clusters of land user types, their enabling/oppositional relations with institutional structures, and implications for forest transition [36].

Table 1 (*Continued*)

Question	State of understanding	Implicit/explicit hypothesis	Understanding gained
8. Effects of environmental policies on forest conservation	Minimal work existed at that time using spatially and ecologically validated empirical data on impacts of countervailing conservation policies.	Improved forest succession and biodiversity of parcels or landscape created by participation in conservation programs.	Conservation structures/policies have unintended or uneven impacts due to varying household dynamics and/or biophysical constraints to local farming (e.g., fail to arrest deforestation due to displacement effect) [37••,38].

parcels of other households (from remote sensing), and the environmental implications of the land covers (from environmental field work) (Table 1 #5–7; Figure 3). This integration revealed the complex array of household types associated with different cropping and forest outcomes, with implications for various theses about tropical deforestation. The rapid spread of intensive, commercial chili cultivation at the time expanded rather than reduced deforestation (Table 1 #5) because an ephemeral market and the vagaries of nature made the maintenance of subsistence (swidden) essential. Households losing male labor to migration, in contrast, deforested less, in part because labor constraints favored short-fallow parcels, leaving other parcels to regrow (Table 1 #6), but resulting in a downward spiral for those parcels under cultivation. Integrating the various data permitted a test of the agency-structure debate that ranged across multiple human-environment subfields-what are the relative roles of household decision making and societal structures in explaining the intensity of cultivation or degree

Figure 3



Data flow among SYPR project parts. Solid rectangles = (# or letter) of questiones/hypotheses/advances in Tables 1 and 2. Dashed rectangles = example of data flows with small arrows indicating direction of flow.

Table 2

Questions and advances in remote sensing and modeling (# in [ ] are references)

Question/task	State of the art	Advances made
Remote sensing		
A. Enlarge the number of land cover types, especially for forests, identified with Landsat TM data alone	3–5 land cover classes were common to studies using these data alone, often with only 1–2 forest cover classes	Developing a step-wise method of assessment, 14 land cover classes were identified, including deciduous, evergreen, and wetland forest types and several stages of secondary forest with an accuracy of >80% [39••,40].
B. Improve the accuracy of the detection of fire frequency & location in dry tropical forests using MODIS thermal imagery	MODIS Terra (for morning) and MODIS Aqua (for afternoon) were the major sources for fire detections, generating the standard product or Global Fire Monitoring	Standard products had a 77% fire omission rate because they were insensitive to small, cool fires used in swidden cultivation. Recalibrating for the local conditions, major detection improved by lowering the MODIS thermal band threshold from 310 K to 305 K [41•].
Modeling		
C. Develop econometric spatial model of deforestation	Such models were bifurcated at the time: theoretical models tested via aggregate data; & empirical models with spatially disaggregate data based on past land uses and environmental factors	Using detailed time series (remote sensing) and household data with GIS and spatial econometric techniques, spatially explicit econometric models were developed with superior results compared with previous approaches and are capable of assessing policy implications [18••,42–43].
D. Develop spatially explicit agent based models (ABMs) of agriculture & attendant deforestation	ABMs were in their preliminary stage of development across the social & natural sciences, and were of interest to various academic communities because they offered a way to better (compared to many other modeling approaches) capture local interactions. Many social science and ecological efforts tended to employ rule sets for agents not grounded on empirical specification	Using much of the same data as the econometric models, the project developed simulation approaches to represent real-world, bounded decision making processes based on empirical data, and developed scenarios that captured a range of dynamics including population growth, migration, institutional change, and varying cultivation practices. This and other empirical specification permitted identification at household plot scale of areas of fallow & secondary forest to be cut [44••,45–47].

of deforestation? Our tests revealed the amount of explained variance lost by focusing on one or the other dimensions and that gained by combining them (Table 1 #7). Overall, differences among households led to distinctively different responses to various policies intended to shape cultivation or forest practices (Table 1 #8).

Innovations in the remote sensing of land covers (Table 2A), foremost the 'step-wise' method of land-cover identification, were only made possible by information gained from the SES research. Linking spectral signals to forest types (upland deciduous, evergreen, secondary, and seasonal wetland forests) and bracken fern employed household information about cultivated parcels (Figure 3). Likewise, enhancements in fire detection relied on household information regarding parcels burned (Table 2B).

Advances in econometric spatial models of deforestation combined remote sensing time series and household data to improve assessments of how many and which parcels of secondary and older growth forest would fall, and by adding environmental data (biomass/carbon), produced assessments of carbon storage and emissions under different policies (Table 2C; Figure 3). Finally, improvements followed the agent based models on land change, as various integrated inputs provided an empirically rich parameterization of rules applied to the agents, leading to robust projections of cultivation and deforestation at the parcel or plot scale.

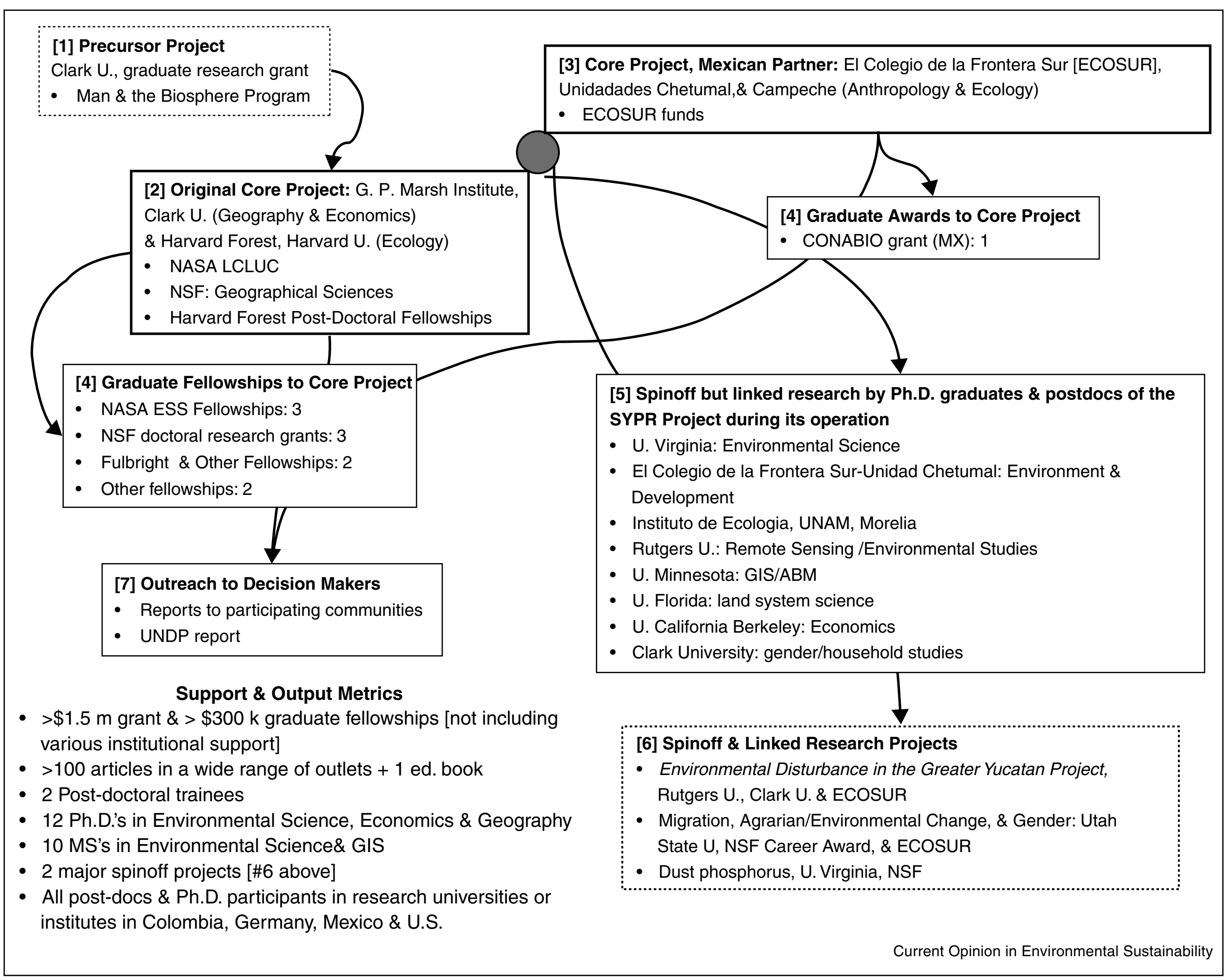
An unintended, theoretical contribution of the project was the use of its findings, such as the role of forest canopy capture of P, coupled with the PI's previous research on ancient land uses in the region, to generate a new synthesis of the collapse and depopulation of the Maya in the region [48•]. This synthesis links the impacts of intensive land-uses to the amplification of climatic drought and to a decline in P, creating new levels of constraint on agriculture and water. These constraints, in tandem with economic losses from changes in trade routes, created a human-environment threshold that played a role in the Maya abandonment of the region.

An integrated program of study: organization, management and problems

The project was organized in four research parts addressing the (i) socioeconomic and (ii) environmental dimensions of land uses and cover, (iii) remote sensing of land cover, foremost forest types and phenology, and of fires, and (iv) spatially explicit modeling of land change (Figures 2 and 3). More than 32 senior and graduate student researchers representing institutions in Mexico and the United States were engaged by the project, including 15 environmental scientists (largely ecologists), 10 social scientists (including three economists), five remote sensors, one GIS-agent based modeler, and several 'tweeners' (human–environment sciences). These members produced an edited book and in excess of 100 research articles in range of environmental, social, and interdisciplinary science outlets and several spinoff research projects that continued beyond the life of the SYPR project (Figure 4). Its two postdoctoral researchers and 12 Ph.D. graduates hold tenure or permanent positions in research institutions in the United States and Latin America.

Various characteristics of the organization and management of the SYPR project contributed to its success. First, the team members were steeped in research about human-environment relationships or, at least, keenly interested in them. They appreciated that the complexity of the SES exceeded the understanding that any disciplinary expertise could bring to bear on it. The service of the professional staff as committee members for the diverse graduate student cohort heightened this appreciation over the duration of the project. Second, the project was designed such that the output of one research part constituted the input for or check on another part; all dimensions of the project were dependent to various

Figure 4



Linkages of the research and sponsoring units (# = phase stages of project).

degrees on the others (Figure 3). Third, the specific objectives of each part of the project were developed by the research specialists in cooperation with the team as whole. These objectives were revised and enlarged as needed, generally related to research discoveries by the team or as new members of the project were added. Fourth, all project members visited the field site at least once, and the overwhelming majority, on multiple occasions. In addition, the project as a whole met in various configurations at two-to-three year intervals over its 12 years of operation to discuss findings, problems, and other facets of the research in what might be labeled an 'adaptive management' approach. Fifth, the participants operated within the problem framing of post-positivist (or mainstream) science, reducing possible friction from alternative problem framings (e.g., structuralist or constructivist approaches), which can loom large within the social sciences. Finally, there were few, if any, limitations set on individual researcher activities and publications or on the ability of junior researchers to connect to the project. Emergent research ideas were encouraged.

The number of organizational and management problems were few and largely involved generic issues that all international, field-based, and SES projects encounter: for example, initial difficulties understanding the methods, framework, and analytical approach of other disciplines. We overcame these potential constraints by meeting frequently to reframe the project, presenting research to one another, and making joint visits to the field. Working at the same sites, including parcels and households, was essential to building interconnected data sets and facilitated research integration by increasing the appreciation for the perspectives and interests of other team members.

Achieving sufficient funds to support fully the breadth of research required is always an issue for a project this kind. Approximately $1.5 million (US) was generated from several NASA and NSF sources for base project research, in addition to about $300,000 for graduate fellowships from those and other sources. In addition, substantial add-on support was provided by Harvard Forest for postdoctoral researchers, by ECOSUR and other Mexican sources for ECOSUR researchers, and for graduate students from their home-institutions (Figure 4). The need to maintain a base camp and field vehicles, which funding agencies are often reluctant to support, escalated overall costs. Efforts to obtain additional funding typically required adding new dimensions to project, stretching the capacity of the project in regard to labor, time, and field-access constraints.

Ensuring data access and sharing in a thorough and timely fashion and navigating different disciplinary publication norms presented occasional problems. Data sharing was, for the most part, unproblematic because of the project's design and the trust developed through shared field work. Facilitating data access from a central storage location proved to be somewhat problematic, however. Data were initially housed with the lead researcher collecting them. Many leads made data available for central storage at Clark University, but some did not, largely owing to the inconvenience involved in doing so. Only one sticky point emerged regarding data sharing, affecting one sub-aim of the project. Modest issues arose over disciplinary rules of authorship (e.g., credit for analysis versus collection of data). Considerable leadership attention was given to ensuring that the large number of doctoral candidates, post-doctoral researchers, and junior-level professors on the project were protected regarding authorship, necessitating care in regard to 'first call' on the data (e.g., for dissertations) versus the data needs of the larger project objectives.

Reflections on project improvements

Several facets of the project could have been implemented during its development and duration that would have improved the output of the research, at least in principle. These are briefly discussed here in order of their significance to the overall output of the project.

Programmatically, it took several years to build acceptable levels of integration between the U.S. and ECOSUR participants, in part because ECOSUR was a distant partner in original funding, and its members had to adjust their research, as did the project at large, as both parties negotiated their way forward. While improvements in cooperation grew throughout the project's existence, a more strongly co-designed and funded effort from the outset would have been a superior, facilitating the two units' research interests and programmatic needs.

The flow of researchers through the project brought new interests and ideas that expanded understanding of one or more parts of the research effort (Figure 4). This understanding, however, was not always fully integrated into the input-output linkages of the initial project design. As a result, model development was not as complete in the SES interactions as originally intended. The biophysical and socioeconomic processes examined were used to produce robust economic and agent-based models of the amount of deforestation, usually of secondary growth in fallowed areas, and its location, down to the household scale. The models did not fully address the reverse, however, such as land abandoned owing to invasive species. A more myopic program of research may have achieved more end-to-end integrated models, but perhaps not uncovered the full range of processes operating in the SES.

The SYPR project was anchored in and funded for primary land system science research, not for outreach to decision making, despite the obvious relevance of the project to various Mexican and NGO programs operating in the region. Several discussions between the project and these programs failed to produce much cooperation, given time and funding constraints for all parties. Direct ties to these communities were left largely to individual researchers or to ECOSUR as part of its mandate, with two exceptions. A 'community report' in Spanish was delivered to each community (*ejido*) cooperating with the project. In simple language, figures, pictures and maps, it provided quantitative information on land and environmental conditions by individual community. In addition, the United Nations Development Program coordinator for the Yucatán Peninsula asked ECOSUR to formulate criteria and indicators for assessment of financial support for projects dealing with environment and development in the Calakmul area. The SYPR project data and results contributed significantly to this report [49]. The SYPR project had the potential to inform regional efforts in practice more than it did, although such efforts would have required increased support, both fiscal and labor in kind.

Remote sensing provided base information for all parts of the SYPR project, including modeling. This part of the project would have been enhanced and made more efficient by the role of a consistent research leader throughout the project's duration, whereas three different leaders were involved at different stages of the project. Fortunately, each remote sensing lead integrated with and enlarged the research of the former lead, strongly assisted by outstanding graduate students bridging the transitions.

While the SYPR project was not framed in terms of a priori theory and hypotheses, specific questions-hypotheses emerged through an inductive process, many addressed experimentally, the results leading to new questions and hypotheses. The process is akin to what others have labeled 'event ecology' following a process of abduction (or reasoning from events to causation) [50•]. The tradeoffs between this approach and an a priori, theory/hypothesis-experimental one are not clear. Focusing on a set of theories, such the 'hollow frontier' [51] or forest transition, would likely have produced more definitive assessments of theory. This approach, however, may have constrained attention to other, important relationships relevant to the SYPR effort, as advanced by champions of abduction [50•], as well as limiting its attractiveness to the talented pool of researchers who found the latitude of the project conducive to their research interests.

Beyond the SYPR case

The question-based, exploratory case studies common in land system science, often engaged in natural experiments, tend to demonstrate how the variance in the conditions and interactions of SESs affect general propositions applied to them, potentially altering or enlarging the relationship in question. The SYPR project generated a number of examples of this kind, as well as important methodological advances. Exemplary are the various insights about general SES dynamics testable in other cases: for example, the nature of forest recovery from swidden cultivation in tropical forests, including carbon stocks constrained by nutrient cycling, the impact of household conditions on forest transitions, and 'hollow' economic frontiers generating pasture. The SYPR also advanced new land classification and modeling methods applicable for all studies employing Landsat TM data and seeking to predict and project land changes and their consequences.

Acknowledgements

Multiple programs and agencies provided funding for various parts of the SYPR project, all of to whom we are grateful for their support. The initial and base funding for project, however, was provided by the Land-Use and Land-Cover Change, NASA (NAG 564006, NAG5-11134, NAG-06GD98G), Center for Integrated Studies, Carnegie Mellon University (NSF-SBR 95-21914), and NSF BCS-0410016. We also thank our Mexican partners, El Colegio de la Frontera Sur (ECOSUR), for their strong support, especially that of Dr. Pedro Antonio Macario Mendoza who transitioned the precursor research effort into the full-blown SYPR project. Barbara Trapido-Lurie prepared our graphics.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

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