Vegetatio **121:** 53–65, 1995.
T. Hirose and B.H. Walker (eds). Global change and terrestrial ecosystems in monsoon Asia

Terrestrial transects for global change research

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Accepted 2 December 1994

Key words: Biogeochemistry, Climate change, Ecosystem, IGBP, Land use, Vegetation dynamics

Abstract

The International Geosphere-Biosphere Program has proposed a set of large-scale terrestrial transects to study the effects of changes in climate, land use, and atmospheric composition ("global change") on biogeochemistry, surface-atmosphere exchange, and vegetation dynamics of terrestrial ecosystems. The transects ($\approx$ 1000 km) will be located along existing environmental and land use intensity gradients that span transitions between biomes in regions likely to be widely affected by forcing from components of global change or where the impacts of global change are likely to feed back to affect atmospheric, climatic, or hydrologic systems. Experimental studies on the transects will examine short-term changes in ecosystem function and biosphere-atmosphere interaction in response to variation in primary controlling variables. A hierarchy of modeling approaches will develop predictions of long-term changes in biome boundaries and vegetation distribution. The proposed initial set of IGBP terrestrial transects are located in four key regions: (1) humid tropical forests undergoing land use change, (2) high latitudes including the transition from boreal forest to tundra, (3) semi-arid tropical regions including transitions from dry forest to shrublands and savannas, and (4) mid latitude semi-arid regions encompassing transitions from shrubland or grassland to forests. We discuss here the rationale and general research design of transect studies proposed for each of these priority regions.

Introduction

Human influence on the environment has grown to a global scale and posseses a momentum that ensures that its effects will persist well into the future. Moreover, the dominant components of anthropogenic "global change" – climate, atmospheric composition, and land use, are occurring, or are expected to occur, very rapidly relative to their historic natural variation. Predicting the consequences of global change for the Earth's biological, geological, and atmospheric systems is an enormous scientific challenge and one which requires multidisciplinary science at scales previously not attempted. The International Geosphere-Biosphere Programme (IGBP)[1] is addressing this challenge through its component core projects, each of which focuses on a different aspect of the Earth system (IGBP Report No. 12 1990).

For terrestrial biological systems major uncertainties exist regarding the effects of global change on the distribution, structure, and function of ecosystems and the ways in which these effects may feed back to the atmosphere and the physical climate system (Steffen *et al.* 1992). Among the research programs promoted by

[1] IGBP includes core projects on Biological Aspects of the Hydrologic Cycle (BAHC), Data and Information Systems (DIS), Global Analysis, Interpretation and Modeling (GAIM), Global Change and Terrestrial Ecosystems (GCTE), International Global Atmospheric Chemistry (IGAC), Joint Global Ocean Flux Study (JGOFS), Land-Ocean Interactions in the Coastal Zone (LOICZ), and Past Global Changes (PAGES).

the IGBP core project on Global Change and Terrestrial Ecosystems (GCTE) to reduce uncertainty in these areas is a set of large-scale terrestrial transects along existing environmental and land use gradients. These transect studies will be used to determine the effects of different global change variables on biogeochemistry, vegetation structure, and their interactions, in a number of regions throughout the world.

This paper provides an overview of the rationale, objectives, and research design of the proposed initial set of transects, which will be located in regions deemed most critical for developing a global understanding of the impacts to, and feedbacks from, terrestrial ecosystems under global change. Although initially conceived in the context of ecosystem biogeochemistry and vegetation dynamics, the transects should also be important research facilities for related disciplines, particularly those concerned with biological aspects of atmospheric chemistry and the hydrological cycle (IGBP Report No. 12 1990; Prinn 1994; Shuttlesworth 1994). They can also be useful for studying the impacts of human land-use on ecosystem structure, composition and function (Steffen *et al.* 1992; Turner *et al.* 1994). Given the emphasis in transect studies on scaling up from small patches to the regional level, they offer an excellent opportunity to apply tools from the field of remote sensing to terrestrial global change problems. Thus, the transects will be international and interdisciplinary research facilities that will add significantly to our understanding of the role of the terrestrial biosphere in global change. A detailed science plan for the transects activity will be presented in a forthcoming publication in the IGBP report series. It is hoped that the present article will serve to encourage scientists to focus their efforts on a common set of transects, in a complementary and collaborative way, building on work that in some cases is already under way.

The rationale for large scale terrestrial transects

Current or predicted changes in atmospheric composition, land use, and climate, collectively considered global change, are likely to alter the biogeochemistry, surface-atmosphere exchange, and vegetation dynamics of terrestrial ecosystems, and consequently, may lead to feedbacks to components of global change. There are several reasons why the capacity to predict global change effects can be gained most effectively by distributing measurements and experiments along existing gradients of each underlying controlling factor. First, comparative studies have long been useful in understanding the patterns and putative controls on ecosystem processes; comparisons based on well-defined and continuous variation in an environmental factor will yield still greater insight into how that factor controls ecosystem structure and function. Second, ecosystem-level experimentation that is replicated along an environmental gradient can be used to analyze interactions among the underlying environmental factor, other environmental variables, and biotic components of ecosystems. Finally, research and associated modeling carried out along gradients enforces an extensive, regional, and realistic (in terms of human influences) perspective on global change studies.

In addition to these general considerations there are particular global change issues that can only or best be addressed using gradient techniques at large spatial scales. These include:

Questions where a long period of prior equilibration is required. For processes of change characterized by long time constants, large-scale gradients in which current spatial variation is used as an analog for expected temporal variation, in conjunction with patch-scale manipulative experiments, provide a powerful approach to understanding long-term responses to global change.

Questions where the spatial context is essential. Processes which operate continuously in space need to be studied along continua. A key uncertainty in many aspects of global change research is whether the net effect of a process at a large scale is simply the sum of the process occurring in patches at smaller scales. This question can only answered by making measurements on contiguous patches and at a range of spatial scales.

Identification of thresholds along a continuum. Ecosystem process response may not be a simple function of a given global change variable. Studies along existing gradients of components of global change (e.g. precipitation or land use intensity) may reveal discontinua which can provide the basis for focused experiments.

The need to unify ecological, atmospheric, and climatic models of global change. The scale to which ecological understanding of global change will ultimately have to be related is that at which the global climate is simulated. For the near future this will be on the order of a 500×500 km square and this is the main motivation for IGBP transects to be of the order of 1000 km, or two GCM grid cells, in length.

There are also organizational advantages to a transect campaign. The transects will provide a multi-national and interdisciplinary platform for collaboration among researchers involved with the different core projects and framework activities of the IGBP and other national and international scientific programs. Integration of activities among different groups will be more easily achieved if research is conducted on the same or related study sites.

Types of transects and selection criteria

Definition of IGBP transects

The IGBP Terrestrial Transects are each chosen to utilize an existing gradient for the purpose of understanding how variation in the factor underlying that gradient influences: (1) terrestrial ecosystem structure, function, and composition, (2) biosphere-atmosphere trace gas and energy exchange, and (3) hydrologic cycling. These transects can be visualized most easily where they represent a simple gradient of a single controlling factor that varies in space, for example, the gradient in precipitation from moist tropical forest to dry savanna. In practice, of course, all of the IGBP transects are more or less complex; multiple factors contribute to the structure and function of any ecosystem, and interact to shape its dynamics. Nevertheless, the presence of a strong underlying gradient shapes the ecosystems along a transect and their interactions with other environmental factors, thereby helping us to understand how these systems function, and how they are likely to change.

In addition to relatively straightforward transects in which a single environmental factor varies continuously in space, we have also identified IGBP transects in which the underlying gradient is one of intensity of land use. These gradients are more complex conceptually than spatial transects; ecosystems that experience differing intensities of land use are rarely distributed in a way that distance along a regional transect corresponds directly to the intensity of land use. Nevertheless, often it is possible to place differing land uses along a gradient of intensity (i.e., from unmanaged forest to selective forest harvesting to clearfelling followed by forest successsion to conversion into pasture to conversion into permanent, high-input agriculture). Sites within a region can then be located and evaluated according to their position along such a gradient, yielding a situation analogous to a spatially-defined moisture or temperature gradient.

It should be pointed out that many globally significant research sites and networks do not fit our definition of transects. Research sites where the ecosystem effects of elevated carbon dioxide is the focus fit into this category, as does the U.S. network of Long Term Ecological Research sites. They are integral to achieving the objectives of IGBP, but in and of themselves they are not transects as defined here. In some cases transects may be located so as to include these sites, which would provide benefits for both the transects and the local studies.

Selection criteria

The proposed initial set of IGBP transects was chosen according to a rather stringent set of criteria. Each transect:

(1) represents a coherent set of sites that differ relatively straightforwardly and continuously in a major environmental factor that is predicted to change significantly (or has already changed) as a consequence of global environmental change;

(2) is located in a region that is likely to be altered by forcing from components of global environmental change, where the alteration is itself likely to be globally significant, or where the alteration is likely to feed back to affect atmospheric, climatic, or hydrologic systems;

(3) is sufficiently broad that (i) understanding gained from research on the transect can be applied beyond a narrow region, (ii) it crosses a transition between systems dominated by different major life forms (e.g. forest/prairie, taiga/tundra), (iii) it requires resources that are ordinarily beyond the scope of individual research groups funded by national sources;

(4) provides a useful resource for a number of IGBP activities, drawn from more than one IGBP core project;

(5) is established or actively developing, with a number of research sites selected, much of the research team in place, and a clearly identified transect scientist who can serve as a representative and a point of contact for the transect.

It must be stressed that the transects selected to date are a proposed initial set. Other transects will be added to this list to the extent that they (i) meet the criteria above, and (ii) add something significant (a new environmental factor, a new transition between biomes, or representation of a globally significant region) to the set of IGBP transects.

The proposed initial set of IGBP transects

The proposed initial transects are located in four key regions (Table 1), identified on the basis of their likelihood to be altered by components of global change and the strength of their potential feedbacks to global change. These include (1) humid tropical forest regions undergoing land use change, (2) high latitude regions extending from boreal forest into tundra, (3) semi-arid tropical regions including transitions from dry forest to shrublands and savannas, and (4) mid latitude semi-arid regions encompassing transitions from shrubland or grassland to forests. The rationale and general design of transect studies proposed for each of these regions are outlined in the following sections. Some of the transects described are currently active and already have been incorporated into IGBP Core Project research programs. The research plans outlined for other transects are still being developed through coordinating meetings of representatives from IGBP Core Projects and other scientists.

The approximate geographic location of each proposed transect is shown in Fig. 1, which depicts a generalized life zone classification (modified from Holdridge by Leemans 1989) for the Earth's terrestrial surface. The several transects proposed within each priority region are meant to encompass the major vegetation assemblages and physical characteristics found globally within these regions. They are clearly not replicates in the statistical sense. It is recognized that an important challenge for each transect study will be to address adequately questions of statistical design in view of the expense and effort required in undertaking such large-scale projects.

The following sections provide brief descriptions of the initial transects proposed for each of the priority regions listed above. Each description includes an overview of the significance of each region in the context of global change, the location of the proposed transects, and a set of key questions to be addressed by each regional set of transects. Along with the specific research questions listed, it should be noted that a major objective common to all the transects along environmental gradients is to determine how the boundaries between biomes may shift in response to the components of global change and how the consequent change in vegetation distribution may influence regional biosphere-atmosphere interactions and the climate system.

I. Land use intensity transects in humid tropical forests

The humid tropics are a high priority region for global change studies because of the significant impact of land-use change (usually the conversion of forests to agriculture) on biogeochemical and hydrological cycles (e.g. Luizao *et al.* 1989; Keller *et al.* 1991; Dickinson 1991; Dixon *et al.* 1994; Reiners *et al.* 1994). Refinements of remote sensing techniques are now permitting mapping of these conversions on the regional scale (Skole & Tucker 1993). The controlling variable on which the humid tropical gradients are based is intensity of land use (normally determined by agricultural strategies and techniques). The impact of land-use can be considered to occur in two phases: (i) the initial clearing of the forests, the techniques of which are important in determining the short-term alterations to biogeochemical cycles, and (ii) the subsequent agricultural or other use, the type and intensity of which are critical in determining the longer term effects.

The humid tropical transects will be designed to answer several key questions including:

(1) What are the effects of land clearing and subsequent land use on quantities, pathways, and processes of carbon and nutrient loss or gain?
(2) How are fluxes of key trace gases (CO_2, CH_4, N_2O) differentially affected by different land use practices?
(3) What are the surface characteristics (albedo, roughness, bulk conductance) of vegetation types arising during different land use sequences?
(4) How are local, landscape, and regional hydrological cycles affected by clearing and subsequent land use?

The Human Dimensions of Global Environmental Change Program's (HDP) project on Land Use and Cover Change (LUCC, Turner *et al.* 1993), which is developing jointly with input from IGBP, has as a major objective the determination of how land use and and associated land cover are changing globally as a result of social and environmental factors. Thus, LUCC has a role with respect to the tropical land use transects that is analogous to that of the general circulation models (GCMs) for the environmental gradient transects in that LUCC can provide the scenarios for future land

Table 1. Priority regions for IGBP terrestrial transects.

Region	Major biomes included	Principal global change variable
Humid tropics	Wet tropical forest & conversions	Land use intensity
High latitudes	Boreal forest to tundra	Temperature
Semi-arid tropics	Forest, woodland, shrubland	Precipitation
Mid latitude semi-arid	Forest, grassland, shrubland	Precipitation

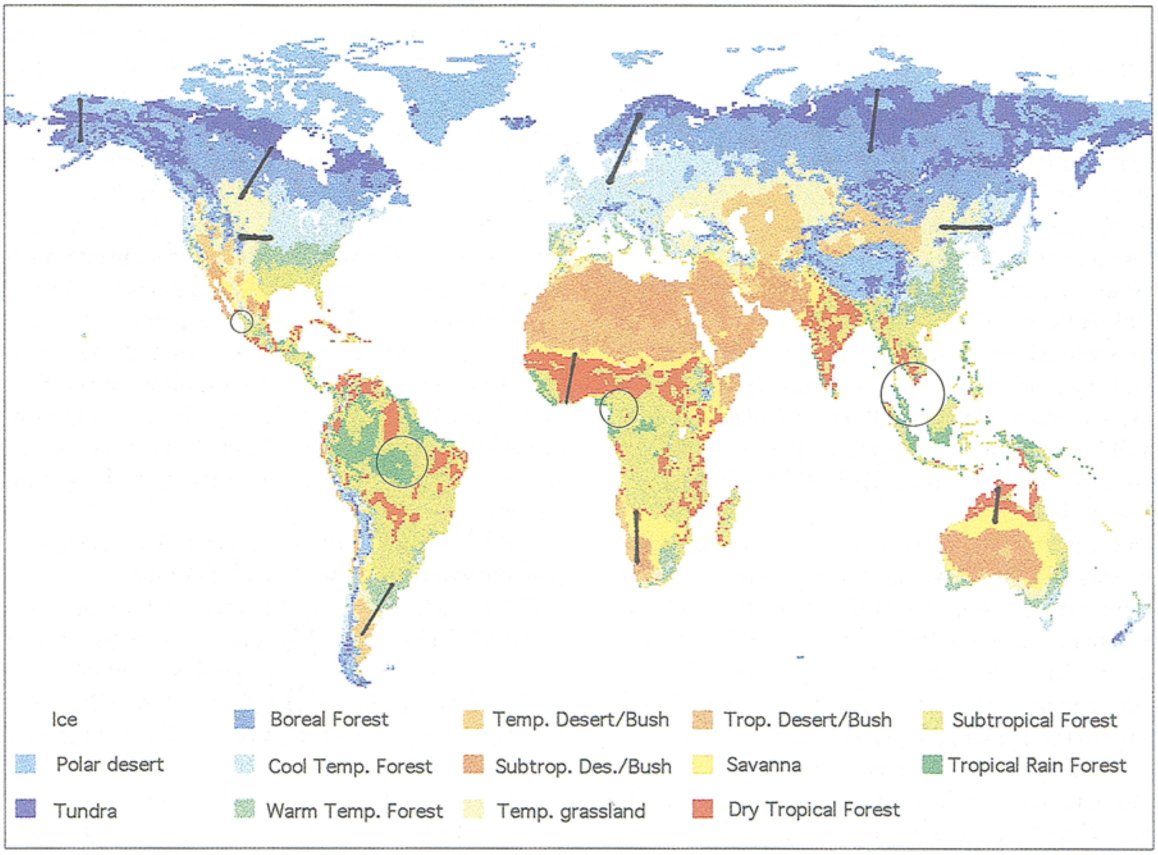

Fig. 1. World map showing approximate locations of the proposed initial set of IGBP terrestrial transects. Vegetation classification is simplified from Leemans (1989). Transects along gradients of major climatic variables (temperature and precipitation) are shown by straight lines. Locations of proposed land use intensity transects are enclosed in circles. Exact location of Siberian transect has yet to be determined.

use patterns upon which regional extrapolation of the results from the land use intensity transects will be based. Together with LUCC research on the social and economic drivers of land use, results from transect studies in the humid tropics will provide the basis for developing much-needed integrated models of land use and global change (Ojima *et al.* 1994).

Six initial locations are proposed for the land use intensity transects in the tropics, two for each of the three major humid tropical regions – Central and South America, Central Africa, and Southeast Asia (Table 2). One transect from each region will focus on humid evergreen forests while the other will be centered on seasonally dry deciduous forests. The infrastructure for establishing transects in some of these locations is in place and for others it will be developed with input from planning workshops.

Table 2. Location of proposed IGBP transects along gradients of land use intensity in the humid tropics. The three locations without question marks are areas where known existing or planned projects can form parts of a study.

Location	Humid forest	Dry forest
Central/South America	Amazon	Mexico
Southeast Asia	Sumatra	Thailand (?)
Central Africa	Cameroon (?)	?

II. High latitude transects

High-latitude regions are a high priority because of the large climatic change (particularly temperature increase) anticipated at high latitudes, the apparent sensitivity of these systems to climate change, and the potential for a significant feedback from high-latitude systems to global change via changes in surface biophysical characteristics and trace gas exchange. High-latitude ecosystems occupy some 25% of the Earth's land area, and harbor as much as one quarter to one third of the carbon stored in global terrestrial ecosystems (Gorham 1991; Apps *et al.* 1993; Dixon *et al.* 1994). These systems generally appear to be quite sensitive to changes in climate, with responses observable at all levels of organization from microbial and vegetation physiology to community-level dynamics, surface hydrology, and the frequency and intensity of disturbances (e.g. Bonan *et al.* 1990; Zoltai & Vitt 1990; Chapin *et al.* 1992). This sensitivity has led biogeographers to suggest that climate warming will tend to cause existing northern high-latitude vegetation to be replaced by vegetation similar to that currently found under warmer climates further south (e.g. Prentice *et al.* 1992; Rizzo & Wiken 1992; Smith *et al.* 1992).

The implications of global change for carbon storage in high-latitude terrestrial systems are unclear. Although high-latitude regions as a whole may currently function as a sink for atmospheric CO_2 (e.g. Tans *et al.* 1990; Dixon *et al.* 1994), there are indications that recent or anticipated global changes may result in accelerated releases of stored carbon from some high-latitude systems, for example, tundra ecosystems under elevated temperatures (Oechel *et al.* 1993). Conversely, elevated temperatures may increase rates of nitrogen mineralization (as well as soil respiration) resulting in increased carbon storage in vegetation on tundra sites where nutrients are currently immobilized (Shaver *et al.* 1992).

The objective of the high-latitude transect studies is to develop a comprehensive understanding of the interacting controls on high-latitude biogeochemistry, hydrology, and vegetation dynamics in order to predict how these dynamics may change in time and space in response to components of global change. The vegetation dynamic studies will focus on developing the capacity to predict how the locations of boundaries between boreal forest and tundra may shift as environmental conditions change. Specific questions that will be addressed include:

(1) What environmental factors (temperature, soil moisture, nutrients, biota, etc.) are most important in regulating the carbon balance of high-latitude systems? Are high-latitude ecosystems currently sinks or sources of atmospheric carbon?

(2) What are the interactive effects of increased temperature and altered nutrient availability on carbon and nutrient pools and fluxes across the transition from boreal forest to tundra?

(3) How is trace gas flux regulated by soil, vegetation, and hydrological characteristics and how will these fluxes change under altered temperature regimes?

(4) How do gradients of temperature and soil moisture regulate biotic processes, such as growth, decomposition and competition, which define biome boundaries? How stable are the boundaries of the high-latitude biomes under current and possible future climates?

(5) How would climate-induced changes in disturbance regimes (e.g. fire, insect attacks) and direct changes in land-use, affect ecosystem carbon balance, surface characteristics (albedo, roughness, bulk stomatal conductance), and vegetation composition? How will such changes influence surface energy balance?

The proposed initial set of high-latitude transects includes one each in Alaska, Canada, Russia and Scandinavia/Northern Europe (Table 3). All the transects include north-south temperature gradients and the interior transects (Canada and Russia) are located in regions predicted by most GCMs to become drier in the future. The Canadian high-latitude transect may encompass the locations of sites utilized in the BOREAS (Boreal Ecosystem-Atmosphere Study) program.

III. Semi-arid tropical/subtropical transects

The savannas of tropical and sub-tropical regions of the world are a priority region for transect studies because

Table 3. Proposed IGBP transects in high-latitude regions along dominant temperature gradients. All include boreal forest, tundra, and tundra-boreal transitions. The Canadian transect also includes the boreal forest-grassland transition at its southern limit.

Transect	Description
Alaska	Decreasing temperature and precipitation northward from boreal forest (Bonanza Creek) to boreal/tundra transition (Chandalar Shelf), upland tundra (Toolik Lake), and coastal tundra (Prudhoe Bay).
Canada	Decreasing temperature northward from prairie-forest transition (Medicine Hat, Alberta) through boreal forest and into low subarctic tundra (Gillam, Manitoba)
Scandinavia	Decreasing temperature northward from boreal forests (northern Europe, site to be decided) into tundra (Abisko, Sweden/Kevo, Finland)
Siberia	Decreasing temperature northward from boreal forest into tundra (location to be decided)

of their sensitivity to many of the components of global change and the significance of their potential feedbacks to atmospheric composition. Water availability is a strong controller of ecosystem structure and function in these regions, with clear contrasts in dominant life form (trees vs. shrubs vs. grasslands) as well as photosynthetic pathway (C_3 vs. C_4) occurring along moisture gradients. The mix of trees and grasses within savannas is inherently unstable and has apparently responded to past climatic fluctuations and human influence (Archer 1990; Scholes & Walker 1993). Human use of semi-arid regions (agriculture, grazing, burning) interacts strongly with climate and is expected to increase as population and development pressures rise (Ellis & Galvin 1994). These factors indicate that future climatic and land use change may greatly affect both carbon cycling and the amount and location of carbon stored (soil vs. vegetation) in semi-arid tropical and subtropical regions.

Tropical semi-arid systems also have an important influence on atmospheric composition. Primary productivity in tropical savannas may have a significantly greater role in the global carbon cycle than has been recognized previously (Scholes & Hall, in press) and a significant portion of total global biomass burning takes place in savannas, releasing large quantities of trace gases (CO_2, CO, CH_4, N_2O, NO) and particulates (Crutzen & Andreae 1990; Cahoon 1992). Understanding the interactions among fire, climate, land use and other dominant processes (e.g. herbivory) and state factors (e.g. soil type) is essential for developing predictions of the role of tropical and subtropical savannas in regulating atmospheric composition (Justice *et al.* 1994).

Developing predictions regarding the complex interactions of semi-arid tropical and subtropical systems with global change will require answering a broad suite of questions. Some of those that will be addressed by the IGBP transect studies include:

(1) What are the interactive roles of water availability, grazing, and fire in controlling the proportions of woody plants and grasses in savannas? How does soil type modify these relationships? What are the likely changes in the extent and location of tropical grassland, savanna, and shrubland given changes in these controlling factors?

(2) What is the magnitude of the carbon sequestration activities of herbaceous and woody components of semi-arid systems under different land use practices? What are the implications of different distributions of above- and belowground carbon stores for susceptibility to climatic and land use change?

(3) What is the significance for evapotranspiration and surface hydrology of differences in rooting depth and canopy roughness of tree and grass components of savannas?

(4) How will changes in ecosystem structure (shrub-grass-tree mix) influence landscape-scale redistribution of surface water, sediments, and nutrients?

(5) What are the impacts of altered precipitation and elevated CO_2 on plant chemical composition (e.g. C/N ratio) and how might this affect processes (nutrient cycling, herbivory, fire) that influence ecosystem structure?

(6) What are the controls on biogenic and pyrogenic emissions of trace gases? What factors regulate the spatial and temporal variation of microbial trace gas production? What is the fire frequency in different vegetation types and under different man-

Table 4. Proposed IGBP transects in semi-arid tropical regions along aridity gradients (precipitation or potential evapotranspiration). Biomes included are forests, shrubland, savannas, and transitions.

Transect	Description
Kalahari	Decreasing precipitation southward from forests of Zambia through woodland to shrub savanna in South Africa
NATT[a]	Decreasing precipitation from woodlands in the north (Darwin) to shrublands in the south (Tennant Creek)
SALT[b]	Increasing aridity northward from forests of the Ivory Coast to the Sahelian savannas of Mali

[a] Northern Australia Terrestrial Transect.
[b] SAvanna in the Long Term.

agement regimes, and how might the pattern and magnitude of pyrogenic emissions change under different scenarios of climate and land use change?

Three transects along strong precipitation gradients are proposed in the semi-arid tropics and subtropics, one each in northern Australia, West Africa, and southern Africa (Table 4). Two of these, the North Australian Tropical Transect (NATT), and Savannas in the Long Term (SALT) in West Africa are currently components of the GCTE Core Research program.

IV. Mid latitude semi-arid transects

Mid latitude regions cover a large proportion of the earth's surface and are predicted to experience relatively large changes in temperature and precipitation under present climate change scenarios. Within these regions strong gradients in water availability (precipitation and potential evapotranspiration) strongly influence vegetation distribution, which ranges from grassland and shrublands at the dry end to deciduous forest at the wet end. The dominant role of water availability in these regions is seen in the strong, but complex, dependence of primary productivity on annual precipitation (Lauenroth & Sala 1992). The proportion of C_3 and C_4 species varies along moisture gradients in the mid latitudes and these functional groups may differ significantly in their responses to global change. Severe droughts are also common in mid latitude regions and may interact strongly with land use to magnify their deleterious effects.

An important feature of mid latitude moisture gradients is that the location and size of the major stores of carbon change over the gradient; carbon stores increase and become proportionately greater aboveground with increasing precipitation. The vulnerability of these carbon pools to components of global change and the regional and global consequences of their perturbation will differ depending upon both the type of change and the location along the transect. Preliminary simulation studies for one area of the central US suggest that the major carbon pool in grasslands (soil organic matter) is more vulnerable to land use modification than to climate change (Burke *et al.* 1991). Transect studies will help evaluate the generality of this result.

Land use (range, agriculture, forestry) in the mid latitudes has had a significant impact on trace gas exchange and global atmospheric carbon content (e.g. Ojima *et al.* 1993; Houghton 1994). In addition to land use, the mid latitudes include regions subject to other important anthropogenic influences including high levels of both nitrogen deposition and tropospheric ozone. These factors, while not initial priorities for the transect studies, will likely play an important role in modifying ecosystem responses to global change and are being addressed as special objectives of IGBP Core Projects (for example, interaction of mid latitude ecosystems and tropospheric ozone is a primary concern of IGAC's developing MILOX program).

The emphasis of transects studies in mid latitude semi-arid regions will be on understanding the effects on ecosystem structure and function of changing water availability due to altered climate or atmospheric composition (i.e., CO_2-induced change in transpiration). Some of the specific questions that will be addressed include:

(1) What are the effects of altered water availability on primary ecosystem processes (primary productivity, nutrient cycling, trace gas exchange, evapotranspiration) in mid latitude semi-arid regions? Do the magnitudes of these responses differ among the dominant vegetation types (shrubland, grassland, forest)?

(2) Do systems characterized by mixtures of functional types (C_3 and C_4) show a greater or lesser ecosystem-level response to altered water avail-

Table 5. Proposed IGBP transects in mid latitude semi-arid regions. The dominant environmental variable is precipitation.

Transect	Description
Argentina	Southwest to northeast aridity transect along grassland cover and composition gradient
Central U.S.	Decreasing precipitation westward from deciduous forests (site undecided) to tall and short-grass prairie (Colorado)
Northeastern China	Decreasing precipitation westward from deciduous forests (Changbai Mtns., Jilin) into temperate shrublands and mid- and short-grass steppe (Xilingele)

ability than do systems dominated by one or the other functional group?

(3) What are the relative rates of change of soil and vegetation carbon pools in response to altered water availability? How do patterns of soil organic matter and nutrient dynamics change through time in response to changes in vegetation?

(4) Are root distributions characteristic of particular plant functional types a key determinant of vegetation structure along a spatial gradient in water availability?

The three proposed transects are located in Argentina, the Peoples Republic of China, and the central U.S. (Table 5). In China and the U.S. precipitation gradients are paralleled by changes in life form, from grasses and shrubs at the dry end to deciduous forest at the wet end, while in Argentina grasslands dominate across the range of environmental conditions. These areas also differ in the intensity of current land use practices and the expected patterns of future exploitation; whereas extensive land use conversion has already occurred in the U.S., much change is yet expected in China.

Research design

The general research design of the IGBP transects involves a hierarchy of observational, experimental, and modeling approaches at different spatial scales. These approaches range from remote sensing of vegetation composition and surface biophysical characteristics over the entire transect to intensive plot-level process studies at a relatively few carefully chosen sites along each transect. The intensive measurements and manipulative experiments will examine controls by the dominant global change variable on primary ecosystem processes (e.g. primary production, nutrient cycling) and biosphere-atmosphere interactions (water, energy, and trace gas exchange) for different vegetation types along the transect. Intensive study sites will be located along the transects in representative ecosystem types and in areas that may be especially sensitive to change, i.e., locations in which the environmental gradients are steep or are effecting significant transitions in ecosystem structure. A further consideration in locating study sites is the existence of long-term datasets that may contribute directly to the objectives of the transect study.

The design of the land use intensity transects in the humid tropics incorporates aspects of the relevant components of the IGAC, BAHC, GCTE, and LOICZ operational plans. The transects will have five elements – (i) intensive process studies emphasizing the development of fully-closed budgets of key elements including carbon, nitrogen, and phosphorous ("budget-closing experiments") at one or possibly two sites in each transect; (ii) a more extensive network of observational studies along the major gradient (land-use intensity); (iii) networks of measurements and development of associated algorithms designed for scaling results to the regional level; (iv) remote sensing studies to determine the extent, rate, and type of land conversion and subsequent land use; (v) modeling studies to synthesize and integrate the experimental results and to quantify the consequences of future land-use change scenarios.

Common sets of measurements and methodologies will be developed for the transects within a given region through planning workshops coordinated by representatives of IGBP Core Projects. Detailed descriptions of research planned for individual transects will be published in a future publication in the IGBP Report Series.

As has been mentioned, a major objective of the IGBP transect studies is to gain an understanding of how patterns of global vegetation distribution have been and will be altered by components of global change. Although any shifts in biome boundaries will likely develop over time periods longer than the transect studies themselves, it is important that the transects are in place for a period sufficient to determine the probable magnitude and direction of changes in these boundaries. This may require ground studies of a few to 10 or more years duration depending upon time constants for relevant processes in different systems.

Determining the effects of elevated CO_2, interacting with other environmental factors, on biogeochemistry and vegetation dynamics is crucial to developing a thorough understanding of global change, and is a key objective of GCTE (Steffen *et al.* 1992; Mooney & Koch 1994). Elevated CO_2 studies that are conducted at intensive studies along IGBP transects, or in closely comparable systems, will provide tremendous added value to the transect studies and will benefit themselves from information gained in the transect studies. Thus, wherever possible, experiments on the ecosystem effects of elevated CO_2 should be incorporated into the design of transect studies and collaboration should be encouraged among researchers working on the transects and on studies focusing on the ecosystem effects of elevated CO_2.

Similarly, there could be benefits in locating land-surface experiments (LSE) at one or more of the sites along an IGBP transect (or locating transect intensive study sites near existing or planned LSEs). Major LSEs tend to be intensive field campaigns carried out over short periods at one or two sites. Ecological studies such as the IGBP transects, on the other hand, require a number of sites distributed along a large spatial and environmental gradient and operated over much longer time periods. Coordinated interaction between LSEs and the IGBP transects could provide benefits to both in terms of adding more extensive ecological understanding to the LSEs and more detailed, fine-scale, information to the transects. Towards this end, a task team of representatives from BAHC, IGAC, and GCTE has begun to discuss the coordination of the relevant studies that could contribute to a more integrated effort. Opportunities for integration exist in all of the priority regions for IGBP transects. For example, research programs organized by or related to BAHC and IGAC exist in the high latitudes (BOREAS and both HESS and BIBEX, respectively), the humid tropics (LAMBADA and both BATGE and BIBEX, respectively), the semi-arid tropics (HAPEX-Sahel and both BATGE and BIBEX, respectively) and in the temperate zone (FIFE and both TRAGEX and MILOX, respectively). Some of these programs have completed their research phase and could provide background information for the transects, while others are in the planning phase and could be implemented in coordination with the transects.

Modeling and spatial extrapolation

Given their spatial scale (1000 km) it will clearly not be feasible to conduct measurements and experiments along even a small fraction of the entire extent of an IGBP Transect. Thus, there is a need to extrapolate understanding gained from intensive patch-level studies at key points along the transect to the landscape and regional scales. The strategy proposed to accomplish this extrapolation involves a hierarchy of models, ranging from patch-scale process models to landscape and regional vegetation dynamic models, and their linkage to geo-referenced databases of major climatic and vegetation (e.g. distribution, structure, biophysical properties) factors. Modeling studies will provide an integrating framework for the experimental and observational studies and for predicting consequences of future land-cover change. For each process of interest, models at the patch and regional scales are required, as well as methodologies for translating between the scales. Ideally patch-scale process models would be developed in conjunction with the planning of the experimental aspects of each transect study. The developing network of modeling centers within GCTE's Long-term Ecological Modeling Activity (LEMA, Steffen *et al.* 1992) may provide a mechanism for linking modeling efforts to the development of particular transects.

Spatial extrapolation will require extension of ecosystem biogeochemical and surface flux process models (e.g. Parton *et al.* 1988; Running & Coughlan 1988; Melillo *et al.* 1993; Potter *et al.* 1993) from the local to the landscape and regional scales by linkage to geographical databases of the major driving variables. Extrapolation in time, yielding predictions of future vegetation distribution, will utilize vegetation dynamic and succession models (e.g. Shugart 1984; Smith & Urban 1988) and models linking land cover change with biogeochemistry (e.g. Alcamo 1994). Ultimately, this hierarchy of models should feed into models of atmospheric transport and chemistry to provide the basis for examining the feedbacks to the atmosphere of global change impacts on terrestrial ecosystems. The development of one or more dynamic global vegetation models is expected to be one of the major products of the GCTE program as a whole (Walker 1994).

A critical tool in developing and implementing scaling methodologies for spatial extrapolation of ground studies is remote sensing. IGBP's Data and Information System (IGBP-DIS) has facilitated interaction between IGBP scientists and the remote sensing community through the CEOS (Committee on Earth Observation Satellites)/IGBP-DIS Data Exchange Pilot Project. The project recognizes the need for providing essential remotely-sensed data to the gloal change scientific community at less-than commercial rates. The overall goal of the pilot project is to develop ways to coordinate the acquisition and dissemination of high resolution satellite data for global change research, thereby using existing technology in new ways to assist in solving fundamental questions about the Earth system. As the IGBP transects program develops, the CEOS/IGBP-DIS initiative provides a framework to enable the provision of high resolution data to researchers working on these transects.

Related studies

In addition to the proposed large-scale transects described above, it is expected that other types of gradient studies will contribute to the overall effort to understand global change effects. In some cases, studies designed with a more limited scope may become incorporated into future IGBP Transects. For example, the European study NIPHYS (Nitrogen Physiology), already a part of the GCTE Core Research program, is examining soil nitrogen transformations, atmospheric nitrogen deposition, and their interactions and consequences for broad-leaved and coniferous trees over a broad North-South climatic range through Europe. Although not a transect in the sense of being a contiguous set of sites connected by relatively undisturbed natural landscapes, NIPHYS is nonetheless addressing questions that are very important for the overall analysis of global change effects on terrestrial ecosystems and it may form a portion of the high latitude transect extending from Scandinavia into Europe.

A second class of studies that will complement the large-scale terrestrial transects are those along altitudinal gradients. The similarity of climatic controls on vegetation zonation with latitude and altitude has long been recognized. Altitudinal transects typically encompass steep gradients of multiple environmental factors including temperature, moisture, CO_2, and UV-B levels, and thus, do not meet the criteria of an IGBP Transect in terms of being dominated by a single factor gradient. They will be very important in their own right for understanding local interactions among multiple components of global change as well as for understanding global change impacts to biodiversity. The latter issue may be particularly important where climatic zones become compressed or expand around high altitude "islands". The Terrestrial Ecosystems in Monsoon Asia (TEMA) project (already a GCTE Core Research project in the area of vegetation modeling) includes a set of altitudinal gradients arranged along a broad latitudinal range in eastern Asia. TEMA may provide the foundation for a focused study examining global change effects among a set of local altitudinal transects which are distributed across a broad regional background of climate and potential climate change.

Timetable

Coordinated research programs are already underway on some transects (e.g. SALT & NATT), while for others much of the infrastructure is in place and research is ongoing, but additional integration and coordination is needed to meet the requirements of an IGBP transect. Thus, the proposed transects will develop over the coming years with different timetables following input from planning workshops and depending on the availability of funding. In 1993 the SALT and NATT transects were incorporated into the GCTE Core Research program and an initial workshop (the basis for this article) was held in California to outline the priorities and possibilities for additional transects. The first BAHC-IGAC-GCTE interaction workshop was held in early 1994 with a second focusing on high-latitude studies scheduled for late 1994. Additional workshops focusing on the southeast Asian land-use transect and the Kalahari transect in southern Africa are planned for 1995. Promoting the organization and support of existing or planned studies that can contribute to the IGBP transects program will continue to be a high-priority for the relevant core projects of IGBP.

Acknowledgements

Much of the plan outlined here is based on a workshop organized by GCTE with support from NASA and held in California in August, 1993. Participants in that meeting and contributors to the ideas expressed in this paper included: I. Burke, W. Cramer, C. Field, P. Högberg,

B. Hungate, J. Ingram, V. Jaramillo, S. Kojima, K. Lajtha, J. Landsberg, W. Lauenroth, S. Linder, J.-C. Menaut, H. Mooney, I. Noble, W. Parton, D. Price, A. Pszenny, J. Richey, O. Sala, R. Scholes, H. Shugart, K. Skarpe, D. Skole, R. Williams, X. Zhang.

Acronyms and abbreviations

BATGE – Biosphere-Atmosphere Trace Gas Exchange in the Tropics: Influence of Land Use Change (IGAC); BIBEX – Biomass Burning Experiment (IGAC); FIFE – First International Field Experiment (ISLSCP); HAPEX-Sahel – Hydrological Atmospheric Pilot Experiment in the Sahel (BAHC); HESS – High Latitude Ecosystems as Sources and Sinks of Trace Gases (IGAC); ISLSCP – International Satellite Land Surface Climatology Program; LAMBADA – Large-scale Atmospheric Micrometeorological and Biospheric Amazonian Data Acquisition study; MILOX – Mid-Latitude Ecosystems and Photochemical Oxidants (IGAC); TRAGEX – Trace Gas Exchange between Mid-Latitude Terrestrial Ecosystems and the Atmosphere (IGAC).

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