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Global vegetation cover changes from coarse resolution satellite data

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Abstract. Land cover plays a key role in various biophysical processes related to global climate and terrestrial biogeochemistry. Although global land cover has dramatically changed over the last few centuries, until now there has been no consistent way of quantifying the changes globally. In this study we used long-term climate and soils data along with coarse resolution satellite observations to quantify the magnitude and spatial extent of large-scale land cover changes attributable to anthropogenic processes. Differences between potential leaf area index (LAI), derived from climate-soil-leaf area equilibrium, and actual leaf area index obtained from satellite data are used to estimate changes in land cover. Further, changes in LAI between potential and actual conditions are linked to climate by expressing them as possible changes in radiometric surface temperatures (T_r) resulting from changes in surface energy partitioning. As expected, areas with high population densities, such as India, China, and western Europe showed large reductions in LAI. Changes in global land cover expressed as summer, midafternoon T_r, ranged from $-8°$ to $+16°$C. Deforestation resulted in an increase in T_r, while irrigated agriculture reduced the T_r. Many of the current general circulation models (GCMs) use potential vegetation maps to represent global vegetation. Our results indicate that there are widespread changes in global land cover due to deforestation and agriculture below the resolution of many GCMs, and these changes could have a significant impact on climate. Potential and actual LAI data sets are available for climate modelers at $0.5° \times 0.5°$ resolution to study the possible impacts of land cover changes on global temperatures and circulation patterns.

Introduction

Previous studies have demonstrated that changes in land cover could be as important as the increase in atmospheric greenhouse gases in climate change [*Bonan et al.*, 1992; *Shukla et al.*, 1990]. For example, deforestation has been found to increase land surface temperatures (T_s) and reduce rainfall, suggesting a warmer and drier climate [*Dickinson and Henderson-Sellers*, 1988; *Lean and Warilow*, 1989; *Shukla et al.*, 1990]. Although it is clear that global land cover has been dramatically altered by human habitation, forest clearing, and agriculture, until now there has been no means of quantifying these changes globally.

Quantitative analysis of the incredible diversity in global vegetation (species, growth habits, and life forms) is a difficult problem [*Running et al.*, 1994a]. Many classification efforts have been attempted, and their results show wide variations in current estimates of global land cover [*Townshend et al.*, 1991]. A detailed discussion of various land cover classification schemes and their problems is given by *Townshend et al.* [1991] and *Running et al.* [1994a]. The consensus from the above studies is that in the advent of rapid anthropogenic changes, only remote sensing data can provide accurate and repeatable means of land cover analysis and monitoring.

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Remotely sensed data have been successfully used to study land cover changes at fine to coarse spatial scales. For example, Thematic Mapper data at 30-m resolution were used in the estimation of urban expansion [*Haack et al.*, 1987] and deforestation [*Green and Sussman*, 1990; *Skole and Tucker*, 1993]. On the other hand, advanced very high resolution radiometer (AVHRR) data at 1- and 16-km resolutions were used to estimate land cover at continental scales [*Malingreau and Tucker*, 1988; *Tucker et al.*, 1985; *Turner et al.*, 1993; *Houghton et al.*, 1993]. At present, all the global satellite databases are derived from the coarse-resolution AVHRR, therefore useful only to study large-scale changes in land cover [*Townshend et al.*, 1991; *Goward et al.*, 1993]. Earlier studies used satellite data primarily for land cover classification. However, recent work has shown that satellite data could be used to quantify biophysical variables such as leaf area index (LAI), canopy cover and fraction of Absorbed Photosynthetically Active Radiation [*Nemani and Running*, 1989; *Pierce et al.*, 1993; *Sellers et al.*, 1994; *Asrar et al.*, 1992].

Land cover is usually quantified by some measure of plant density. LAI, area of leaves per unit ground area, provides a simple measure of plant canopy density. LAI varies from less than 1 in deserts to greater than 10 over tropical rain forests; therefore changes in LAI can also be indicative of land cover change [*Woodward*, 1987]. LAI is widely used in land surface characterization and for estimating canopy energy and mass exchange processes. In this study we used LAI, instead of

vegetation classes, as a key parameter to estimate changes between climate- and soil-defined vegetation (potential) and actual vegetation. By using a biophysical variable (LAI), we assumed the influence of the inconsistencies in current vegetation classification schemes could be minimized.

The purpose of this paper is to present a quantitative analysis of the spatial distribution of global land cover changes. Our focus is on anthropogenic changes in land cover, which have occurred over extensive areas, between potential (natural conditions) and present vegetation.

Methods

To allow for global comparability, we define land cover changes only in terms of differences in maximum LAI. We believe the differences in seasonal maximum LAI are strong indicators of a land cover change and provide a much needed starting point for global land cover change analysis. Maximum LAI under potential and actual conditions for each 0.5° × 0.5° latitude/longitude grid cell was estimated as follows.

Potential LAI

To represent vegetation that would have existed before large-scale human influences began, we used a potential biome map, which uses biogeographic principles associating vegetation with long-term climate [*Leemans and Cramer*, 1990] and soil characteristics [*Zobler*, 1986], produced at 0.5° × 0.5° resolution. This geographic biome distribution is based on specific physiological responses of different plant types to cold tolerance, growing season heat sums, and drought stress [*Prentice et al.*, 1992]. Using the same climate and soils data, we also computed geographic variations in potential maximum LAI based on well-established principles of climate-soil-leaf area hydrologic equilibrium [*Eagleson*, 1982; *Nielson*, 1995; *Woodward*, 1987; *Nemani and Running*, 1989]. The hydrologic equilibrium theory (HET) suggests that plants adjust their leaf area to optimize the use of climate and soil resources. For example, areas with longer growing seasons of optimum temperature and water balance conditions support higher leaf area. This definition of vegetation does not account for natural disturbances such as fire, insects and diseases, and wind extremes on biome distribution.

We used BIOME-BGC, an ecosystem simulation model, to exploit the HET and estimate potential all-sided LAI for each 0.5° × 0.5° grid cell [*Running and Hunt*, 1991]. The model uses climate (solar radiation, humidity, air temperature, and rainfall), soil (texture and depth), and vegetation (biome, LAI) information to compute carbon (photosynthesis and respiration) and hydrologic budgets (interception, evaporation, transpiration, and outflow). Snowpack dynamics are simulated using air temperatures and rainfall. Vegetation, taken from potential biome map, is represented only as broadleaf, needle leaf, and grass.

For each grid cell the model starts with an absolute maximum LAI value of 10 [*Nielson*, 1995]. Stand LAIs greater than 10 are found in nature (10–15 [*Gholz*, 1982]), however, as an average grid cell value we chose 10 as the upper limit. Then, through an iterative process canopy, LAI is optimized until the peak canopy water stress is below critical level (predawn leaf water potential less than −2.0 MPa) and positive carbon balance (assimilation greater than respiration) is maintained at the end of the growing season [*Woodward*, 1987; *Nielson*, 1995].

Actual LAI

We used the National Oceanic and Atmospheric Administration (NOAA) Global Vegetation Index (GVI) data collected during 1985–1990 mapped to a 10-min grid. These data were calibrated by K. Gallo of NOAA and distributed by the National Geophysical Research Center, Boulder, Colorado. As we are interested in comparing only the maximum LAI that a particular area can achieve under potential versus actual conditions, we first computed a yearly maximum normalized difference vegetation index (NDVI) for the 6 years and then averaged the six maximum values. We assume this 6-year average maximum value to minimize the impact of cloud contamination, atmospheric influence, and interannual variability in climate. Finally, NDVI for each 0.5° × 0.5° grid cell was produced by taking an average of all the 10-min grid cells within each 0.5° × 0.5° area.

To account for the differences in structural and optical properties among different vegetation types, we used separate NDVI-LAI relations for grass (LAI = NDVI × 1.71 + 0.48 [*Asrar et al.*, 1985]), needle leaf (LAI = (NDVI/0.31)$\hat{0}$.26 [*Spanner et al.*, 1990; *Nemani and Running*, 1989]) and broadleaf canopies (LAI = (NDVI/0.26)$\hat{2}$ [*Pierce et al.*, 1993]). We used *Olson et al.*'s [1983] vegetation map to represent actual vegetation in terms of grass, needle, and broadleaf canopies. The empirical relations based on field studies were found to corroborate theoretically derived forms of NDVI-LAI relations [*Asrar et al.*, 1992; *Sellers et al.*, 1994]. For example, because of their canopy structure, needle leaf canopies have higher LAI per NDVI than do broadleaf canopies [*Sellers et al.*, 1994]. We acknowledge that the simple empirical relations do not account for problems like variations in background, atmospheric influences, and viewing geometry [*Asrar et al.*, 1992]. However, we believe that using only maximum NDVI values would reduce the impact of many of the above problems.

To quantify the changes in land cover we assumed an accuracy of plus or minus 1 for LAI in both cases [*Woodward*, 1987; *Nemani and Running*, 1989; *Pierce et al.*, 1993]. Further we also used a 20% of maximum LAI (5 for grass and shrubs, and 10 for forests) as a threshold for detecting changes. Grid cells with LAI differences less than 20% maximum for each biome are considered unchanged.

Land Cover Change and Climate

Radiometric surface temperature measured by orbiting satellite sensors such as AVHRR, though not always coupled to the ambient surface temperature, provide a useful measure of surface energy partitioning [*Price*, 1984]. Satellite observations show a strong linear relation between LAI and midafternoon surface radiometric temperatures (T_r), confirming the critical role vegetation plays in regulating surface climate [*Nemani et al.*, 1993; *Goward et al.*, 1985] (Figure 1). Contributions by soil evaporation and transpiration to surface latent heat flux vary with changes in LAI. Under dry soil surface conditions (no soil evaporation), a strong relation is generally observed between LAI and T_r over a wide range of vegetation types [*Nemani et al.*, 1993; *Goward et al.*, 1985; *Choudhury*, 1991; *Smith and Choudhury*, 1990]. For example, satellite observations over deforested areas of Amazonia, Brazil, clearly show a reduction in LAI and an associated increase in T_r by as much as 14°C (Plate 1). Since surface temperature provides a key link between land cover and climate, we used the relation in Figure 1 to express the magnitudes and spatial extent of global land cover changes in terms of T_r. We must note that T_r from satellites is generally

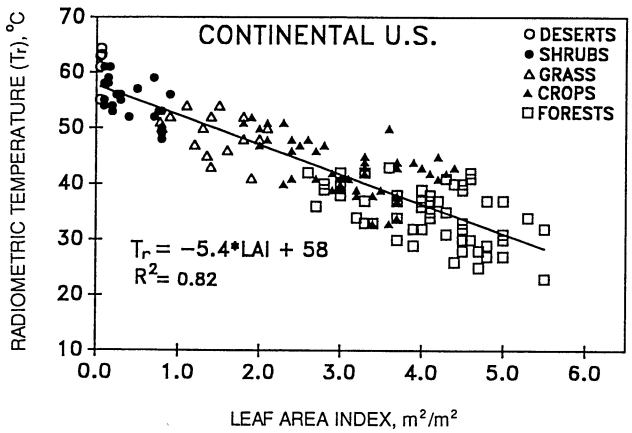

Figure 1. Observed relation between afternoon radiometric surface temperature (T_r) and leaf area index (LAI) over the continental United States from 1-km advanced very high resolution radiometer (AVHRR) data collected between July 1 and 15, 1992. Data from 110 locations falling on six north-south transects across the continental United States were extracted. Each point represents an average of four 1-km pixels. T_r was estimated from channels 4 and 5 and represents instantaneous temperature under clear sky, midsummer, afternoon conditions implicitly selected by the automated compositing of satellite data [*Price*, 1984]. LAI was derived by translating normalized difference vegetation index (NDVI) (channels 1 and 2), using a land cover map [*Loveland et al.*, 1991] and biome specific NDVI-LAI relations (see text).

greater than T_s simulated by climate models; the magnitude of their differences depend on aerodynamic roughness and wind speed [*Choudhury*, 1991].

Results and Discussion

Global Land Cover Changes

Spatial distributions of LAI under potential and actual conditions are shown in Plate 2. LAIs ranging between 0 and 10, strongly driven by climate gradients, are observed in both cases. Spatial variation in actual LAI is higher in many parts of the world (Asia, Africa, and Europe); presumably this is due to anthropogenic processes. At 0.5° × 0.5° resolution these LAI estimates are difficult to validate. However, geographic variations of LAI followed general trends of LAI observed on the Oregon coast, United States [*Gholz*, 1982], Australia [*Specht and Specht*, 1989], and tropical rain forests [*Woodward*, 1987].

Agriculture and human settlements replacing native forest vegetation with high potential LAI resulted in a decrease in LAI, as in the case of southeast Asia, Africa, Madagascar, India, and western Europe. On the other hand, crops replacing native vegetation in arid and semiarid areas, for example, the central valley of California, Australia, the midwestern United States, and parts of northern India, resulted in an increase in LAI over potential conditions. Increase in population and the associated pressures on natural resources have been identified as chief causes of land cover changes [*Flint and Richards*, 1991; *Myer and Turner*, 1994; *Houghton*, 1994; *Turner et al.*, 1993]. Results from this study show that areas with high population densities such as India, China, and western Europe also exhibited the largest changes in LAI [*Myer and Turner*, 1994].

Land Cover Changes and Climate

Global changes in LAI were translated to changes in surface radiometric temperatures (T_r) using the relation shown in Figure 1. The changes in T_r represent possible deviations from ambient surface temperatures with potential vegetation, under midsummer, midafternoon conditions (high solar radiation intensity) (Plate 3). Large areas in China, India, Bangladesh, and western Europe show increase in T_r ranging from 8°–16°C. Croplands in arid and semiarid areas show a decrease in T_r of 4°–8°C compared to potential vegetation. This scenario is particularly evident in several regions around the world (midwestern United States, Australia, etc.) where extensive irrigation is used. Managed ecosystems such as forest plantations (southeastern United States) and dryland farming (central Canada, central Europe) also show a decrease in T_r.

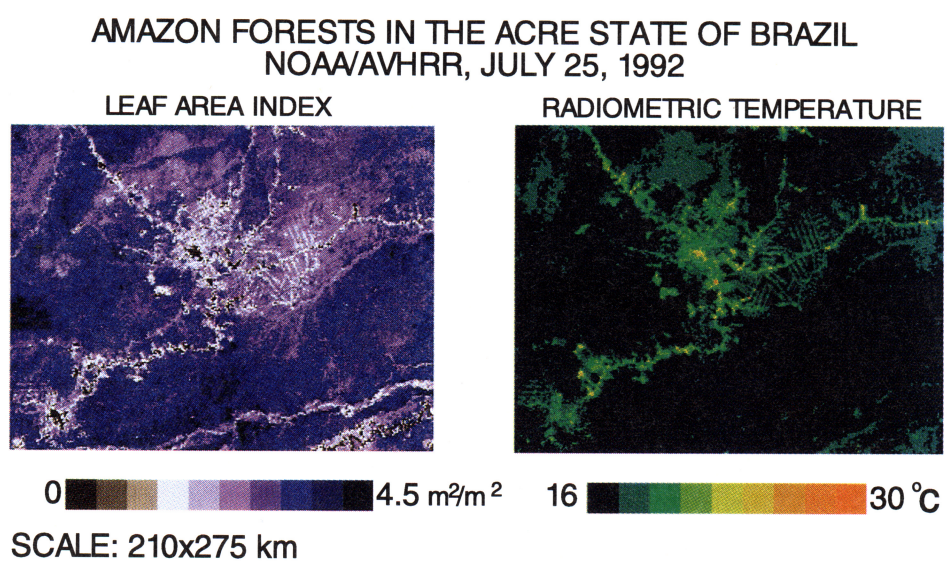

Plate 1. Impact of deforestation on LAI and radiometric surface temperature over tropical rain forests of Amazonia observed from AVHRR data collected at 1450 UT on July 25, 1992. The fish bone patterns from forest clearing and road construction in this 200 km × 300 km area from the Acre state of Brazil illustrates the local impacts of deforestation on surface temperature and the ability of satellite data to monitor such land use changes [*Malingreau and Tucker*, 1988].

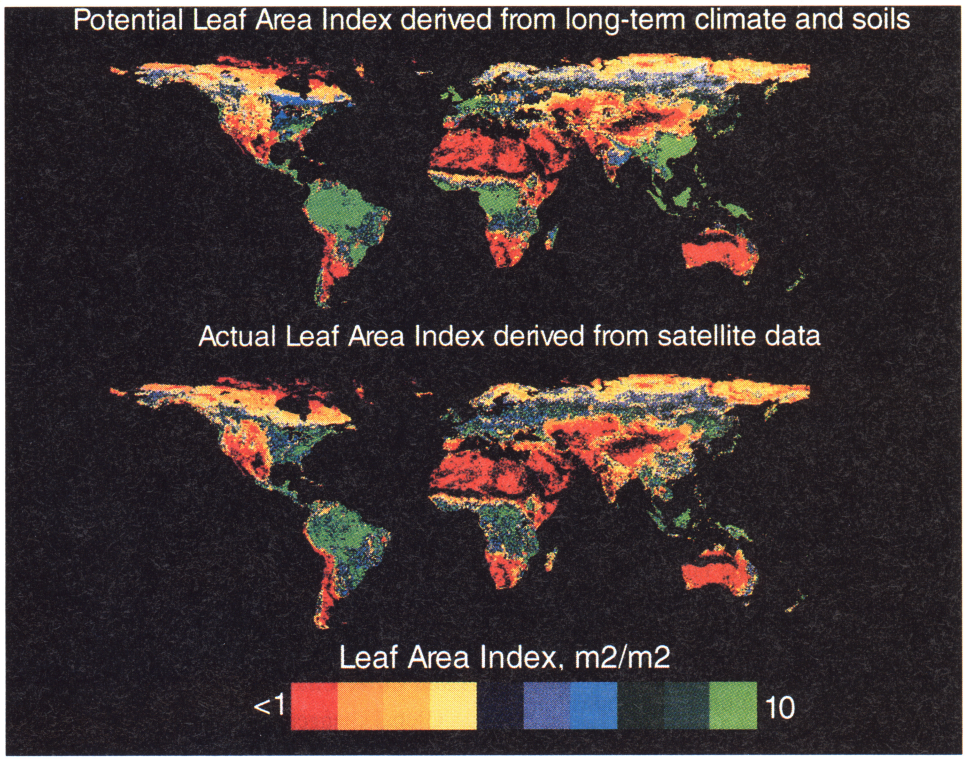

Plate 2. Spatial distributions of potential LAI, derived from climate-soil-leaf area hydrologic equilibrium using long-term climate and soils data, and actual LAI estimated from coarse-resolution NOAA/AVHRR data.

Few areas showed spuriously high amounts of land cover change. Notable among these are Llanos of South America and Cape York peninsula of Australia. In Llanos climatic potential for vegetation is limited by seasonal flooding that arrests plant growth; this is not accounted for in potential LAI estimation. In Australia we found the extrapolated long-term climate to be wetter than existing conditions, leading to high potential LAI over Cape York peninsula.

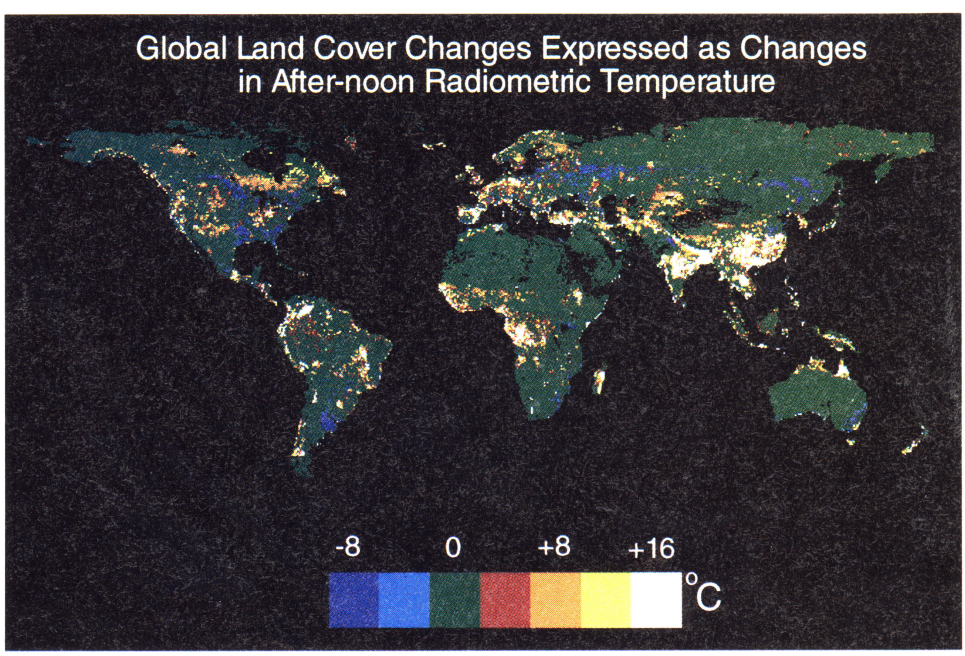

Plate 3. Changes in global land cover as a result of human activities, expressed as differences in afternoon radiometric temperatures (T_r). The changes in T_r represent deviations from ambient surface temperatures under natural vegetation during midsummer, clear sky conditions. Increases in T_r result from deforestation, while decreases in T_r are due to irrigated agriculture.

It is important to realize that changes in T_r, as a result of changes in LAI, are only indicative of maximum possible changes under clear weather, midafternoon conditions, and should be interpreted with caution. Because of the poor coupling between T_r and T_s, the actual changes in T_s would be much smaller in magnitude [*Choudhury*, 1991]. Accurate assessment of the impact of land cover changes can only be done with climate models using potential and actual vegetation parameters as inputs.

Phenological differences between forests and crops replacing forests with low canopy cover during springtime may also enhance the warming effect. Such a scenario is common over much of the temperate latitudes. These springtime changes in energy partitioning may be partly responsible for the consistent increase in global air temperatures during April and May [*Swartz and Karl*, 1990]. We are currently working on producing monthly LAIs for potential and actual conditions, which should improve seasonal land surface representation in GCMs.

Estimated land cover changes (Plate 3) seem to indicate that spatial heterogeneity in heat fluxes, the most important factor in altering local- to regional-scale circulation patterns, is likely to have increased from preagricultural times [*Pielke and Avissar*, 1990; *Segal and Aritt*, 1992]. Strong horizontal thermal contrasts exhibited in Plate 3 are found to be sufficient to trigger circulation patterns leading to severe thunderstorm activity that may not have occurred in preagricultural times [*Anthes*, 1984]. As a result, these mesoscale effects are now deemed necessary to be included in weather prediction and environmental assessment [*Cotton and Pielke*, 1994]. The predominantly local- to regional-scale changes in vegetation roughness, albedo, and wetness from irrigation, and the corresponding changes in surface fluxes are not well represented in current coarse-resolution general circulation models (GCMs) [*Li and Avissar*, 1994]. Advanced GCMs with appropriate spatial resolution are needed to study the impact of land cover changes on global climate.

Finally, we would like to emphasize that land cover changes from our approach should be viewed only as gross features useful for global carbon and climate models. Accurate estimation of LAI at $0.5° \times 0.5°$ resolution is not an easy task even with ground-based methods. While the techniques for computing potential and actual LAI are validated at stand level, their global application relies heavily on the quality of input data. In spite of the constraints with climate extrapolation, soils data, and spatial resolution associated with our potential LAI and actual LAI estimates, our analysis seems to provide a relatively accurate picture of land cover changes useful for global models. Significant improvements in the analysis can be made with better global data sets. For example, AVHRR data from the Pathfinder effort is better calibrated and comes at an 8-km resolution compared to the 16-km GVI. The proposed algorithms for the Earth Observing System–era sensors such as the moderate-resolution imaging spectrometer (MODIS) would account for various problems that limit application of current AVHRR products [*Running et al.*, 1994b]. Change detection is a highly scale-dependent process. While top-down approaches such as this study provide rough estimates, high-resolution studies along with cause-to-cover relations must be pursued [*Skole and Tucker*, 1993].

Conclusions

Consistent and accurate monitoring of global land cover changes required in many global change issues is possible using satellite data [*Townshend et al.*, 1991; *Running et al.*, 1994b]. Changes in surface temperature resulting from land cover changes is an important aspect of climate change that needs to be better quantified. Land cover changes also produce several indirect effects on climatic processes through the release of CO_2 from deforestation, biomass burning, trace gas emissions, land degradation leading to an increase in albedo, and changing hydrologic retention. Better monitoring of land cover changes and resulting biophysical responses is necessary to understand the true impacts of land cover changes on global environment and habitability.

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