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DRIVING TERRESTRIAL ECOSYSTEM MODELS FROM SPACE

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Introduction

Regional air pollution, land-use conversion and projected climate change all affect ecosystem processes at large scales. Changes in vegetation cover and growth dynamics can impact the functioning of ecosystems, carbon fluxes, and climate (NRC, 1988; IGBP, 1990). As a result, there is a need to assess and monitor vegetation structure and function comprehensively at regional to global scales.

To provide a test of our present understanding of how ecosystems operate at large scales we can compare model predictions of CO_2, O_2 and methane exchange with the atmosphere against regional measurements of interannual variation in the atmospheric concentration of these gases (Mattthews and Fung, 1987; Tans et al., 1990). Recent advances in remote sensing of the Earth's surface are beginning to provide methods for estimating important ecosystem variables at large scales. Ecologists attempting to generalize across landscapes have made extensive use of models and remote sensing technology (Tucker et al., 1986; Running et al., 1989). The success of such ventures is dependent on merging insights and expertise from two distinct fields. Ecologists must provide the understanding of how well models emulate important biological variables and their interactions; experts in remote sensing must provide the biophysical interpretation of complex optical reflectance and radar backscatter data.

Ecosystem models quantify the movement of carbon, water, and nutrients within and through terrestrial ecosystems and keep balance sheets on a daily, monthly, and annual basis. These models consider the source and fate of matter and energy that enter and leave ecosystems as a result of specified processes such as photosynthesis, respiration, decomposition, and the uptake and recycling of nutrients.

Through the process of photosynthesis, leaves of plants capture CO_2 to make simple sugars while producing O_2. Respiration returns CO_2 to the atmosphere using sugars in the growth process to construct complex organic compounds and to maintain living cells. Transpiration moves liquid water carrying dissolved nutrients from the soil through the vascular system of plants to the leaves where water evaporates into the atmosphere. Decomposition is performed by microbes that utilize organic substrates, recycling nutrients and releasing gaseous products such as methane and CO_2 to the atmosphere. To drive ecosystem models from space requires recognizing those structural features and environmental controls that affect the rates of key processes (the role of ecologists) and then finding ways of interpreting these variables remotely from space (the role of remote sensing experts).

Because this is a SAR workshop, I will mention some special contributions that synthetic aperture radar may make in improving the estimates of fluxes from global-scale ecosystem models. My main theme, however, is to emphasize the value gained by combining information from a number of sensors to obtain confidence through independent estimates of critical variables and to predict relationships impossible to obtain from single sensors alone.

Estimating Photosynthesis from Space

The upper limit on photosynthesis, given a specified atmospheric CO_2 level, is set by how much chlorophyll pigment can be packed into a landscape and by the amount of visible light intercepted by the chlorophyll. At any given latitude, on any given date, the solar radiation reaching the atmosphere is known. The challenge is to estimate the effects of clouds on attenuating the radiation through the atmosphere. Daily satellite-derived estimates of cloud cover can be made with a number of sensors. The TOMS (Total Ozone Mapping Spectrometer) satellite, which measures reflectance in ultraviolet waves lengths, provides monthly integrated estimate of visible radiation reaching the vegetation that correspondence directly with measurement recorded at ground stations (Eck and Dye, 1991).

The amount of chlorophyll available to intercept light can also be estimated at monthly intervals from observing seasonal changes in the greenness of vegetation using the NOAA AVHRR series of weather satellites. The Normalized Difference Vegetation Index (NDVI), estimated from near-infrared and red reflectance measurements, is closely related to the chlorophyll content and the photosynthetic capacity of the vegetation (Yoder, 1992 ; Goward and Huemmrich, 1992). Adverse conditions for plant growth reduce this "greenness index" whereas improved conditions favor increases in the index in response to added synthesis of chlorophyll.

Frequently, environmental conditions constrain photosynthesis below the potential established by the amount of visible light absorbed by chlorophyll. For example, stomatal pores close and halt all photosynthesis when leaves freeze at 0 to -2° C. Thermal sensors, coupled with measurements of NDVI, provide good estimates of ambient air temperatures on clear days when most extreme conditions occur (Fig. 1). Fundamental to predicting air temperature from satellites is the realization that (a) dense canopies of tall vegetation associated with maximum values of NDVI are within 2°C of ambient air and (b) that air temperatures can be estimated for less dense vegetation by linear extrapolation of the surface temperature/NDVI response to the maximum NDVI reference (Fig. 2). Because of a large change in dielectric constant when water freezes in the stems and branches of perennial plants, synthetic aperture radar provides an alternative means of evaluating freezing conditions (Way et al., 1990).

In the unfrozen state, plant tissue varies in turgor and in water content. This variation in water status affects growth, photosynthesis, and transpiration in different ways. When water moves rapidly through the vascular system of plants some of the water columns in capillaries may break. As an adaptation, plants have evolved to close their stomata when flow rates approach critical levels during the day (Tyree and Sperry, 1988).

Because CO_2 enters through stomata, closure of these pores reduces photosynthesis as well as transpiration.

The driving force on transpiration and the movement of water through plants is the humidity deficit established between the water-saturated cells within leaves and the air immediately surrounding. The absolute humidity of the air can be estimated using two different thermal bands, one sensitive to water vapor in the atmosphere and one insensitive (Justice et al. , 1991). NOAA weather satellites (Advanced Very High Resolution Radiometer) provide the required combination of red, near-infrared, and two thermal bands to derive simultaneous estimates of the absolute humidity of the atmosphere along with estimates of ambient air temperature near the ground (Goward et al., 1993). With these two values the humidity deficit of the air around the vegetation can be calculated on clear days and a judgement made as to the extent that transpiration and photosynthesis are constrained below potential rates.

Ecosystem models are particularly sensitive to the water status of vegetation at night when transpiration ceases and no (or very little) water uptake from the roots occurs. Under sustained drought, as progressively more water is extracted from the rooting zone, tension is placed on capillary water columns. Predawn measures of tensions on these water column allow prediction of how wide stomata can open the following day to permit photosynthesis and transpiration to proceed (Fig. 3).

It is extremely difficult to estimate the rooting depth of vegetation and even more difficult to define the amount of water available, yet both of these variables plus daily precipitation are required by most ecosystem models to calculate a water balance and derive estimates of predawn plant water tensions. As an alternative, Goward et al. (1993) has demonstrated a correlation between the steepness of the Temperature/NDVI relationship (Fig. 2) and measured predawn water tensions (see also Nemani and Running, 1989; Goward and Hope, 1989). The relationship proved useful in estimating predawn water stress in a Douglas-fir/oak woodland in Oregon during summer months (Fig. 4). The relationship is empirical, however, as illustrated by lack of correlation at times when small amounts of precipitation affected surface wetness but did not reach the roots.

Synthetic aperture radar, in principle, offers a more straight forward biophysical basis for estimating predawn tensions or a combined index that reflects major reductions in the hydraulic conductivity of branches and stems (Running and Waring, 1978). One would expect a reduction in the dielectric constant of the free water in conducting tissue, and accordingly, a reduced backscatter from L or P-Band radar (Narayanan and Vu, 1992). Diurnal variation in water tension is not nearly as useful in interpreting constraints of ecosystem processes (McDonald et al., 1992). On the other hand, if SAR can define progressive reduction in stem and branch water content during periods of high evaporative demand and restrictive soil water supply, it would provide a biophysically sound and more integrative basis for recognizing water stress on vegetation.

Ecosystem models that include just those variables that constrain photosynthesis predict measured forest growth across a steep environmental gradient in Oregon rather well (Fig. 6). In the analysis, the effective or utilized visible radiation ranged from over 90% of all that intercepted by maritime coastal forests (Sites 1a & 1h) to less than 25% of the radiation intercepted by juniper woodland (Site 6).

Estimating Plant and Soil Respiration from Space

Respiration associated with maintaining living cells increases with temperature and with the amount of protein in living biomass (Ryan, 1991). The leaves of plants contain the most active cells, the branches and stems contain progressively fewer live cells per unit weight. X-band (but not C-band) SAR shows potential for estimating the fresh weight of foliage, although seasonal and diurnal variation in leaf-water content may confound interpretations. Stem and branch biomass can be estimated with addition of L-band, but only up to levels of biomass in the range of 100-150 metric tons of dry weight per hectare (Ranson and Sun, 1992; Dobson et al., 1992). Other approaches using optical sensors offer a wider range of predictive abilities before saturating (See Fig. 5; Li and Strahler, 1986).

Soil respiration of CO_2 is also a function of temperature. Respiration from the surface litter decreases with drought; the drying of litter is related closely to the increased steepness of the Temperature/NDVI relationship described earlier. Energy balance equations can be applied to estimate soil temperatures and thermal sensors have been used to infer heat storage capacity (Luvall and Holbo, 1989).

Methane production from soils is a special kind of microbial respiration particularly important in the tundra region of the Northern Hemisphere where a combination of standing water and hollow sedges offer a uniquely active environment for the generation of methane (L.A. Morrissey, NASA Ames Research Center; S.L. Durden, J.P.L., personal communication). The ability of SAR (C-band, VV polarization) to distinguish standing water and the upright stems of sedges provides an accurate measure of where methane production in the tundra is concentrated. SAR should offer a similar ability to identify subtropical and temperate rice paddies and other vegetation types that are periodically inundated and under such conditions produces methane in some abundance.

Summary

Ecosystem models predict many variables that can not be easily sampled over broad areas in a timely manner that reflects inter- and intra-annual variation in the rates of important processes. The net exchange of CO_2 and other important trace gases, however, can be generated from ecosystem models. What is lacking is the means of initializing and driving these models at regional and global scale under continually changing conditions. To this end, satellites carrying a variety of remote sensing instruments appear the best means of testing the general reliability of regional-scale models. Some ecosystem variables require almost continuous monitoring such as cloud cover, as this affects the daily solar radiation reaching the Earth's surface. Other variables such as the "greenness" of the landscape may be recorded less frequently, dependent upon the degree of change seasonally.

There are advantages in synchronous coverage as shown in estimating vegetation greenness, ambient air temperature, surface wetness, and the humidity deficit of the atmosphere . By combining these series of remotely sensed observations limits on rates of photosynthesis, transpiration, respiration, nutrient uptake, and other ecosystem processes may be possible with present satellite technology. An evaluation of standing biomass and other structural characteristics of vegetation is required less frequently and therefore can be made at finer spatial resolution. Future satellites equipped with synthetic aperture radar (L and P bands) should be able to provide estimates of standing biomass below levels of about 150 metric tons/hectare. SAR appears ideal for recognizing some unique combinations of standing water and low stature vegetation associated with high rates of methane production in tundra and other landscapes. SAR also appears well suited to identify when vegetation is frozen. One of the most intriguing possibilities is that SAR technology may be able to provide a more direct biophysical measure of vegetation experiencing drought-stress than any other remote sensing system. This latter possibility warrants careful testing and documentation across a range of vegetation.

References

Eck, T., and D. Dye. 1991. Satellite estimation of photosynthetically active radiation at the Earth's surface. Rem. Sens. Envir. 38: 135-146.

Dobson, M.C., F.T. Ulaby, T. LeToan, A. Beaudoin, E.S. Kasischke, and N. Christensen. 1992. Dependence of radar backscatter on coniferous forest biomass. IEEE Transactions on Geoscience and Remote Sensing 30:412-415.

Goward, S.N., and A.S. Hope. 1989. Evapotranspiration from combined reflected solar and emitted terrestrial radiation: preliminary FIFE results from AVHRR data. Adv. Space Res. 9:239-249.

Goward, S.N., and K.F. Huemmrich. 1992. Vegetation canopy PAR absorptance and the normalized difference vegetation index: an assessment using the SAIL model. Rem. Sens. Envir. 39:119-140.

Goward, S.N., R.H. Waring, D.G.Dye, and J. Yang. 1993. Ecological remote sensing at OTTER: regional satellite observations. Ecol. Appl. (in review).

IGBP (International Geosphere Biosphere Programme). 1990. The International Geosphere Biosphere Programme: a study of global change. The Initial Core Project's Report, No. 12. The International Council of Scientific Unions. Stockholm, Sweden.

Justice, C.O., T. Eck, D. Tanre, and B.N. Holben. 1991. Effect of water vapor on the normalized difference vegetation index derived for the Sahelian Region from NOAA AVHRR data. Int. J. Rem. Sens. 12:1165-1188.

Li, X. and A.H. Strahler. 1986. Geometric-optical bidirectional reflectance modeling of a conifer forest canopy. IEEE Trasactions of Geoscience Remote Sensing 24:906-919.

Luvall, J.C. and H.R. Holbo. 1989. Measurements of short-term thermal responses of coniferous forest canopies using thermal scanner data. Rem. Sens. Envir. 27: 1-10.

Matthews, E., and I. Fung. 1987. Methane emissions from natural wetlands: global distribution, area and environmental characteristics of sources. Global Biogeochem. Cycles 1:61-86.

McCreight, R.W., R.H. Waring, and S.N. Goward. 1993. Ecological remote sensing at OTTER: ultralight aircraft site-scale observations. Ecol. Applic. (in review).

McDonald, K.C.., R. Zimmermann, J.B. Way, and R. Oren. 1992. An investigation of the relationship between tree water potential and dielectric constant. pages 523-525. In: Proceedings of the Int. Geoscience and Remote Sensing Symp., IGARSS'92, Houston, Texas, May 26-29.

Narayanan, R.M. and K.T. Vu. 1992. Microwave sensing of moisture content in selected fruits and vegetables. pages 1181-1182. In: Proceedings of the Int. Geoscience and Remote Sens. Symp., IGARSS' 92, Houston, Texas, May 26-29.

Nemani, R.R., and S.W. Running. 1989. Estimation of surface resistance to evapotranspiration from NDVI and thermal-IR AVHRR data. J. Climate and Appl. Meteorology 28:276-294.

NRC (National Research Council). 1988. Toward an understanding of global change: initial priorities for U.S. contributions to the International Geosphere Atmoposhere Program. National Academy Press, Washingtion, D.C.

Ranson, K.J. and G. Sun. 1992. Mapping biomass for a northern forest ecosystem using multi-frequency SAR data. Proceedings of the Int. Geoscience and Remote Sensing Symp. IGARSS' 92 II:1220-1222.

Tans, P.P., I.Y. Fung, and T. Takahashi. 1990. Observational constraints on the global atmospheric CO_2 budget. Science 247:1431-1438.

Tucker, C.J., I.Y. Fung, C.D. Keeling, and R.H. Gammon. 1986. Relationshipo between atmospheric CO_2 variations and a satellite-derived vegetation index. Nature 319:195-199.

Tyree, M.T., and J.S. Sperry. 1988. Do woody plants operate near the point of catastrophic xylem dysfunction caused by dynamic water stress? Plant Physiol. 88:574-580.

Running, S.W., R.R. Nemani, D.L. Peterson, L.E. Band, D.F. Potts, L.L. Pierce, and M.A. Spanner. 1989. Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation. Ecology 70:1090-1101.

Runyon, J., R.H. Waring, S.N. Goward, and J.M. Welles. 1993. Environmental limits on above-ground production: observations from the Oregon transect. Ecol. Applic. (in review).

Ryan, M.G. 1991. The effect of climate change on plant respiration. Ecol. Appl. 1:157-167.

Waring, R.H., and S.W. Running. 1978. Sapwood water storage: its contribution to transpiration and effect upon water and conductance through the stems of old-growth Douglas-fir. Plant, Cell and Environment 1:131-140.

Waring, R.H. and W.H. Schlesinger. 1985. Forest ecosystems: concepts and management. Academic Press, Orlando, Fla.

Way, J.B., J. Paris, E. Kasischke, C. Slaughter, L. Viereck, N. Christensen, M.C. Dobson, F. Ulaby, J. Richards, A. Milne, A. Sieber, F. Ahern, D. Simonett, R. Hoffer, M. Imhoff, and J. Weber. 1990. The effect of changing environmental condions on microwave signatures in forest ecosystems: preliminary results of the March 1988 Alaskan aircraft SAR experiment. Int. J. Remote Sens. 11:1119-1144.

Yoder, B. J. 1992. Photosynthesis of conifers: influential factors and potential for remote sensing. Ph.D. thesis, Oregon State University, Corvallis, OR.

Figure Captions

Fig. 1. Ambient air temperatures for twelve months were estimated from remotely sensed temperature measurements and vegetation "greenness obtained from NOAA AVHRR weather satellite for a series of sites ranging from temperate rainforest to juniper woodland (Goward et al. (1993).

Fig. 2. On a 9 X 9 km grid, AVHRR thermal sensors were used to estimate surface temperature (Ts) on a drought-prone ponderosa pine forest with variable stocking density. When the 81 separate estimates of surface temperature were analyzed in conjunction with paired estimates of vegetation greenness (NDVI), the ambient air temperature could be estimated by extrapolating the relationship to the maximum NDVI, representing a canopy intercepting more than 99% of all visible radiation (Goward et al., 1993).

Fig. 3. Under static conditions of no transpiration at night, tension measured on the water columns of twigs (predawn water potential) predicts the extent that stomatal will open during the day (Waring and Schlesinger, 1985).

Fig. 4. Seasonal comparison of predawn leaf water potential measurements and the NDVI/Ts slope were derived from near-infrared, red, and thermal channel measurements obtained from an ultralight aircraft flying at 300 m altitude. A steeping slope of the NDVI/Ts relationship correlates well with increasing drought stress measured on Douglas-fir trees, but some deviation occurs following small storms that only wet the surface litter (McCreight et al., 1993).

Fig.5. Classification of shadow in video images of forests correlate well with forestry estimates of above-ground foliage and woody biomass up to levels near 700 Mg/ha (McCreight et al., 1993).

Fig. 6.An ecosystem model that evaluates the light utilized by photosynthesis on an annual basis correlates well with observed above-ground growth of forests across a transect in Oregon. Only where forests have reached maximum height (Site 1, old-growth) was it necessary to take into account the increased respiration and reduced hydraulic conductivity of older trees to match observed growth (Runyon et al., 1993).

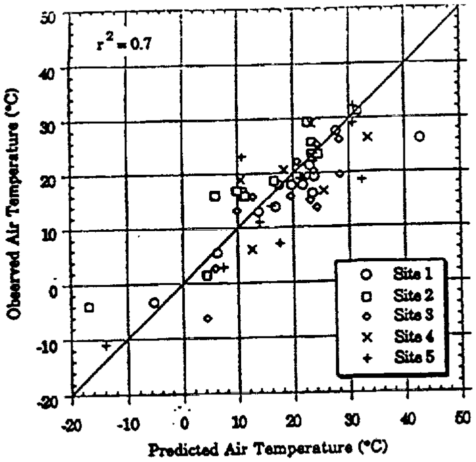

Figure 1

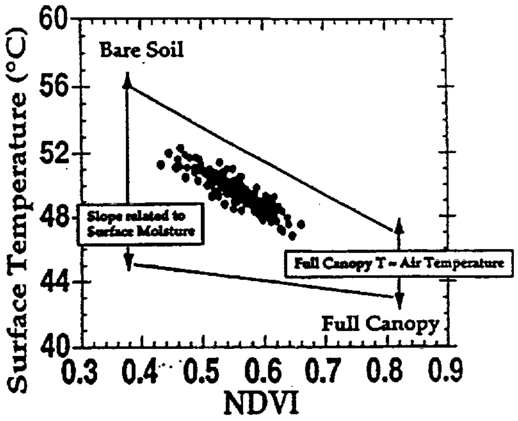

Figure 2

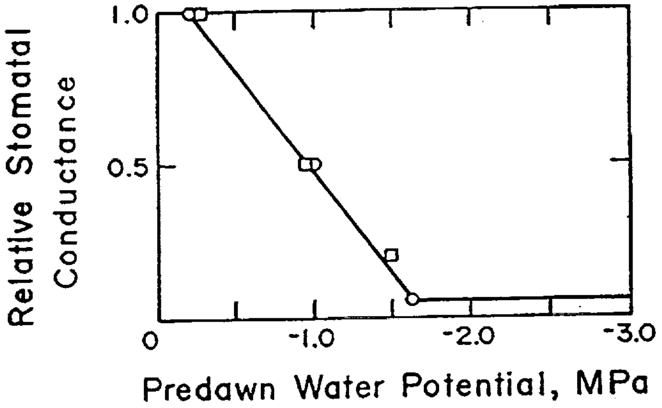

Figure 3

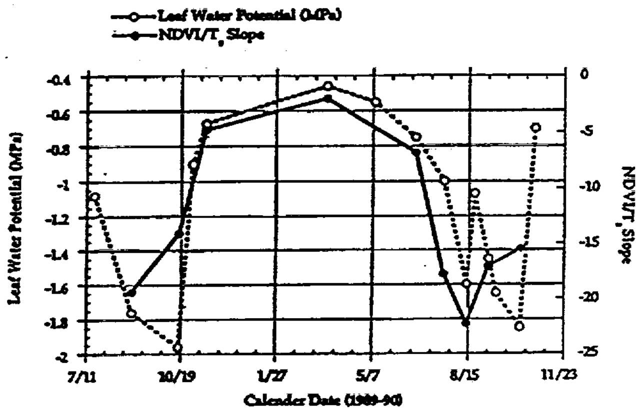

Figure 4

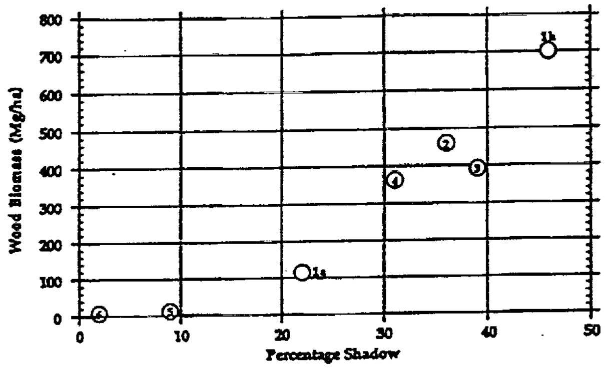

Figure 5

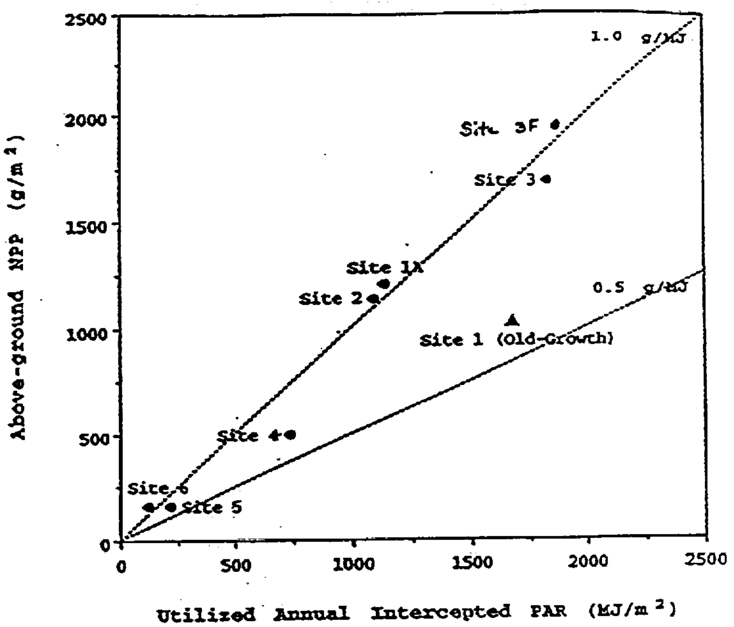

Figure 6