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SOIL–PLANT–ATMOSPHERE CONTINUUM

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Introduction

The dominant distinguishing feature of the Earth, in comparison with all other celestial bodies we observe, is the presence of life. Humans, as a part of life on Earth, attempt to understand all of the life system, albeit from an anthropocentric perspective. James Lovelock proposed a perspective that was unsettling to some and appealing to others when he suggested that the entire Earth may be functioning as a living organism. As our integrative understanding of living systems within the soil–plant–atmosphere continuum (SPAC) grows, the idea that a whole ecosystem can function as a living entity becomes more acceptable.

Consider a terrestrial ecosystem on land: The most essential ingredient for life on Earth is water and most of the water is not on the land. However, a rapid, long-distance system for transporting water from oceans to land is available through the atmosphere, much like the xylem system in a tree, which transports water long distances (relative to cell sizes) from the soil to the leaves high above the ground. This long-distance atmospheric transport system is driven unceasingly by the uneven, solar heating of the Earth. On the land, where many organisms reside, water moves much more slowly through the soil than through the atmosphere and this provides an essential storage reservoir that maintains the critical continuous flow of water to plants in the presence of fluctuations in the atmospheric supply. The rapid atmospheric transport system that is so critical to moving water from the ocean to the land also fluctuates wildly over the life span of most organisms. The combination of a low-storage, highly fluctuating system for rapid global transport in the atmosphere and a large-storage, stable, low-flow buffer in the soil redistributes water over the Earth to sustain life on land. This is a highly structured system like an organism. Furthermore, the living systems exert a strong influence on this larger system to enhance their functioning, just as we humans modify our environment to improve our lot.

Water is the most obvious component of the SPAC, and the interaction of this water with energy is the cornerstone of our understanding of how life interacts with its environment. Every schoolchild learns the water cycle: evaporation of liquid water from surfaces supplies water vapor to the atmosphere, where air currents lift this water to heights that cool it and cause condensation of the water vapor back to the liquid form of droplets, which fall back to the Earth to be recycled. The extraction of energy from the surface as a result of evaporation and the release of energy to the atmosphere by condensation represent the primary means by which the energy from the sun ultimately warms the atmosphere. This 'latent heat,' which is associated with the change of phase of water between liquid and vapor states, and not a temperature change, provides the key feedback between water and energy cycles that stabilizes the soil–plant–atmosphere system, permitting it to sustain life.

Materials such as water flow through the ecosystem seamlessly, moving from place to place, serving innumerable functions, and consuming or releasing energy to achieve a phase suitable to the medium that contains it. This is the SPAC; 'continuum' here does not refer to the material storage forms so apparent to our eyes such as plant leaves or roots, lakes, raindrops, the soil itself, or even the air we breathe; rather it refers to the unimpeded flow of many forms of material and energy throughout an elegant system for sustaining life on land. Animals are as much a part of this system as plants, but in this article plants are our emphasis. This ceaseless flow of material and energy sustains life at every level; from the molecular interactions that sustain and mutate the genetic 'memory,' to cellular processes that make up whole organisms, to the global level of a living, breathing planet.

Living systems cycle matter through the SPAC and themselves to create and maintain their structure and extract energy for powering their life functions. All material necessary for sustaining life is cycled on all spatial levels from subcellular to global. The connectedness and functioning of the SPAC can be illustrated by reference to water, the most critical mass constituent to life on Earth. However, understanding the SPAC through water will necessarily involve some considerations of at least carbon and energy.

Fundamental Principles

Two general principles are indispensable for studying the SPAC: (1) the conservation principles that take the form of mass and energy 'budgets,' and (2) the transport principles that relate the flow of some quantity to the difference or gradient of other quantities that influence or 'force' the flow and describe the 'state' of the exchange process.

The principles of conservation of mass and energy are the backbone of integrative studies of the SPAC. Because mass and energy can take many forms as they move throughout the SPAC, and even interact with each other, budgets are constructed to quantify the important stores and flows of important life-enabling constituents such as water, carbon, or energy. A budget is simply the application of the conservation principles (mass or energy) to a specific system that must be carefully defined. This system may be defined as a leaf, a community of plants, or even the entire Earth. Like balancing a bank account, a budget is a formal statement of the following: Incoming quantity minus outgoing quantity equals the increase in storage of the quantity in the system. In the case of water (W), carbon (C), and energy (E), the budgets become the following (Figure 1):

$$W_{\mathrm{IN}} - W_{\mathrm{OUT}} = \Delta W$$

$$C_{\mathrm{IN}} - C_{\mathrm{OUT}} = \Delta C$$

$$E_{\mathrm{IN}} - E_{\mathrm{OUT}} = \Delta E$$

The intertwined budgets of water, carbon and energy inflow, outflow and storage within the soil–plant–atmosphere system are shown in Figure 1. Understanding the SPAC through the role of water will involve simultaneous consideration of carbon and energy budgets on a spatial scale appropriate for living systems.

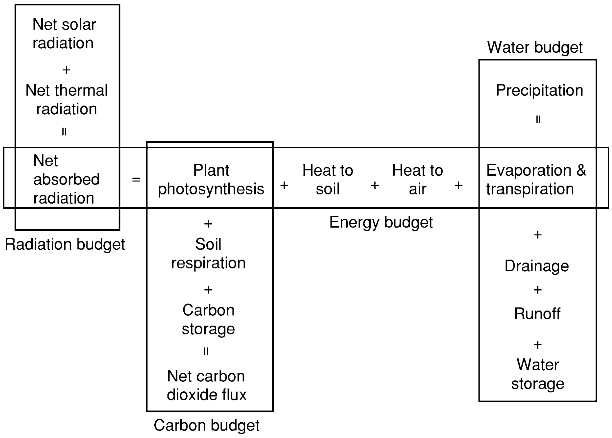

Figure 1 The interlocking energy and mass budgets for water, carbon, and energy in the soil–plant–atmosphere continuum. Altering individual components can cascade through the system and affect many seemingly unrelated factors.

Consider the energy budget: Energy can exist in many forms as it flows through the soil–plant–atmosphere system, and the energy budget represents a way to keep track of the energy, no matter what its form. The rate of energy flow (joules per second = watts) per unit of area (meters squared) is a convenient way to describe the energy budget for a particular land area, because the size of the area does not matter and the emphasis can be on the energy exchanges. The radiant energy from the sun and surroundings can be absorbed by a leaf (this is referred to as the net radiation) and be transformed to the following: (1) sensible heat energy that is convected away from the leaf by moving air that is cooler than the leaf; (2) latent energy in molecules of water that are converted from liquid to vapor inside the leaf as they are transpired (evaporated) from the leaf; and (3) biochemical energy in the form of organic compounds such as sugars and starches created through photosynthesis and other physiological processes to sustain life. These components of the leaf energy budget are shown in Figure 1.

The transport principle simply states that the flow of some quantity such as water is equal to an appropriate 'driving force' divided by a resistance to transport exerted by the various media through which the quantity moves. The transport principle is more difficult to use than the conservation principle because the 'driving forces' and transport resistances depend on the characteristics of the system and mechanism of transport. For example, the diffusion of liquid water depends on the water potential difference across a hydraulic transport resistance, whereas the transport of water vapor depends on the water vapor pressure difference across a diffusive transport resistance. In addition, movement of liquids or vapor by mass flow is 'driven' by pressure differences across transport resistances. In general, diffusion is an effective mode of transport over small distances, but mass flow can move materials and energy over longer distances. Heat transport is driven by temperature differences. The relevant thermal resistance depends on whether the heat is moving through a solid such as soil (conduction, which is analogous to diffusion), or through a moving fluid such as air (convection, which is analogous to mass flow and is a much more rapid transport mechanism than diffusion). Heat transport by radiation depends on still-different formulations. Thus much research on the SPAC relates to determining appropriate transport resistances and state variables for characterizing the flow of important quantities throughout the system. A complete understanding of this soil–plant–atmosphere system is a formidable task, but such an understanding will improve the ability of humans to make choices that will sustain a diverse and resilient ecosystem, upon which our survival depends. The fundamental concepts of energy and mass conservation and transport relations constitute the theoretical backbone of environmental biophysics (the study of the SPAC).

Water in the Soil–Plant–Atmosphere-Continuum

The smallest spatial scale that is usually associated with the SPAC is a field plot (square meters to thousands of square meters) from the bottom of a root zone (a few meters deep) to a few tens of meters above the top of the vegetation. Although individual studies may use smaller systems such as individual leaves or potted plants to reveal mechanisms, the scale of at least a small field is required to encompass most of the essential components of the natural SPAC and yet be accessible to direct measurement. Researchers generally use formulations nearly identical to those measured in field plots to represent idealized patches of the Earth's surface thousands of square kilometers in size; then they combine these patches to understand better the human influence on global climate processes. Typical time scales for small-scale studies vary from minutes to months or even years. On these spatial and temporal scales, researchers attempt to measure all the important flow and state variables, which are used to validate models that can be applied in systems that cannot be measured directly. After all, society cannot afford to measure everything everywhere, but will support measuring some things in many places and many things in a few places.

The transport and storage of water in the SPAC are shown in Figure 2. The flow of liquid water from the soil into the plant depends on the plant having a lower water potential than the soil; thus the soil water potential determines the availability of soil water for diffusion into the plant. The water potential is the amount of energy (joules) that can be obtained from moving a mass of water (kilograms) to a pool of pure water at atmospheric pressure and specified elevation; and in the soil and plant it is usually negative, indicating that energy must be expended to remove the water. As soils dry, the water potential decreases, making it more difficult for plants to obtain the water they need to grow. The soil water potential is related to the water content of the soil through the 'moisture-release curve,' which varies from soil to soil. Moisture-release curves have been measured for many different soil types. Typically soils can provide an amount of water to plants from storage that is equivalent to 5% (sands) to 20% (silt loams) of the plants' rooting depth. Thus for a plant rooted to a depth of 1 m, soils can provide approximately 50–200 mm of water to the plant. With evapotranspiration rates of 2–10 mm day^{-1}, soils can store enough water to sustain plants for a month or more without rainfall or irrigation.

Once water enters the plant through its roots, it moves through the plant vascular system to the leaves if the leaves have lower water potentials than the roots. Since the transport resistance to mass flow in the stem xylem is usually less than the transport resistance to diffusion through the root, and the flows through both root and xylem must be equal according to conservation principles, the water potential difference from the soil to the root xylem will usually be greater than the water potential difference from the root xylem to the leaf.

Water is lost from plants through pores in the leaf surfaces, called stomata. Evaporation from cells just below the stomatal pores draws water from the leaf cells, which in turn are hydraulically connected to a continuous water column down to the roots. As water is transpired through the stomata, additional water is drawn through the xylem to replace it, very much like suction applied to a straw in a soda. Of course, this evaporation that occurs just below the leaf surface consumes most of the Sun's energy that is absorbed by the leaf, because water vapor molecules carry away latent energy that was not contained in the liquid water that came up from the roots. While the flow of liquid water from the soil to the leaf is proportional to water potential differences, the flow of water

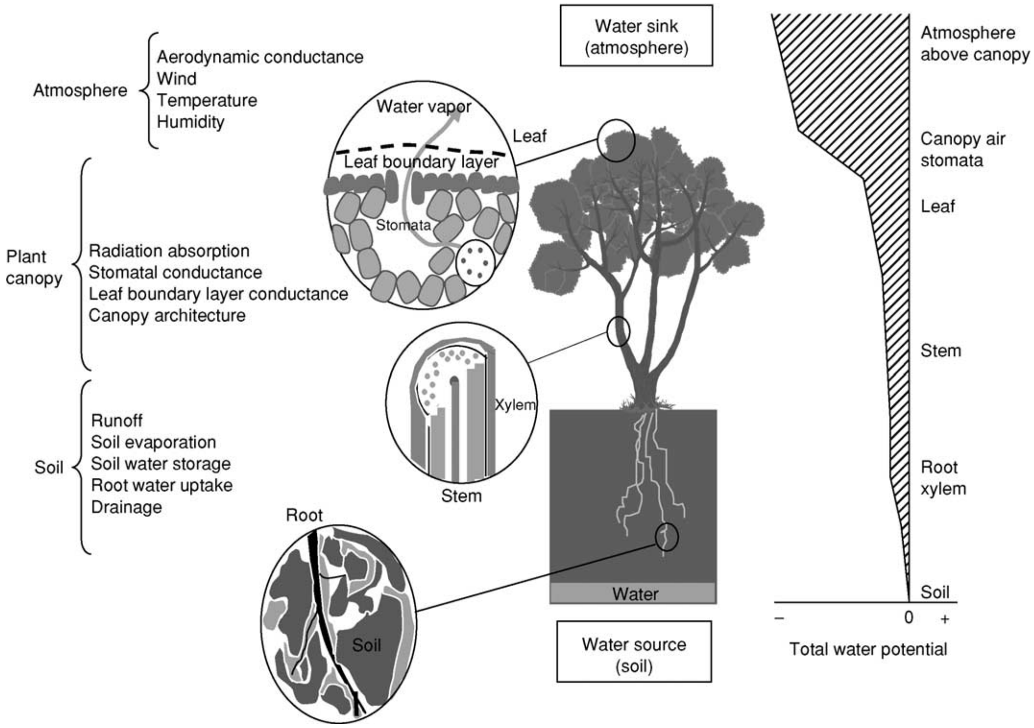

Figure 2 Water movement and storage in the soil–plant–atmosphere continuum. The graph on the right indicates the decrease in water potential that occurs as water moves from the soil to the atmosphere. On the left the three components of the soil–plant–atmosphere system are listed with the major factors for each that should be considered in a model of intermediate complexity.

vapor from inside the leaf to the leaf surface is proportional to water vapor pressure differences. At the interface, a near-equilibrium exists between the liquid water and the water vapor in contact with it. Although different processes are used to describe water movement in different parts of the system, the flow of water is continuous across these discontinuities of processes.

A very small amount of the water that passes from the soil to the atmosphere through the plant remains in the plant as storage as the plant grows (less than 5%). An even smaller amount of the hydrogen and oxygen in the water taken up from the soil remains in the plant in the form of organic molecules synthesized by the plant.

Water that exits the stomata must pass through a thin, still-air layer adjacent to the leaf, called the leaf boundary layer, and be transported through the canopy space by turbulent mixing along the path of decreasing water vapor pressure. Ultimately the water vapor exits the plant canopy, passes through the planetary boundary layer in the lower few thousand meters of the atmosphere, and is lifted high into the atmosphere, where it condenses into clouds and eventually falls back to the Earth as precipitation to repeat the cycle.

Small-Scale Observations and Model Building

In plant-environment studies, research derives and validates the transport principles on small, manageable systems in the laboratory or in field plots where direct measurements are possible. These principles are then applied at the ecosystem and global levels, where direct measurements are not possible, to obtain estimates of the important flow or state variables to quantify human impacts.

Consider the measurements that are necessary to understand the cycling of water in the SPAC. Precipitation falls on a field and either runs off the soil surface to streams or infiltrates into the soil itself (studied in the discipline of hydrology). The infiltrated water may be stored in the soil matrix (soil physics), evaporated from the soil surface (micrometeorology), transpired from plants (plant physiology), or drain below the plant root zone. Water that drains below the plant roots becomes part of the groundwater system (hydrogeology) and may reenter rivers (hydrology). Plants are sustained by the water stored in the soil, and the quantity of this storage depends on the type of soil. Nearly all the water taken up by plants is transpired to the atmosphere at a rate that depends on solar radiation absorbed, weather variables, and the amount of vegetation. The amount of vegetation is estimated from the fraction of ground area covered by plants (vegetative cover). By keeping track of the daily water budget (Figure 1 and Table 1), the amount of water stored in the soil can be estimated, and in turn the influence of this stored water on direct evaporation from the soil and plant transpiration (together referred to as evapotranspiration) can be quantified. The maximum amount of water available to plants depends not only on soil properties, but also on plant rooting depth. Plant physiologists have measured rooting depths for the major classes of vegetation so that, given vegetation type and soil maps, the amount of water available to the plants for growth and transpiration can be estimated.

Table 1 contains an example of a 40-day-long water budget for a corn crop that begins about a month after emergence, during the period when the crop is growing rapidly. The incoming solar radiation column represents the maximum amount of evapotranspiration that could occur if all the solar radiation were used to evaporate water; of course some

Table 1 Simulation of corn growth and water use from 31 to 70 days after emergence, during a rapid growth phase. The solar radiation is in units of millimeters per day of evaporation that could occur if all solar radiation were to evaporate water. Vegetative cover increases as the crop grows and crop biomass increases. Soil evaporation tends to decrease as the soil surface dries out after rainfall and as vegetative cover increases; evapotranspiration (transpiration plus soil evaporation) exceeds rainfall so soil water storage is gradually depleted

Days after emergence	*Rainfall (mm)*	*Radiation (mm day^{-1})*	*Vegetative-cover fraction*	*Biomass (kg m^{-2})*	*Transpiration (mm day^{-1})*	*Soil evaporation (mm day^{-1})*	*Water stored in soil (mm)*
31	0	11.02	0.17	0.047	1.16	2.91	177
32	0	10.10	0.21	0.061	1.26	2.53	173
33	0	6.76	0.24	0.073	0.97	1.13	171
34	0	11.70	0.26	0.083	1.83	1.53	168
35	0	6.93	0.31	0.101	1.23	0.72	166
36	0	11.17	0.34	0.113	2.13	0.99	163
37	0	7.62	0.38	0.135	1.61	0.57	161
38	0	6.04	0.41	0.151	1.35	0.39	159
39	0	11.63	0.43	0.164	2.72	0.67	155
40	0	10.94	0.47	0.191	2.75	0.53	152
41	20	5.60	0.51	0.219	1.49	0.74	170
42	10	6.53	0.53	0.234	1.78	0.82	177
43	0	11.41	0.55	0.252	3.20	1.45	173
44	11	5.82	0.59	0.284	1.70	0.62	181
45	0	9.43	0.60	0.301	2.81	0.95	178
46	0	11.61	0.63	0.329	3.55	1.07	173
47	0	10.70	0.66	0.364	3.36	0.89	169
48	0	11.03	0.69	0.398	3.54	0.83	164
49	0	11.49	0.71	0.433	3.76	0.78	160
50	0	11.31	0.73	0.471	3.76	0.69	155
51	0	11.13	0.75	0.509	3.75	0.62	151
52	0	10.16	0.77	0.546	3.45	0.52	147
53	0	9.88	0.78	0.581	3.39	0.46	143
54	0	12.13	0.79	0.614	4.19	0.38	139
55	0	10.51	0.81	0.656	3.65	0.24	135
56	0	10.83	0.82	0.693	3.79	0.20	131
57	0	12.19	0.83	0.731	4.28	0.19	126
58	0	12.76	0.84	0.773	4.50	0.17	122
59	0	9.08	0.85	0.818	3.21	0.10	118
60	20	6.70	0.85	0.851	2.38	0.19	136
61	0	11.61	0.86	0.874	4.13	0.32	131
62	0	11.98	0.86	0.916	4.27	0.31	127
63	0	11.04	0.87	0.958	3.94	0.27	123
64	0	11.12	0.87	0.998	3.97	0.26	118
65	0	11.05	0.87	1.037	3.95	0.25	114
66	0	12.14	0.88	1.077	4.35	0.27	109
67	0	10.83	0.88	1.120	3.89	0.23	105
68	0	10.71	0.88	1.159	3.84	0.23	101
69	0	9.87	0.88	1.198	3.54	0.20	98
70	0	8.32	0.88	1.233	2.99	0.17	94

radiation is reflected so the actual evapotranspiration is the sum of the transpiration and direct evaporation from the soil, which is approximately one-third of the maximum possible evapotranspiration. The maximum amount of water that can be stored in the rooting zone of the soil is 200 mm for this soil, and clearly the corn crop is using water faster than the rainfall is replenishing it, so that at the end of 70 days of growth approximately half of the maximum soil water storage has been used up. At this point the water depletion in the soil will begin to cause the growth rate of the corn to decrease unless there is more rainfall. This buffering capacity of soil is crucial to growing crops in continental climates all over the world.

Measurements of water transport and storage are difficult and expensive to make, so they can only be done at a few sites under a few conditions. Models that capture the fundamental conservation and transport principles are therefore essential to applying results of limited SPAC studies to a wider range of conditions than could possibly be measured directly. A wide array (hundreds) of computer models are available for quantifying the role of water in the SPAC and the range of applicability of such models depends on having a minimal, faithful representation of critical factors in each component of the SPAC; namely in the soil, the plant, and the atmosphere. SPAC models can be divided into three classes: simple, intermediate, and complex.

Simple SPAC models are the easiest to create, generally emphasize the knowledge base of one discipline with a narrowly focused purpose, and are the most limited in applicability. For example, the Simple Inverse Yield Model, for precision agriculture, and the CERES Maize model, for crop yield and water-use prediction, neglect the effect of vegetation roughness and wind on evapotranspiration, reflecting their agricultural roots and limited applicability. There is also a simple micrometeorological model of evapotranspiration that omits soil processes, reflecting its atmospheric origins and limited applicability.

Intermediate SPAC models incorporate at least a minimal consideration of key soil, plant, and atmospheric components to provide wide applicability without undue complexity. These intermediate models incorporate atmospheric factors (radiation, wind, temperature, humidity, and precipitation), vegetation factors (plant type, vegetative-cover fraction and height, rooting depth), and soil properties (soil evaporation, root-zone water transport and storage). Examples of Intermediate SPAC models include the Two-Source Model, for remote sensing applications, and the ALEX (atmosphere–land exchange) model, for local site-specific studies.

Complex SPAC models incorporate most of the processes known to be important at small (leaf to field) scales, and can be applied to a wide range of cover types and climatic conditions. Because they are very detailed, they generally involve a large array of coefficients related to specific plant and soil types. For this reason, complex models are often not well-suited to regional scale applications, where these myriad of parameters need to be defined at all locations. The greatest value of complex SPAC models lies in improving our understanding of key processes and using this knowledge to derive intermediate models with the fewer parameters and wider applicability.

An example of this use of a complex SPAC model is the derivation of the Two-Source and ALEX models from the complex Cupid model. The Cupid model predicts plant–atmosphere exchanges of carbon, water, and energy in a very detailed mechanistic way, and it requires dozens of species-specific coefficients related to plant physiology. By studying the behavior of the Cupid model, the ALEX model could be created using only a few carefully chosen physiological coefficients and yet achieve a surprising level of generality compared with Cupid. Not only does ALEX link growth and water use in a way nearly as fundamental as Cupid, but it does so with a widely used 'light-use efficiency' coefficient that is already tabulated for most vegetation types around the world. The result of this process is a robust model suitable for continental-scale applications.

Complex SPAC models have also been used to study the relation between the architecture of vegetation canopies and their remotely sensed signatures from aircraft and satellites. Since remote sensing is the only way to characterize vegetative cover on the regional and continental scales, we must understand how to interpret remotely sensed land observations to accommodate the profound influence of vegetation density on energy and material exchanges in the SPAC. For example, in Table 1, the increased importance of transpiration (and extraction of soil water to great depths by plant roots) over evaporation from the soil (water extraction to only a few centimeters of soil depth) is apparent as the vegetation cover increases from 17% to almost 90% during the 40 days of growth.

Determining the level of complexity appropriate for an application depends on the objective of the endeavor; typically, the simplest model that provides adequate results is the model of choice. Our understanding of energy and water flows in the SPAC is sufficiently well developed to extend this knowledge to larger scales, where direct measurements are only rarely, if ever, possible and evaluate implications of human activities on ecosystem health.

Application to Regional and Global Scales

The impact of humans on the global ecosystem has become so profound that extending our understanding of biophysical processes from small fields to whole regions is becoming critical for our survival. The extension of process-level understanding of energy and material flows in the SPAC to larger scales imposes a severe constraint that is not present in plot-scale studies; namely, that the allowable input quantities are limited to state variables that can be monitored over large areas. Only a few state variables are routinely measured widely in networks across the world and thus can be considered generally available for monitoring the SPAC. For example, near-surface weather variables (air temperature, humidity, wind speed and direction, precipitation, and cloud cover), solar radiation, atmospheric carbon dioxide, soil maps, vegetation-type maps, river and stream monitoring, and satellite images are routinely obtained at many locations in many countries of the world. This means that these are the main quantities that can be assumed to be generally available everywhere (not always true, but a reasonable assumption). All other inputs required for SPAC models must be computed from fundamental principles or from quantitative relations derived from validation experiments at small scales. This pursuit has been exceedingly challenging, but systematic research over decades in numerous disciplines has identified many of the critical processes, and integrative computer modeling has synthesized much of this information so that monitoring water transport and storage on continental scales may now be possible.

Consider an example of a suite of models that has been assembled to explore systematically the energy and material flows in the SPAC over a range of scales from small fields to the continental USA (Figure 3).

At the heart of this suite of models is a pair of Intermediate SPAC models; namely ALEX for computing in the forward direction and the Two-Source Model for inverse computation using satellite observations as inputs. When the sky is cloudless for a few hours in the morning, operational satellites can be used to quantify vegetative cover and monitor surface temperature to estimate the surface flows of

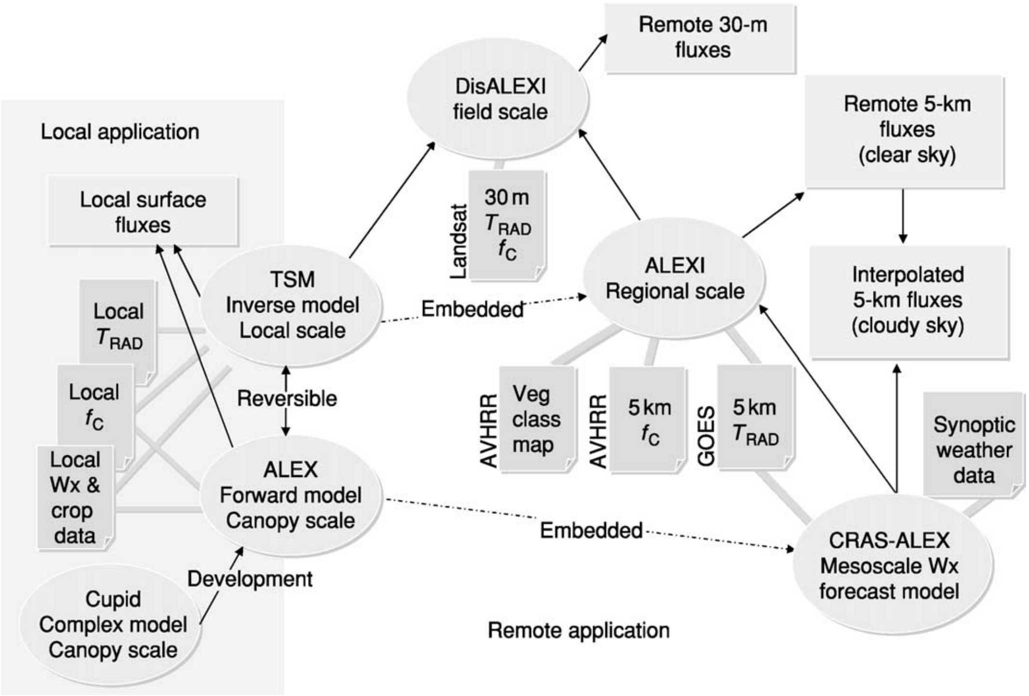

Figure 3 Suite of models for estimating evapotranspiration on large spatial scales (remote application) based on measurements from studies on small fields (local application). Cupid, the Atmosphere–Land Exchange model (ALEX), and the Two-Source Model (TSM) are used on the field scale and require inputs that can be directly measured in field studies. ALEX Inverse (ALEXI) disaggregation ALEXI (DisALEXI), and CRAS-ALEX (Cooperative Institute for Meteorological Satellite Studies (University of Wisconsin) weather forecast model) are used on the 5- to 10-km-grid scale for continental-sized applications, and they require inputs from satellites (Landsat, AVHRR, or GOES) or national weather measurement networks (synoptic weather data). The TSM is used at the local scale, embedded in ALEXI for use at the continental scale, and used in DisALEXI for remote estimates at the large field scale; likewise, ALEX is used at the local scale and also embedded in the weather forecast model for use on the continental scale. GOES, geosynchronous operational environmental satellite; AVHRR, advanced very-high-resolution radiometer satellite; T_{RAD} radiometric temperature; f_C, fraction of vegetative cover on the ground; Wx, weather.

energy and water at the 5- to 10-km scale and larger using the atmosphere–land exchange Inverse ALEXI model (**Figure 3**). ALEXI is a combination of the Two-Source Model and a meteorological model of the behavior of the lower 2000 m of the atmosphere (the planetary boundary layer). The ALEXI model can be used to update a mesoscale weather forecast model wherever a cloudless morning occurs. Likewise, the weather forecast model can be used to interpolate quantitites used in ALEXI whenever the satellite view is obscured by clouds. Mesoscale weather forecast models capture important feedbacks between land and atmospheric processes so that, as humans change the land characteristics, these models consider how these changes may affect subsequent weather. Meteorologists have refined these mesoscale models for decades and can now capture the transport of quantities from spatial scales of approximately 10 km and time scales of minutes to continental spatial scales over days, months, or even years of time.

The combination of the mesoscale model and ALEXI can yield time-continuous maps of the flow of water and energy in the SPAC at scales of 5–10 km and larger. How can the accuracy of such estimates be validated? Two methods have been used: (1) the use of research aircraft in intensive field experiments, and (2) the application of a disaggregation technique (DisALEXI), which uses data from a high-spatial-resolution satellite (such as Landsat, with a 30-m spatial resolution) to disaggregate 5- to 10-km ALEXI flux estimates to the spatial scale of in situ ground measurements (hundreds of meters) based on micrometeorological methods such as eddy covariance. Not only can the DisALEXI model assist with validation of the ALEXI model, but it can be used to update crop growth and water-use models in agriculture by providing occasional independent estimates of the flow of energy and water on the fine spatial scale of 30 m.

This process of using fundamental principles to infer global implications of plot-scale measurements reminds one of a statement Mark Twain once made: "There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact." Clearly the power that fundamental principles give scientists to extend the influence of humans is difficult for nonscientists to comprehend.

Institutional Issues

Studies of the SPAC are interdisciplinary (involving research in areas that are not claimed by existing disciplines) and multidisciplinary (requiring collaboration among scientists from numerous disciplines). For example, to understand the influence of vegetation on weather forecasts involves the following activities: meteorologists study the effect of the surface energy and water exchanges on the lower few thousand meters of the atmosphere called the planetary boundary layer; physiologists characterize the dependence of photosynthesis and stomatal processes on atmospheric and soil environmental factors; soil scientists measure the heat- and water-holding characteristics of the soil as well as carbon-exchange processes; micrometeorologists relate vegetation-canopy characteristics and atmospheric variables to the exchange of heat, mass, and momentum with the atmosphere; and hydrologists consider the runoff characteristics of the soil surface and the recharge of groundwater by percolation. The study of vegetative-canopy architecture, within-canopy processes, and the interaction between remote sensing and vegetative cover are key interdisciplinary areas that are not associated with any particular discipline.

Most scientific research is funded by government agencies and conducted within a disciplinary structure of research establishments or universities; therefore, competition among disciplines for funding and the limited perspective of individual researchers mitigate against developing an integrated view of the SPAC. Although much lip service has been paid to the value of interdisciplinary and multidisciplinary research, no sustaining structure in the research establishment is apparent for such integrative activities, and progress continues to be dominated by ad hoc efforts from committed individuals or teams with determination and vision. One strategy that has been most valuable in recent decades is the organization and execution of large, international, multidisciplinary, intensive field experiments, with broad objectives that appeal to scientists in many disciplines. The wide distribution of and open access to data from such experiments have been responsible for tremendous gains in understanding of the SPAC in recent years. Two examples of such experiments are the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) in the grasslands of Kansas, USA, and the Boreal Ecosystem Atmosphere Study (BOREAS) in the Canadian boreal forest.

The time-honored reductionist perspective of 'changing a single variable and holding all other factors constant' is not possible in holistic studies of the profoundly interconnected SPAC. Instead the challenge of exploring important processes without the constraints of limiting paradigms and parochial disciplines must be confronted, a formidable challenge for environmental scientists. Efforts to synthesize knowledge from various components of the SPAC into a holistic view continue to be challenging in a scientific world dominated by technological reductionism. The view of the Earth as a complex, self-organized system gains wider acceptance as our knowledge of the interconnectedness among components of the SPAC improves.

See also: **Energy Balance**; **Evapotranspiration**; **Water Cycle**; **Water-Use Efficiency**

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SOLUTE TRANSPORT

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Introduction

The movement of chemicals in soils and groundwater aquifers (solute transport) plays a central role in global biogeochemical cycling. Human activities have placed many new chemicals into the environment and greatly enhanced the local loading of wastes to the subsurface. Obvious applications of an understanding of solute transport in porous media include the efficacy and fate of agricultural chemicals (fertilizers and/or pesticides); the treatment and disposal of wastewaters and wastewater treatment products from human, animal, and industrial sources; and contamination resulting from landfills, mining operations, industrial activities, high-level radioactive waste disposal, etc. Given its great importance in the maintenance of safe water supplies, the nourishment