State and Transition Ecosystem Models—Application to Soil Survey and Dynamic Soil Properties Databases

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State and transition models. Arid and semiarid rangelands are hypothesized to function as nonequilibrium systems (Westoby et al. 1989). Models that capture these nonequilibrium dynamics at the site (groups of similar soil map units; *sensu*, Shiflet 1973) level are called **state and transition models (STMs)**. Although the application of STMs is at an early stage, relatively large gains in understanding rangeland function are being realized by implementing this new approach. Developing an information system to manage this knowledge will require the reinterpretation of existing data and new observations and experiments within a precisely defined structure if we are to make progress in providing better quality information for land management decisions.

Plant communities that can potentially exist on a given site can be organized into multiple **states**, distinguishable from other states by relatively large differences in abiotic and biotic processes (Stringham et al., 2001). Currently, state indicators are based on vegetation (i.e., plant functional groups), but dynamic soil properties or more subtle differences in soil/plant interactions, such as spatial or temporal patterning, may differentiate states. The shifts between states are referred to as **transitions**. Transitions represent changes in the types or magnitude of ecological processes that control the movement of energy and nutrients within the community. In most cases, transitions are initiated by a particular combination(s) of management and climate. **Thresholds** are the boundary between reversible and irreversible transitions and correspond to state boundaries. State and transition models, then, are graphical and textual representations of hypotheses about the causes of persistent changes in soils and vegetation at the ecological site level and should offer testable predictions as well as guidance in how to achieve, or avoid, change.

La Copita case study. Through the literature, we examined the changes in soil properties that have occurred as a result of changes in vegetation on a sandy loam upland in the shrublands of south Texas. The research was conducted on the Texas Agricultural Experiment Station, La Copita Research Area in Jim Wells County, 15 km SW of Alice, TX (27^o 40'N; 98^o 12'W; elevation 80 m) in the eastern Rio Grande Plains of the Tamaulipian Biotic Province (MLRA 83c). The climate is subtropical with warm winters and hot summers. Mean annual temperature is 22.4 ^{o}C with a growing season of 289 days. Mean annual precipitation (720 mm) is highly variable (C.V.=35 percent).

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Uplands in the area, which have been grazed by cattle since the late 1800s, are savanna parklands consisting of discrete clusters of woody plants organized beneath *Prosopis glandulosa* (honey mesquite). Intercluster spaces are dominated by perennial grasses, primarily *Chloris cucullata* (windmill grass). See Archer et al. (1988) for details on plant community structure and successional patterns. The long-term interaction of heavy livestock grazing, reduced fire frequency, and increased seed dispersal by domestic stock has resulted in a shift from grassland to woody plant dominance over the past 75-100 years. See Archer et al. (1988) for a complete description.

Soils of the uplands at La Copita are mapped Rungee fine sandy loam, 1 to 3 percent slopes (USDA, 1979) and are in the Sandy Loam 83c-Central Rio Grande Plain ecological site. The convex sandy loam uplands support discrete clusters and herbaceous zones that are associated with soils having a well-developed argillic horizon (Typic Argiustolls); whereas groves occur on inclusions with minimally developed Bt horizons (Typic Ustochrepts) (Archer, 1995). Soils on the clay loam lowlands are Pachic Argiustolls and are in a different ecological site. Conditions suggesting that vegetation changes are not a result of erosion include low topographic relief, slopes of 1 to 3 percent, little evidence of erosion in the form of rills or gullies, and no evidence of deposition in the low-lying areas (Archer et al., 2001).

As vegetation has changed, soil properties have changed dramatically as well. States and transitions can be utilized to organize the plant-soil dynamics that have occurred at La Copita. The state and transition model (figures 1 and 2) includes three plant communities in “state 1”: A—tall and mid grasses; B—mid and short grasses; and C—short grasses and annuals. Plant communities D (clusters and groves) and E (woodlands) are in “state 2.”

In this presentation we will look at clay content, bulk density, pH, carbon, and nitrogen for the herbaceous plant community, clusters, and groves within the sandy loam ecological site. Because we are interested in the soil-plant dynamics for a single ecological site, soil data for the clay loam lowlands (woodland plant community) are not shown. Data and simulated values show that soil properties vary among and within states. Nutrient redistribution associated with the replacement of grasses by shrubs has resulted in the formation of “fertility islands” (Virgina, 1986; Hibbard et al., 2001). These changes in the vertical and horizontal spatial distribution of soil constituents can greatly constrain the options of managers. Soil data for plant community C may be critical to the identification of threshold values.

Where the soils are Typic Argiustolls and the plant community is clusters, these data (table 1) show significantly lower values for bulk density and significantly higher values for carbon and nitrogen in the shrub-invaded grasslands of plant community D (state 2) as compared to the short grasses of transitional plant community C (state 1). The 1.4 percent soil organic matter content under the groves of plant community D is not significantly different from the content under the short grasses or the clusters. The different soil, Typic Ustochrepts, might explain this lack of difference.

Table 1. —Soil properties, 0-10 cm (Hibbard et al., 2001).

Soil properties	Typic Argiustolls		Typic Ustochrepts
	C Short grasses	D Clusters	D Groves
Clay (%)	20 (0.7)^{a}	20 (1.0)^{a}	18 (0.7)^{a}
Bulk density (g/cm^{3})	1.4 (0.01)^{a}	1.1 (0.04)^{b}	1.1 (0.03)^{b}
pH	6.7 (0.2$^{)a}$	6.8 (0.2)^{a}	5.8 (0.2)^{b}
Carbon (%)	0.84 (0.05)^{a}	2.2 (0.23)^{b}	1.4 (0.2)^{a,b}
Nitrogen (%)	0.07 (0.00$^{)a}$	0.18 (0.02)^{b}	0.12 (0.01)^{a,b}

Notes: Means (1 SE) within a row followed by different letters were significantly different (n = 12).

Current herbaceous production reported at La Copita is less than 2,700 kg/ha (about the same as lbs/ac) for the short perennial grasses and annual forbs (Vega, 1991; Hibbard, 1995). The potential production of mid to tall perennial grasses is 5,000-6,000 kg/ha (USDA, 1979). Hibbard (1995) simulated the changes in soil organic carbon (0-20 cm) for the sandy loam uplands (figure 3). The decline in soil organic carbon corresponds to the onset of heavy continuous grazing and the exclusion of fire and shows that the management regime and disturbances affect soil properties. We have derived a soil organic carbon content of 1.2 percent in 1750 for plant community A (tall and mid grasses) from this simulation for comparison with today's 0.84 percent SOC content for plant community C.

Importance of dynamic soil properties. Changes in soil properties can affect the capacity of the soil to function. Increased availability of dynamic soil property information will allow the development of additional management tools to support sustainable management based on consideration of soil functions and the resistance and resilience of the soil to disturbances.

The drivers of change that can affect plant and soil properties may include natural disturbances, such as fire, drought, floods, insects, or disease, or management induced disturbances, such as absence of fire, catastrophic fire, long-term heavy grazing, invasive plants, erosion, or compaction. The interaction of natural and management-induced disturbances may cause changes when individual disturbances might not prompt a change. Changes in vegetation, and hence in soil organic matter, can result in a change in other measurable soil properties, including aggregate stability, infiltration, surface crusts, water-holding capacity, bulk density, nutrients, and pH. Because these properties have an effect on nutrient and water availability and resistance to erosion, they also affect production. Production in turn affects the biomass available for conversion to soil organic matter. This "plant biomass-soil property-plant biomass feedback loop" illustrates the importance of understanding the drivers of change and the degree and rate of change in dynamic soil properties for the management of rangelands.

Some soil properties change very little and others change a great deal in response to disturbances. Those that are relatively static over periods of hundreds of years or more together with those that are dynamic determine the capacity of the soil to function. These functions include: (1) sustaining biological activity, diversity, and productivity; (2) regulating and partitioning water and solute flow; (3) filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic material, including industrial and municipal by-products and atmospheric deposition; (4) storing and cycling nutrients and other elements within the earth's biosphere; and (5) providing support for socioeconomic structures and protection for archaeological treasures associated with human habitation (Karlen et al., 1997).

The importance of change in a soil property is reflected in the various ways in which that property affects the capacity of the soil to function. For example, soil organic matter is a dynamic soil property affecting many other soil properties and is related to soil functions in several ways. Soil organic matter

- binds soil particles together into stable aggregates which increase porosity and infiltration, enhance root penetration, and reduce erosion,
- contributes to soil fertility and plant productivity by improving the soil's ability to store and supply nutrients, water, and air,
- provides habitat and food for soil organisms that transform and release nutrients,
- sequesters carbon from the atmosphere, and
- reduces soil physical crusting, thus improving seedling emergence and water infiltration.

The capacity of a soil to continue to function through a disturbance depends on the resistance of the soil to change, and the capacity of the soil to recover functional and structural integrity following a disturbance or change depends on the resilience of the soil (Seybold et al., 1999). Knowledge of resistance and resilience are important planning considerations for range management, restoration, and recovery. For example, if an increase in bulk density caused by compaction results in a decrease in porosity and infiltration, the capacity of the soil to perform one of its functions, i.e., to regulate and partition waterflow, is altered (figure 4). Information about the change in a dynamic soil property may also serve as an early warning indicator of possible future degradation by reflecting an irreversible transition. Beyond this irreversible transition, one or more of the primary ecological processes of a state must be actively restored with management inputs before there can be a return to the previous state (Stringham et al., 2001).

Uses of dynamic soil property data. Dynamic soil property data are needed in planning activities, including assessment, prediction, and monitoring. These data will provide more accurate results for soil interpretations, such as hydrologic soil group. They will enhance our ability to predict soil resistance, soil resilience, vegetation changes, and the effects of disturbances or climate change. They will provide reference values that are important for management decisions related to maintaining soil function or to restoring soil function, and they will facilitate predictions of management outcomes, such as carbon sequestration potential. The data for the transitional plant community is particularly important because it may provide early warning information that will facilitate management intervention before a threshold is crossed.

Database framework. The National Soil Survey Information System (NASIS) currently includes soil property information for the relatively unchanging static soil properties, such as texture, and also for some important dynamic soil properties, such as soil organic matter. However, it does not distinguish the values of dynamic soil properties according to their management history, or “state.” NASIS needs to be enhanced to allow the storage of dynamic soil property data in a way that shows soil-plant-management interactions. State and transition models can help to organize this information. A framework of ecological sites and STMs can encompass soil properties that differ as a result of disturbances, type of management, and type of land use. This type of framework will enhance our ability to organize information related to soil-plant and soil-management interactions that affect soil properties and plant communities over time and at multiple scales. Reference or benchmark soils and eventually all soil map unit components used as rangeland will require a dynamic soil property database entry for each state, each plant community, and each state threshold of the STM that represents the dynamics of that soil component.

Database population strategies. We need to identify measurable soil properties that reflect ecological processes and the functional capacity of rangelands. Strategies that minimize the workload of populating a dynamic soil properties database are needed. Selection of a limited number of essential data elements for inclusion in the dynamic soil properties database along with a framework that organizes the relationships among the data will allow us to be data rich and information rich. A combination of 1) field data collection activities to determine critical relationships in various regions and 2) modeling technologies can be used to minimize sampling needs. Benchmark soil sampling will also allow us to reduce sampling needs and enhance our ability to extrapolate plant-soil relationships. State and transition models can be used to help select sites for sampling. The research needed to support the development and population of a dynamic soil properties database includes:

- testing of STMs,
- identification of thresholds and drivers of change,
- extrapolation and modeling technologies, and
- sampling strategies that account for variance and obtain the required level of accuracy.

The feasibility of incorporating other land uses into state and transition models needs to be studied so that potentially all land uses can be organized within the database in a similar and efficient manner.

Summary. Sustainable land management requires that we have a well-developed understanding of plant-soil dynamics and communicate them to a wide variety of audiences. Predicting the outcomes of soil-vegetation interactions is critical to implementing realistic land management strategies and operations. State and transition models have high utility for describing the effects of management and climate on soil/plant interactions and can serve as a basis for decision-making. The databases and knowledge systems that support natural resource management need to be adapted to encompass new ideas about how soils and vegetation change and respond. However, we need to remember that models are representative of what we know and may well be incomplete or just plain wrong and that even systematic observations are likely to create the impression of linear change or miss critical events. Therefore, it is important to use observations and existing literature to construct critical experiments that determine important events, patterns, and changes that will provide an accurate and understandable basis for land management decision-making.

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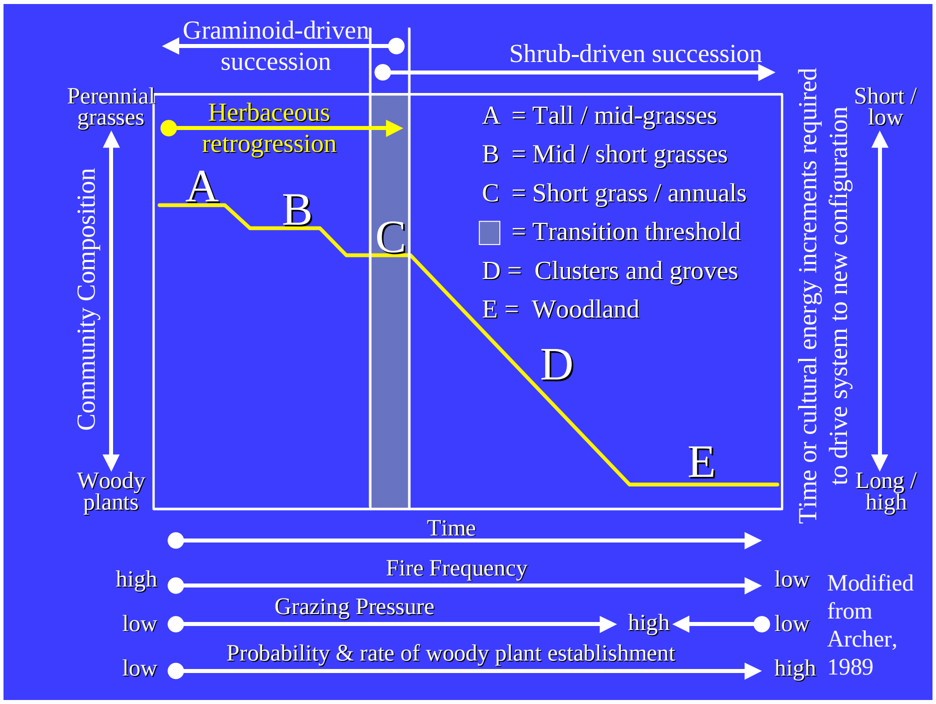


Figure 1.—State and transition model for sandy loam uplands of the La Copita study (modified from Archer, 1989),

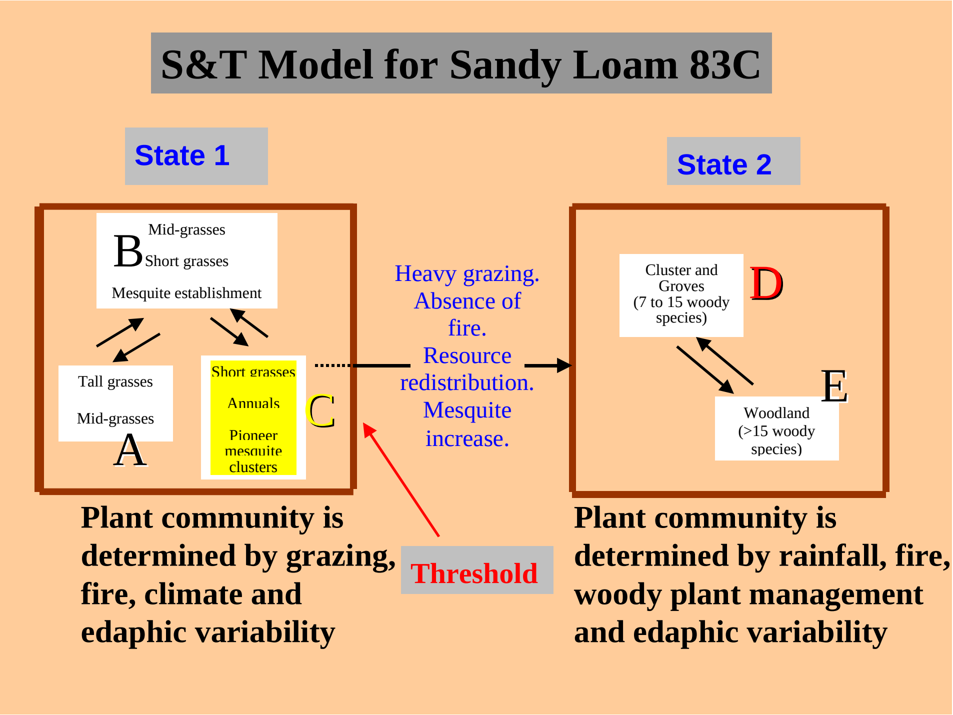


Figure 2.—State and transition model for Sandy Loam 83c in standard format for ecological site descriptions. See Stringham et al. (2001) for definitions and examples.

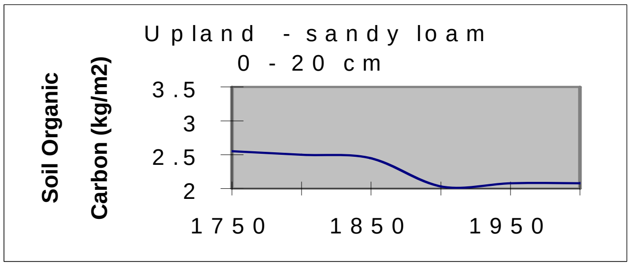
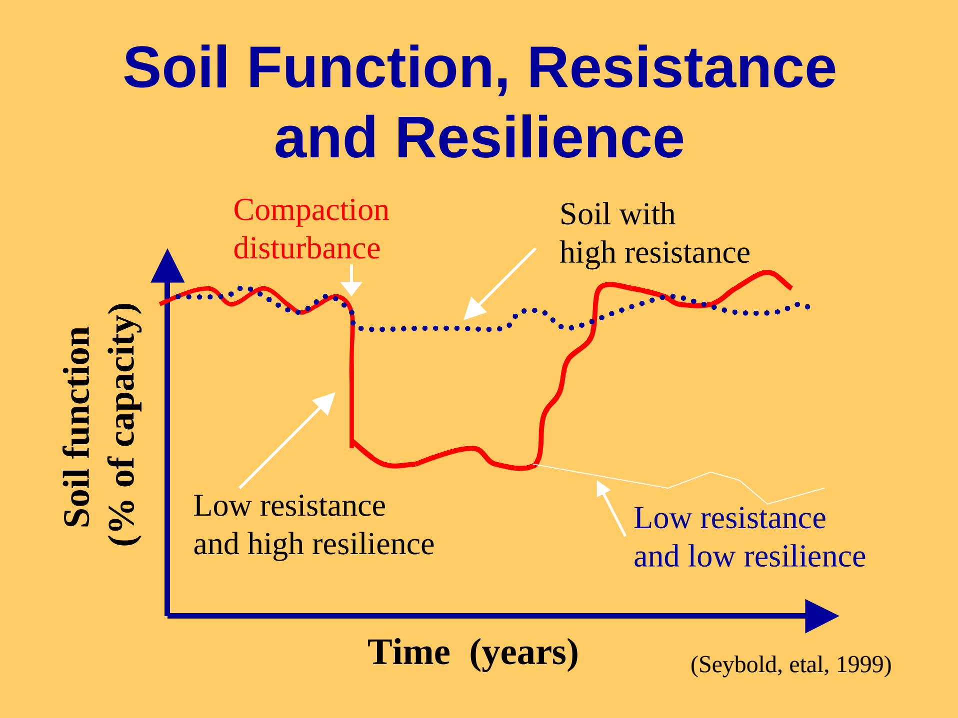


Figure 3.—Simulated soil organic carbon, 1750 to 2000 (Hibbard, 1995; redrawn from Archer et al., 2001).



Soil Function, Resistance and Resilience

(Seybold, etal, 1999)

Figure 4.—Soil resistance and resilience in relation to the capacity of the soil to function (Seybold et al., 1999).