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The Inappropriate Use of Crop Transpiration Coefficients (K_c) to Estimate Evapotranspiration in Arid Ecosystems: A Review

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The transpiration coefficient (K_c) method estimates evapotranspiration as a proportion of the evapotranspiration of a reference crop growing in ideal conditions. This approach was designed for irrigated crops and assumes that plants are not subjected to resource limitations. Other assumptions are that plants have high leaf area index and little stomatal resistance to water loss. These conditions are not common for arid-land vegetation. However, mainly due to its simplicity, some studies have proposed the use of transpiration coefficients as a method of determining evapotranspiration in arid environments. In this article, the documented applications of the K_c method in arid environments and their accuracy are reviewed. We also critically discuss the physiological and agronomic concepts that support the K_c method as they relate to water-limited environments. The K_c method typically overestimates water use when plants encounter suboptimal conditions of soil water because it does not consider stomatal regulation and plant adaptations to drought. We conclude that, although the transpiration coefficient method is simple to implement and widely recognized, it is not suitable for determining evapotranspiration of vegetation adapted to arid conditions.

Keywords arid-land vegetation, desert plants, stomatal control, rangeland, water use

Water issues in arid areas of the world are subject to increasing debate due to the scarcity of fresh water and the growing demand for urban and agricultural uses. Evaluations of evapotranspiration in desert ecosystems are important because they provide valuable information for watershed management. These evaluations have been conducted with the objectives of (1) predicting rangeland production and assessing grazing effects (Wight & Hanks, 1981; Floret et al., 1982; Frank, 2003), (2) providing basis for groundwater management (Or & Groeneveld, 1994; Xu et al., 1998; Steinwand et al., 2001), and (3) achieving a better understanding of hydrological processes, which are essential in ecological modeling and land management of arid areas (Wight et al., 1986; Stannard, 1993; Malek et al., 1997; Liu & Kotoda, 1998; Goodrich et al., 2000).

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A number of techniques have been used to estimate evapotranspiration in arid regions, including lysimeters (Wight, 1971; Evans et al., 1981; Xu et al., 1998), remote sensing (Goodrich et al., 2000), micrometeorological techniques (Stannard, 1993; Malek et al., 1997; Goodrich et al., 2000; Frank, 2003), and transpiration coefficient methods (Wight & Hanks, 1981; Wight et al., 1986; Wight & Hanson, 1990; Or & Groeneveld, 1994; Steinwand et al., 2001). Transpiration coefficient methods are based on procedures developed originally for irrigated agriculture (Doorenbos & Pruitt, 1977; Allen et al., 1998). The core of these methods is the determination of the crop transpiration coefficient (K_c), which represents the evapotranspiration of a given crop as a proportion of the evapotranspiration of an ideal (reference) crop grown under no limitations of water and nutrients.

K_c methods are based on an engineering approach that is widely recognized in irrigation agriculture (Zhang et al., 2004). Because of its wide recognition, K_c methods are erroneously considered a "conventional approach" to calculate evapotranspiration at regional levels using geographic information systems (Li et al., 2003). The approach is simple to use when its basic assumptions are met, that is, that crops will be managed to avoid water and nutrient limitations and that crops have low resistance to transpiration and high leaf area index. The method, however, has serious limitations when these assumptions are not satisfied (Lascano, 2000).

Native vegetation of arid lands grow in conditions that clearly depart from those of irrigated crops. Because of their adaptation to water limitations, desert plants typically display high resistance to transpiration and low ground cover (Caldwell et al., 1977; Hanson & Dye, 1980; Evans et al., 1981). Despite these obvious deviations from the basic assumptions, K_c methods have been inappropriately used to estimate evapotranspiration in arid and semiarid plant communities (Wight & Hanks, 1981; Wight et al., 1986; Wight & Hanson, 1990; Or & Groeneveld, 1994; Steinwand et al., 2001). Allen et al. (1998) proposed the use of adjustment factors to recalculate K_c in plants subject to water deficits. However, the adjustments are complex and have not been applied in recent reports of K_c for desert vegetation (Steinwand et al., 2001).

The objective of this review is to analyze the suitability of K_c parameters to estimate accurately evapotranspiration in water-limited ecosystems. Our analysis is based on a critical review of the physiological and agronomic concepts that support the method and their adaptation to native desert environments. We do not attempt to provide a quantitative evaluation of the method. However, we analyze the accuracy of evapotranspiration estimations obtained by K_c methods in arid and semiarid native vegetation as reported in scientific literature.

Overview of the K_c Method

In 1977, the United Nations Food and Agriculture Organization (FAO) published the revised Irrigation and Drainage Paper No. 24, "Crop Water Requirements" (Doorenbos & Pruitt, 1977), which was an initial attempt to standardize the calculation of irrigation water for crops. In 1998, FAO published the Irrigation and Drainage Paper No. 56 (Allen et al., 1998), incorporating technological advances to improve the original 1977 version and to define clearly the FAO approach as the standard to determine crop water requirements. This method recognizes three main factors that affect evapotranspiration: (1) meteorological, (2) crop characteristics, and (3) crop management. The influence of these three factors is represented in the following conceptual equation:

$$\text{Climate} + \text{Reference crop} = ET_o. \tag{Eq. 1}$$

Equation 1 represents the influence of climatic variables (solar radiation, temperature, wind speed, and humidity) over a reference crop that is grown in ideal soil conditions. The reference crop is affected by meteorological variation only because it is not limited by water or nutrients and is free of diseases and pests. Therefore, ET_o, which is known as reference evapotranspiration is strictly a measure of the capacity of the atmosphere to influence water loss from an ideally vegetated surface that is subject to no resource limitations (Allen et al., 1998). The goal of establishing ET_o is to have a reference value of evapotranspiration for a given location against which the evapotranspiration of any crop can be related.

There are a number of equations to calculate ET_o from meteorological data (Ventura et al., 1999). The Penman-Monteith combination equation is widely accepted and recommended by FAO (hence it is also known as the FAO Penman-Monteith equation) (Allen et al., 1998; Zhang et al., 2004). This equation is derived from the original Penman equation, which calculates water transfer to the atmosphere from an open-water surface. To incorporate the effect of plants, the FAO Penman-Monteith equation includes a resistance factor that represents the combined resistance to water transfer exerted by (1) the crop surface (mainly regulated by stomata) and (2) the boundary air layer surrounding vegetative surfaces (aerodynamic resistance). After incorporating these resistance parameters for a reference grass, the FAO Penman-Monteith equation is expressed (Allen et al., 1998) as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}, \tag{Eq. 2}$$

where ET_o is reference evapotranspiration (mm day^{-1}), Δ is slope vapor pressure curve (kPa°C^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), γ is the psychrometric constant (kPa°C^{-1}), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s^{-1}), and $e_s - e_a$ is saturation vapor pressure deficit (kPa).

Grasses and alfalfa are well-documented plants that have been used as reference crops. To avoid ambiguities, however, current FAO guidelines (Allen et al., 1998) establish that the reference crop must be a hypothetical crop with an assumed height of 0.12 m, a fixed surface resistance to water loss of 70 s m^{-1}, and an albedo of 0.23. These parameters are incorporated in the FAO Penman-Monteith equation to calculate ET_o of an idealized extensive surface (big-leaf model) of actively growing grass of uniform height, completely shading the ground, and adequately irrigated (approximately once a week). ET_o is related to the evapotranspiration of a crop as follows:

$$K_c = \frac{ET_c}{ET_o}, \tag{Eq. 3}$$

where K_c is crop transpiration coefficient, ET_c is crop evapotranspiration, and ET_o is reference evapotranspiration.

Evapotranspiration under standard conditions of a specific crop (ET_c) occurs under optimum irrigation, fertilization, and management conditions and can be obtained experimentally. Both ET_o and ET_c are obtained under optimum conditions, and their difference is due to the intrinsic nature of the crop or the species. ET_o and ET_c are determined to calculate K_c as in Equation 3. Therefore, K_c parameters are dictated by how different a crop responds to the weather in relation to the reference crop. When K_c for a given crop is known, it is used together with ET_o to calculate the irrigation requirements or evapotranspiration (ET_c) of the crop. Usually, state agencies provide the values of K_c and ET_o for farmers to calculate irrigation amounts, thus using this engineering approach can be very simple if its assumptions are met. The method may vary in its applications and the procedures to obtain ET_o, ET_c, and K_c, but its essential feature is the use of K_c parameters, hence our inclination to call it the K_c method.

Use of the K_c Method in Arid-land Vegetation

Wight & Hanks (1981) used K_c parameters to estimate evapotranspiration in a semiarid grassland in Montana. They used free-water (pan) evaporation as ET_o and determined ET_c from lysimeters cropped with native vegetation growing under nonlimiting soil water conditions. K_c values were obtained as in Equation 3 and ranged from 0.7 in the spring to 0.9 during midgrowing season. A growing season K_c average of 0.85 was used in their calculations. K_c was multiplied by ET_o and leaf area index (LAI) to estimate potential transpiration (T_p). T_p was modified to determine actual transpiration (T) as follows:

$$T = (LAI \times ET_o \times K_c)\frac{SWS}{AW}, \qquad \text{(Eq. 4)}$$

where $LAI \times ET_o \times K_c$ is equal to T_p, SWS is existing available soil water, and AW is available soil water storage capacity. Therefore, T was recalculated from T_p according to the soil water available.

Wight et al. (1986) used a K_c model to estimate evapotranspiration in a semidesert sagebrush (*Artemisia tridentata*) area in southwestern Idaho. Their ET_o was calculated with the Jensen-Haise equation with alfalfa as reference crop. They used the value of $K_c = 0.85$ obtained by Wight & Hanks (1981). The product of ET_o and K_c was considered potential evapotranspiration. This was multiplied by a plant growth coefficient obtained from a relative growth curve, which had the same function as the LAI curve used in Wight & Hanks (1981). Potential evapotranspiration was also multiplied by an empirical coefficient of plant water use in order to represent the portion of evapotranspiration that could be transpired at peak standing crop.

Wight & Hanson (1990) determined crop coefficients for three semiarid grasslands in South Dakota, Wyoming, and Idaho. ET_o was calculated with the Jensen-Haise equation based on a well-irrigated alfalfa crop and ET_c was determined with lysimeters on days when soil water was not limiting. Their average K_c values ranged from 0.79 to 0.85, very similar to the K_c value reported by Wight & Hanks (1981).

Or & Groeneveld (1994) determined K_c to estimate evapotranspiration of desert vegetation in Owens Valley, California. Their objective was to use the estimated evapotranspiration data in a water balance equation to calculate available soil water under fluctuating water tables. ET_c was calculated as the product of plant transpiration rate and LAI. Transpiration rates of typical plants of the study area were obtained by porometry in nonstressed plants, and LAI was determined during the peak of the growing season. The California Irrigation Management Information System (CIMIS) provided ET_o data. Daily estimates of ET_c and ET_o were used to obtain daily values of K_c per species as in Equation 3. The estimated K_c were subsequently multiplied by ET_o values to calculate vegetation ET_c. In their calculations it was inappropriately assumed that there was no soil evaporation.

Steinwand et al. (2001) calculated K_c of three Great Basin shrubs, *Atriplex lentiformis* ssp. *torreyi*, *Chrysothamnus nauseosus*, and *Sarcobatus vermiculatus* to estimate evapotranspiration of plant communities. Similar to Or & Groeneveld (1994), ET_c was obtained as the product of transpiration rate and LAI. Transpiration rates were obtained by porometry in plants growing under adequate soil water conditions, and LAI was obtained during the peak of the growing season. It was considered that ET_c represented vegetation water requirements without considering soil evaporation losses. Reference evapotranspiration (ET_o) was obtained as in Or & Groeneveld (1994).

Evaluation of the K_c Method Assumptions

The applications of the K_c method in arid and semiarid vegetation have in common that plant water requirements can be determined if K_c and LAI are known. In these applications, ET_c is estimated in nonstressed plants, as it is required by the the K_c method (Allen et al., 1998). Avoiding low transpiration rates is consistent with the method guidelines, but produces artificially high K_c parameters that are not representative of the real field conditions in arid environments.

Further, the necessary assumptions—(1) that transpiration rates of a species are constant for a given day of the year, since they are a function of the species inherent potential water use (K_c) in relation to the maximum water use of a plant under ideal conditions (ET_o), and (2) that the only variable that determines water use of a plant is its leaf area—are inappropriate and impossible to meet in arid systems. Also, it is assumed that plants had maximum foliage cover throughout the growing season, since LAI is obtained during the peak of the growing season. This further overestimates plant water use. Lastly, the K_c method does not consider stomatal regulation that occurs in plants with well-developed canopies under water or nutrient shortages as a means of limiting water loss (Jones et al., 1980; Malek et al., 1997; Maroco et al., 2000; Mata-González et al., 2002, Xiongwen, 2002).

Many studies have illustrated that stomatal regulation commonly occurs. Jones et al. (1980) found that swards of perennial ryegrass (*Lolium perenne*) subjected to water deficits experienced lower transpiration rates than well-irrigated swards of similar leaf area. Malek et al. (1997) reported that evapotranspiration by natural vegetation in a Great Basin valley was very dependent on precipitation and concluded that plants adjusted their stomata to control water loss in dry years. Mata-González et al. (2002) found that desert grasses developed a vigorous leaf area as a result of increasing the availability of nutrients in the rooting medium. Increased stomatal conductance and transpiration accompanied the initial increase in leaf area. Leaf area continued to increase with nutrient availability, but stomatal conductance and transpiration decreased up to 50% as plants began experiencing water limitations at the root level. Therefore, while a well-developed canopy is advantageous for desert plants, this does not necessarily translate into a correspondingly higher water usage because plants display stomatal regulation to limit water loss (Pereira, 1995; Maroco et al., 2000).

Plants with well-developed canopies can also regulate water loss by moving, rolling, or curling leaves to reduce incident solar radiation and exposure to wind (Ehleringer, 1988; Brown, 1995). These morphological adaptations can reduce transpiration by 40% in native grasses (Rychnovská-Soudková, 1966, cited in Larcher, 1995). The K_c method is intended for crops growing in adequate conditions of soil moisture and, therefore, does not address stomatal regulation and plant adaptations to drought.

Accuracy of the K_c Method in Arid-land Vegetation

Results comparing K_c method with lysimeter estimations in Wight & Hanks (1981) in multiple years indicate that unadjusted K_c overestimated evapotranspiration by 23 to 100%. The accuracy values were obtained by dividing the K_c estimations by the lysimeter estimations provided by the authors. After adjusting K_c by soil water content, estimations of evapotranspiration ranged from overestimating (14%) to underestimating (20%) the lysimeter evapotranspiration measurements. Wight & Hanks (1981) established that the reason for the discrepancies was the lack of a mechanism to account for the effects of drought in years of high evaporative demand.

Evapotranspiration was estimated over a three-year period utilizing the adjusted K_c method and lysimeters and comparisons were reported for 17 months by Wight et al. (1986). It was found that for six of the 17 comparisons, the K_c method estimated evapotranspiration values that represented 25% to 52% of those obtained in lysimeters. During the year in which soil available water was lowest, the K_c method estimated, on average, 58% of the actual lysimeter evapotranspiration. In the wetter years, the K_c method estimates were 75% of those of lysimeters. In another study, Wight & Hanson (1990) conceded that their K_c determinations were crude because the high soil water requirement for the determinations of ET_c were met only few times during the year.

Or & Groeneveld (1994) used their estimates of evapotranspiration in a water balance equation to calculate soil water storage. Thus, their soil water storage calculations were dependent on the determination of evapotranspiration by K_c parameters. Since Or & Groeneveld (1994) also calculated soil water content, an indirect estimation of the accuracy of the K_c parameters can be established. They reported that soil water storage obtained from water balance was overestimated by more than 100% during periods of water stress. They attributed this to the inability of their deterministic model to predict water uptake by plants subjected to water limitations because K_c parameters were obtained under no stress conditions.

The estimations of evapotranspiration in Steinwand et al. (2001) were not compared to reliable field measurements of plant stand water use. There were only comparisons with field estimations based on porometer readings, which due to the problem of scaling from the leaf to the plant community, tend to overestimate plant transpiration (Ansley et al., 1994)

Adjustments of the K_c Method for Arid Conditions

Allen et al. (1998) suggested that the K_c method can be used in native vegetation under water deficits. For this, adjustments for low soil water available, low leaf area, and high stomatal resistance were suggested. The adjustment for low soil water available involves the determination of K_s, a water stress coefficient that is used to modify K_c and to calculate and adjust ET_c for water stress conditions as follows:

$$ET_{cadj} = K_c \times K_s \times ET_o, \tag{Eq. 5}$$

where ET_{cadj} is crop evapotranspiration adjusted for low soil water available, K_c is crop coefficient, K_s is water stress coefficient, and ET_o is reference evapotranspiration.

The value of K_s ranges between zero and one. When there is adequate soil water available, no stress is imposed in plants ($K_s = 1$). For this to happen, soil water content should be between field capacity and the readily available water (RAW) threshold. Below this threshold, water is more tightly held by the soil and transpiration cannot occur fast enough to respond to the evaporative demand. Then plants are under drought stress, and K_s becomes less than one. As soil water declines and reaches the wilting point, K_s becomes zero. The values of K_s are governed by the following equation (Allen et al., 1998)

$$K_s = \frac{TAW - D_r}{TAW - RAW}, \tag{Eq. 6}$$

where K_s is a water stress coefficient, TAW is total available water (field capacity-wilting point), D_r is water shortage relative to field capacity, and RAW is readily available water.

The calculation of K_s erroneously assumes that wilting point (−1.5 MPa) is the lowest water potential at which plants can transpire and survive. This is the typical agronomic interpretation of soil water constants, which has little relation with the ability of desert plants to survive under water stress.

For example, the desert shrub *Larrea tridentata* maintains photosynthesis and transpiration at –7.0 to –8.0 MPa under field conditions (Yan et al., 2000), well below the wilting point. Other desert shrubs (*Atriplex confertifolia* and *Ceratoides lanata*) can extract water from soils at –8.0 MPa (Caldwell et al., 1977). There are also reports of desert shrubs surviving at water potentials of –10.3 to –12.0 MPa (see MacMahon & Schimpf, 1981, for a review). Clearly, the agronomic concepts behind Equation 6 are not applicable to desert vegetation. Therefore, the K_c method would overestimate evapotranspiration if the K_s adjustment is not applied, but would underestimate it if the K_s adjustment is applied.

Allen et al. (1998) also suggested an adjustment for low leaf area (sparse vegetation) since the K_c method was originally planned for crops covering the soil surface. For natural vegetation, ground cover is often reduced and extensive bare areas are present, which favors water losses by evaporation when the soil surface is wet. In this case, K_c is divided into K_{cb} and K_e, representing water losses due to transpiration and soil evaporation, respectively. Allen et al. (1998) provided estimations of K_{cb} for a number of crops based on the original K_c values under standard conditions. However, there are no estimations of this type for native desert vegetation. Another difficulty in adjusting K_c for sparse vegetation is the estimation of K_e because it involves measurements of soil water content and soil water balance during those periods of time when the soil is wet. Partitioning evaporation and transpiration can also be simulated by mechanistic models (Qiu et al., 1999), but this would greatly increase the level of complexity in determining K_c.

The K_c method is not intended for plants with a high degree of stomatal control, hence the low value of leaf diffusive resistance of the reference crop (70 s m^{-1}). Resistance values of 50 to 100 s m^{-1} are indicative of open stomata and tend to increase as stomata closes (Rosenberg et al., 1983). For plants adapted to arid conditions leaf diffusive resistance can be much higher: *Atriplex confertifolia*, 2000 s m^{-1} (Caldwell et al., 1977); *Prosopis glandulosa*, 4000 s m^{-1}(Hanson & Dye, 1980); *Artemisia tridentata*, 5000 s m^{-1}(Caldwell, 1979). Allen et al. (1998) suggested also an adjustment of K_c for vegetation with high degree of stomatal control. The following equation (based on Equation 2) calculates such adjustment factor (F_r), which ranges from near zero to one and is multiplied by K_c (or K_{cb})

$$F_r = \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma(1 + 0.34[r_l/100])}, \qquad \text{(Eq. 7)}$$

where F_r is the stomatal adjustment factor, Δ is slope vapor pressure curve (kPa°C $^{-1}$), γ is the psychrometric constant (kPa°C^{-1}), u_2 is wind speed at 2 m height (m s^{-1}), and r_l is leaf diffusive resistance. Calculating F_r for some desert shrubs with leaf diffusive resistance of 2000 to 5000 s m^{-1} would result in reducing K_c by 75 to 90%.

In theory, these adjustments could make the K_c method more adaptable to arid vegetation. In practice, implementing the K_s adjustment would result in assuming zero transpiration at wilting point when in reality desert vegetation can still transpire. Implementing the dual coefficient (K_{cb} and K_e) and the F_r adjustment would greatly increase the complexity of the calculations. Wight & Hanks (1981) used an adjustment for available soil water (Equation 4), but more recent applications of the K_c method in desert vegetation (Or & Groeneveld, 1994; Steinwand et al., 2001) emphasized the simplicity of the method and avoided adjustments for drought stress, leaf area, and stomatal control. An important objective of using the K_c method in arid-land vegetation is to provide a widely accepted approach for calculating vegetation water requirements (Steinwand et al., 2001). Based on our review, however, the appropriateness of this approach seems questionable.

In an agricultural setting, a study estimated evapotranspiration of barley and wheat by the K_c method incorporating K_s adjustment for drought and dual crop coefficients (K_{cb} and K_e), and compared it to results obtained with lysimeters (Eitzinger et al., 2002). They reported that the K_c method and the lysimeter results were similar in one year of favorable precipitation. However, in the next year with lower precipitation, the K_c method estimated more than double evapotranspiration than the lysimeters. These results indicate that even applying the adjustments for water-limited crops, the K_c method is not reliable when applied in water-limited conditions.

According to Lascano (2000), the K_c method is not reliable even in crops that are purposely maintained at suboptimal irrigation. In these crops, irrigation can be made on a frequent basis and with small quantities of water. However, the use of the K_c method to calculate irrigation requirements often leads to an overestimation of these requirements.

Summary and Conclusions

A list of the variables involved in the determination of K_c and a summary of how they typically overestimate the determinations of evapotranspiration in arid systems is shown in Table 1. Our review indicates that the transpiration coefficient method is not suitable to determine water use by arid-land vegetation. The method was

Table 1. General variables involved in the calculation of transpiration coefficient (K_c) and their effect in the determination of evapotranspiration in arid systems

Variable	Effect in determining evapotranspiration
Crop evapotranspiration (ET_c)	High values obtained under optimum irrigation overestimate K_c
Leaf area index (LAI)	High values obtained under peak-growth season overestimate ET_c
Transpiration rate	High values obtained in well-watered plants overestimate ET_c

specifically designed for irrigated crops and is based on the assumption that plants are growing under nonlimiting conditions of soil water and nutrients. Based on these conditions, the transpiration coefficient method also assumes that plants have high leaf area index and low resistance to transpiration. This is clearly not the case for the vegetation of arid environments. Because of their adaptation to arid conditions, desert plants have low leaf area index and a strong tendency to regulate stomatal water loss. These two characteristics are incompatible with the assumptions of the K_c method.

Results from a number of research papers indicate that the accuracy of the transpiration coefficient method decreases as plants face increasing limitations of soil water. Although the simplicity and wide recognition of the method can be alluring, we suggest that this method should not be used to determine water use of native vegetation in arid environments.

Accurate estimations of evapotranspiration in arid environments remains a pressing need. The problem is one of scale. Accurate representations of evapotranspiration at the level of individual plant or plant stand can be obtained by using soil water budgets in conjunction with the determination of canopy transpiration. The limitation of this approach is the potential error incurred in extrapolating the results to the landscape level due to the heterogeneity of soils and vegetation. On the other hand, micrometeorological methods such as eddy covariance provide gross estimations of evapotranspiration flux at the landscape level that lack the level of accuracy obtained at smaller scales.

Improvement in instrumentation will undoubtedly result in better micrometeorological estimations of evapotranspiration. However, determinations of soil evaporation and plant transpiration at the local level would be necessary to "ground-truth" the landscape determinations. A compromise between these two scales of determination can be achieved by the use of ecosystem models with the capability to simulate soil and plant processes mechanistically at multiple spatial scales (Childress et al., 1999, 2002).

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