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Soil Moisture: A Central and Unifying Theme in Physical Geography

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Soil moisture: A central and unifying theme in physical geography

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Abstract

Soil moisture is a critical component of the earth system and plays an integrative role among the various subfields of physical geography. This paper highlights not just how soil moisture affects atmospheric, geomorphic, hydrologic, and biologic processes but that it lies at the intersection of these areas of scientific inquiry. Soil moisture impacts earth surface processes in such a way that it creates an obvious synergistic relationship among the various subfields of physical geography. The dispersive and cohesive properties of soil moisture also make it an important variable in regional and microclimatic analyses, landscape denudation and change through weathering, runoff generation and partitioning, mass wasting, and sediment transport. Thus, this paper serves as a call to use research in soil moisture as an integrative and unifying theme in physical geography.

Keywords
biogeography, climatology, geomorphology, hydrology, soil moisture

I Introduction

Soil moisture or the available soil water content – the water contained in the root zone of the soil and available for plant utilization – is an

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essential component of the hydrologic cycle (Mahmood, 1996). In the fundamental equation that describes the hydrologic cycle:

$$\begin{aligned} dS/dt = {} & (P_r + M) - (E + T) \\ & - \left(R_o + R_s + R_g\right) \end{aligned} \tag{1}$$

the time rate of change of soil moisture (*dS/dt*) is balanced by the moisture input from rainfall (P_r) and snowmelt (*M*) and the moisture loss through soil evaporation (*E*), plant transpiration (*T*), overland runoff (R_o) through either saturation or Hortonian flow, lateral subsurface flow (R_s), and percolation to groundwater (R_g). At the basic level, soil moisture content describes the temporal condition of water available to plants as well as providing an integrated assessment of the relative state of water supply versus water demand.

In addition to its obvious importance to hydrology, soil moisture is a variable whose importance extends to all aspects of physical geography. It provides the reservoir of water through which the fluxes of energy and moisture between the land surface and the atmosphere interact; it establishes the ground conditions upon which water movement from saturated, parched, or frozen soils can occur; and it supplies the necessary ingredients for the existence and development of plant life through both transport (lateral and vertical) and solubility. By its very nature, therefore, soil moisture serves to integrate physical geography. Figure 1 highlights these linkages and discusses impacts of various levels of soil moisture and climate, biogeography, and geomorphology.

Soil moisture is estimated by either in situ measurements, remote sensing techniques, or by atmospheric or hydrologic modeling. In the absence of a well-integrated program of sampling and scaling, the limited areal coverage over large land surface areas makes it difficult to use in situ measurements for studies more extensive than field-scale (Robinson et al., 2008; Robock et al., 2000; Verstraeten et al., 2008; Wu and Li, 2009). By contrast, remote sensing of soil moisture can be advantageous owing to its continuous temporal and spatial coverage. A combined data assimilation approach with remotely sensed estimates and hydrologic modeling, calibrated with in situ measurements to quantify errors and uncertainties, is the most promising approach for soil moisture estimation involving large areas, although it too is likely to have deficiencies. A complete discussion of soil moisture measurements is beyond the scope of this topical review, but for a more thorough discussion of methods to measure soil moisture, the reader is encouraged to consult the following references. Observations – Francesca et al. (2010); Robinson et al. (2008); Vera et al. (2009); Vereecken et al. (2008). Models – Choi and Liang (2010); Fulakeza et al. (2002); Steiner et al. (2005). Remote sensing – Anderson and Croft (2009); Kerr (2007); Kidd et al. (2009); Schmugge et al. (2002); Tang et al. (2009); Wagner et al. (2007a, 2007b). Data assimilation – Balsamo et al. (2007); Dorigo et al. (2007); Ni-Meister (2008); Reichle et al. (2004).

II Soil moisture and climate

In its most basic role, climatology (and climate science in general) seeks to describe the spatial and temporal fluxes of energy, moisture, and momentum between the atmosphere and the land surface, for which soil moisture plays an integral part (Thornthwaite, 1961; McCumber and Pielke, 1981; Chen and Avissar, 1994; Mahmood, 1996; Mahmood and Hubbard, 2002; 2004; 2007; LeMone et al., 2007). Water, in general, and soil moisture in particular are of fundamental importance to the ‘topoclimatology’ espoused by C.W. Thornthwaite (1953; 1961) and forms the basis of much of the subfield of hydroclimatology (Mather, 1991). *Topoclimatology* was defined by Thornthwaite as the study of those interactions between climate and the earth’s surface that lead to geographical

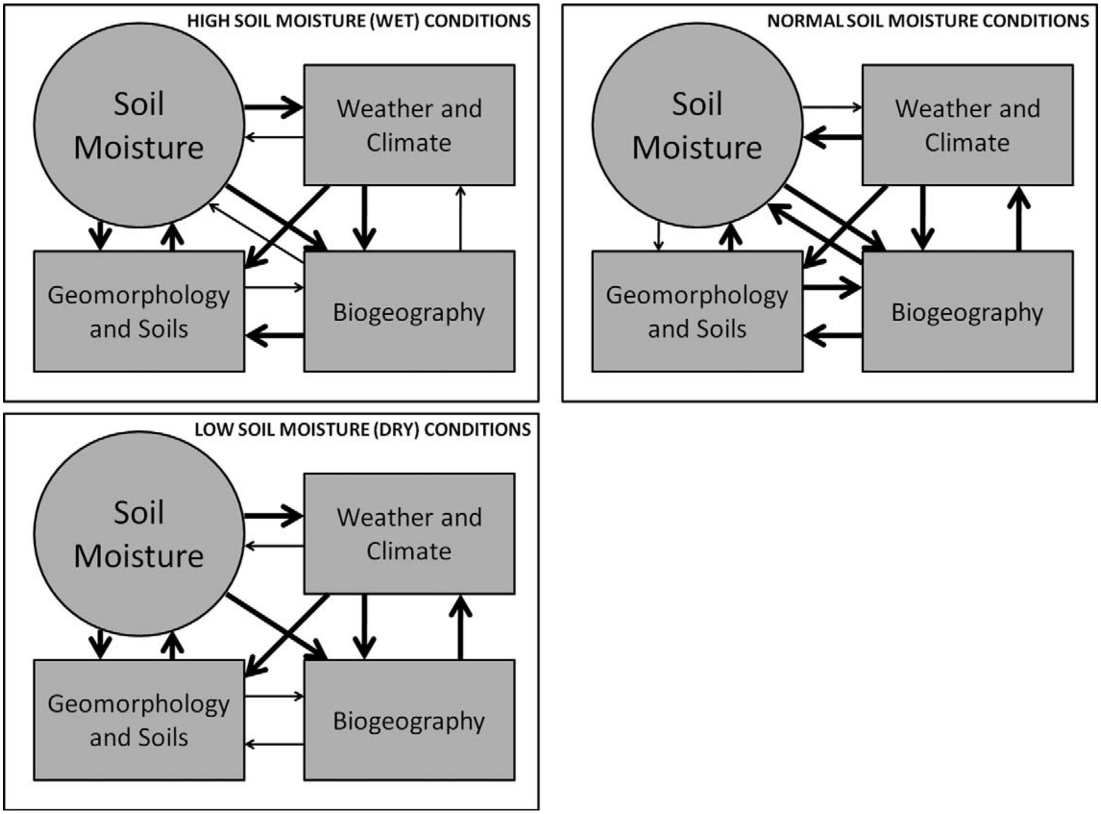

Figure 1. Schematic showing simplified interactions between soil moisture, weather and climate, geomorphology and soils, and biogeography for high (upper left), normal (upper right), and low (lower left) soil moisture conditions. Bold arrows imply stronger linkage. In particular, soil moisture affects climate during dry and wet conditions (albedo change and partitioning between latent and sensible heat) while during normal conditions, climate variability drives fluctuations in soil moisture. Soil moisture is affected by fluvial processes during dry conditions and aeolian processes during wet conditions whereas geomorphology and soil type dictate the water-holding properties of the soil. Soil moisture affects biogeography during both wet (root rot and waterlogging), normal, and dry (wilting) conditions whereas the influence of biogeography on soil moisture is strongest during normal conditions. Interactions among the three subdisciplines also are shown.

variability of climate. Soil moisture is an integral component of the topoclimate.

Indeed, the concept of climatic classification has often focused on the interplay between moisture availability (precipitation) and moisture demand (potential evapotranspiration, with air temperature often used as a surrogate). It is no surprise then that moisture indices derived from climate classifications are reflective of the temporal characteristics of the soil moisture condition (Feddema, 2007; Mather, 1985; Thornthwaite, 1948; Willmott and Feddema, 1992). Indeed, the temporal variability of soil moisture in a given region is fundamental to the definition of its climate.

Far from being simply a resultant statistic, soil moisture itself is an active variable. It has been suggested that local evapotranspiration (i.e. latent heat flux) is the source of 10 to 30% of atmospheric water vapor (Brubaker et al., 1993). Obviously, soil moisture plays an important role in regulating the rate of the evapotranspiration. Moreover, Chen and Avissar (1994) noted that the development of clouds and precipitation in a dry atmosphere is critically dependent on these local sources of moisture. Research has shown that changes to soil moisture modify the surface Bowen ratio (Rosenberg et al., 1983; Thom, 1972), the convective available potential energy (Clark and Arritt, 1995; Pielke, 2001), development of cloud (Ek and Holtslag, 2004; Findell and Eltahir, 2003), precipitation (Ookouchi et al., 1984; Pal and Eltahir, 2001; Pan et al., 1996; Quintanar et al., 2008; 2009), and the daytime evolution of the planetary boundary layer (Zhang and Anthes, 1982), particularly its wind field (Segal and Arritt, 1992). For example, Rabin et al. (1990) found convective clouds formed first over mesoscale-size areas of harvest wheat in Oklahoma with high sensible heat flux, in comparison to adjoining areas dominated by growing vegetation. Clouds were suppressed over relatively long bands downwind of small lakes and heavy tree cover represented by high latent heat flux. The more recent empirical and modeling study of Santanello et al. (2007) examined interactions between planetary boundary level height, initial atmospheric stability, and soil moisture using observed radiosonde data and a one-dimensional model. Both positive and negative feedbacks were identified that explained the land surface-atmospheric interactions; for example, a positive feedback resulted for dry soils with entrainment on soil drying, surface heating, and residual boundary layer growth.

Additional studies have focused specifically on the interactions of soil moisture and patterns of precipitation. Dong et al. (2007) noted a positive relationship between soil moisture and precipitation over grassland while Chang et al. (2009) found that antecedent soil moisture (wetter and warmer) further intensifies landfalling monsoonal low pressures. In a detailed regional modeling study, Koster et al. (2004) found areas of strong coupling, or ‘hot spots’, between soil moisture and precipitation. These so-called ‘hot spots’ are generally located in transition zones between wet and dry climates such as those found in the central Great Plains of North America, the Sahel, equatorial Africa, and India. In these regions, potential evapotranspiration is consistently high while actual evapotranspiration is sensitive to soil moisture availability. Koster et al. (2004) further found that the response of the atmosphere to soil moisture is non-linear and not unidirectional and, moreover, wet soils can both increase and decrease the possibility of convection and precipitation, depending upon the initial state of the atmosphere (cf. Findell and Eltahir, 2003).

Owing to the lack of high-density networks over much of the globe, proper initiation of soil moisture in numerical models is often difficult. Studies that have reasonably prescribed soil conditions in atmospheric models have noted improvements in simulated forecasts (Dirmeyer, 2000; Douville et al., 2001; Hong and Kalnay, 2000; Huang et al., 1996; Schlosser and Milly, 2002). Dirmeyer (2000), in particular, noted a reduction in root-mean-square error in modeled near-surface temperature and improved rainfall patterns with reasonable specification of root zone soil moisture. Similarly, both Huang et al. (1996) and Schlosser and Milly (2002) found a strong correlation between subsurface water storage and modeled near-surface temperature and precipitation. Grasso (2000) has also noted an improvement in modeled forecasts with proper specification of both soil moisture and overlying vegetation.

Latent and sensible heat fluxes are affected by variations in soil moisture, both spatially and temporally, which alter the near-surface air temperature and humidity. This, in turn, can alter precipitation (Clark et al., 2004; Jones and Brunsell, 2009; Walker and Rowntree, 1977), temperature (Brown and Wax, 2007; De Laat and Maurellis, 2006), atmospheric circulation (Namias, 1959; Ookouchi et al., 1984; Pinty et al., 1989; Walker and Rowntree, 1977), and the climate in general (Rind, 1982; Shukla and Mintz, 1982; Yeh et al., 1984) which often accentuates and extends anomalous conditions

(Andreadis and Lettenmaier, 2006; DeLiberty and Legates, 2003, 2008; Entin et al., 2000; Koster and Suarez, 2003; Oglesby and Erickson, 1989; Rasmusson and Arkin, 1993). As a consequence, weather conditions may be affected by abnormal soil moisture conditions, provided the anomaly is of sufficient spatial and temporal size and intensity.

Because droughts are directly related to soil moisture conditions, much effort has been put into drought monitoring (e.g. Narasimhan and Srinivasan, 2005; Quiring, 2004), drought mitigation (Wilhite, 1997), and insurance protection (Abbaspour et al., 1992). However, flood events too can be exacerbated by high antecedent soil moisture conditions (Gamble and Meentemeyer, 1997; Hossain, 2006; Lacava et al., 2005). Gamble and Meentemeyer (1997) showed, for example, that high soil moisture with moderate rains often produced unseasonable floods in the southeastern United States. Indeed, the impact of too little as well as too much soil moisture can adversely affect crop yields such that accurate forecasts are needed to monitor the situation (e.g. Quiring and Legates, 2008). Soil moisture can be both a symptom of drought as well as a contributing factor. Although remote forcings such as sea-surface temperature (SST) anomalies in the Pacific and Atlantic Oceans are often the primary cause of North American droughts (e.g. McCabe et al., 2004, 2010; Quiring and Goodrich, 2008), Wu and Kinter (2009) distinguished the timescales of droughts and found the roles of SST forcing and local soil moisture differ significantly for long-term versus short-term droughts. Moreover, it has recently been demonstrated that soil moisture can play a significant role in modifying summer precipitation during the periods when SST anomalies are weak (Meng and Quiring, 2010). Local precipitation recycling can contribute to the intensity and duration of droughts and, therefore, an understanding of local land-atmosphere interactions (e.g. soil moisture) is a key to understanding and predicting the occurrence of droughts.

III Soil moisture in geomorphology and hydrology

The dispersive and cohesive properties of soil moisture makes it an important variable in landscape denudation through weathering (e.g. Anderson, 2005; Richards and Kump, 2003; Stockwell et al., 2006), runoff generation and erosion (e.g. McDowell and Sharpley, 2002; McDowell et al., 2001; Seeger et al., 2004), and mass wasting (e.g. Acharya et al., 2009; Korup et al., 2004; Schuerch et al., 2006). It is also responsible for increasing soil moisture capacity through soil development (Phillips et al., 2008) and promoting the development of vegetation that can limit erosion (Harden and Scruggs, 2003). Specifically, the spatial and temporal variation in soil moisture in a drainage basin has implications for understanding environmental processes such as runoff generation and continuity as well as the erosion and sedimentation driven by overland flow. Overland runoff is generated through either the saturation of the soil to the surface (i.e. saturation overland flow) or through precipitation exceeding infiltration rates (i.e. Hortonian overland flow). The latter is the dominant mechanism in arid and semi-arid environments and depends on the precipitation rate relative to the infiltration capacity of the soil; it is therefore dependent on how much water is already in the soil. Infiltration capacity is greatest at the start of a storm and decreases rapidly until a constant infiltration rate is reached (Horton, 1933).

1 Flow partitioning and mass wasting

In humid-temperate regions, saturation overland flow is generated when the soil becomes totally saturated and is unable to receive any more water (Kirkby and Chorley, 1967). These variable source areas are responsible for storm runoff (e.g. Dunne and Black, 1970; Hewlett and Hibbert, 1967; Tsukamoto, 1963) and first develop where the water table is relatively shallow. Regardless of the environment, antecedent moisture in the soil promotes the development of overland flow earlier in a precipitation event, meaning that a significant volume of water is contributed to the main channel network in a short time. In this respect, Vertessy and Elsenbeer (1999) argued that a poor understanding of soil moisture remains one of the most significant weaknesses in process-based storm flow models and the ability to predict runoff generation and erosion, while Grayson et al. (1992) argued that antecedent moisture is the parameter most likely to undermine model predictions (see also Mahanama et al., 2008).

Through its role in flow partitioning, antecedent soil moisture is also an important physical control on nutrient and sediment loss by overland flow (Casenave and Valentin, 1992; McDowell and Sharpley, 2002; McDowell et al., 2001) and has been demonstrated in several studies (Ceballos and Schnabel, 1998; Fitzjohn et al., 1998; Karnieli and Ben-Asher, 1993). The degree to which soil moisture is a primary control on runoff generation and erosion depends on basin size and the characteristics of the precipitation event. Castillo et al. (2003) have shown that the peak discharge and runoff during high-intensity, low-frequency storms is independent of initial soil water content, but is important in controlling runoff during medium- and low-intensity storms that are primarily responsible for erosion in semi-arid environments (see also Merz and Bardossy, 1998; Poesen and Hooke, 1997). Soil moisture is more important where vegetation increases the spatial variability of soil characteristics and produces a range of runoff and infiltration sites (Castillo et al., 2003). Similarly, Fitzjohn et al. (1998) have shown that spatial heterogeneity of surface moisture can reduce widespread catchment runoff and erosion by promoting discontinuity in hydrological pathways through the isolation of runoff-producing areas and the reabsorption of runoff generated upstream. By contrast, antecedent moisture can reduce surface crusting through dissolution and disturbance, which limits runoff and interrill erosion (Le Bissonnais and Singer, 1992). Higher soil moisture contents are also responsible for limiting the development of hydrophobic compounds that coat particles and create a water-repellent layer following forest fires (Robichaud, 2000; Robichaud and Hungerford, 2000), similarly limiting post-fire runoff and erosion.

Spatial and temporal variations in soil moisture and other physical properties of the soil (e.g. clay composition, buried organic matter) are partly responsible for significant variation in the generation of overland flow (Godsey et al., 2004; Sharma et al., 1980; Sidle et al., 2000; Uchida et al., 1999; Ziegler et al., 2001). Soil moisture variation depends in part on the distribution of vegetation (Harden and Scruggs, 2003), topography (Julien and Moglen, 1990), and surface characteristics (Katra et al., 2008; Poesen et al., 1999); variables that are themselves dependent on the distribution of soil moisture. This spatial variation affects the amount and source of sediment delivered to the main channel. Seeger et al. (2004) found that variations in suspended sediment concentration during flood events are associated with different levels of humidity and rainfall, indicating different mechanisms for the development of runoff and sediment transport. A high level of antecedent soil moisture promotes runoff generation and sediment supply to the nearby channel, leading to an increase in suspended sediment concentration over the course of a storm as compared to ‘normal’ moisture levels that limit runoff and the sediment source to near the channel. The impact of antecedent soil moisture is much greater in small catchments (Seeger et al., 2004). More sediment is available to overland flow from dry soils that break down faster through slaking caused by the compression of entrapped air, while moist soils prevent slaking and limit the ability of the soil to be disaggregated (McDowell and Trudgill, 2000).

Sediment delivery to channels and the long-term shaping of a watershed can also occur through mass movements triggered by soil at or close to saturation (e.g.Acharya et al., 2009; Benda and Dunne, 1997; Korup et al., 2004; Schuerch et al., 2006; Schwab et al., 2008). The frequency of mass movements is correlated with an increase in pore pressure resulting from heavy precipitation (Johnson and Sitar, 1990) and wetter climates (Brooks and Richards, 1994; Grove, 1972; Innes, 1983; Pitts, 1983). These events exhibit a threshold dependence on soil moisture since pore pressure, internal friction, and cohesion are primarily dependent on soil moisture content (Iverson, 2000; Pelletier et al., 1997; Ray and Jacobs, 2007; Van Asch et al., 1999). Numerous field studies have shown that antecedent soil moisture and surface runoff from upslope are important controls on the frequency and size of mass movements (e.g. Iverson, 2000; Larsen and Simon, 1993; Van Asch and Sukmantalya, 1993; Van Asch et al., 2009; Wieczoreck and Glade, 2005). The importance of soil moisture in controlling mass wasting is highlighted by the strong correlation between the location and frequency of landslides with soil drainage and the storage properties of soil moisture (Pelletier et al., 1997; Ray and Jacobs, 2007).

2 Aeolian processes

In addition to flow partitioning and mass wasting, soil moisture is also of particular importance in controlling sediment mobility in wind-blown environments; indeed, the role of moisture in surface deflation has been the focus of several field and laboratory studies (e.g. Azizov, 1977; Bisal and Hsieh, 1966; Brazel et al., 1986; Chepil, 1956; Davidson-Arnott et al., 2005; Fecan et al., 1999; Hotta et al., 1984; Jackson and Nordstrom, 1997; Logie, 1982; McKenna-Neuman and Maljaars, 1997; 1998; Sarre, 1987; Smalley, 1970; Wiggs et al., 2004). Several field studies have shown that the role of soil moisture is especially important in controlling the exchange of sediment between beach and dune (e.g. Arens, 1996; Bauer et al., 2009; Hotta et al., 1984; Sherman et al., 1998; Svasek and Terwindt, 1974; Wiggs et al., 2004; Yang and Davidson-Arnott, 2005) where spatial and temporal variations in soil moisture can degrade the ability of currently available models to predict sediment transport (Sherman et al., 1998). Similarly, empirical relationships between dust events and climate tend to be inaccurate for prediction unless soil moisture is explicitly modeled (McTainsh et al., 1998). These relationships are complicated by the growth of vegetation in response to surface moisture. Vegetation can increase the threshold shear velocity by directly covering part of the surface and absorbing part of the wind momentum that would otherwise go to the sediment surface (Lancaster and Baas, 1998; Wolfe and Nickling, 1993). The role of vegetation in controlling dust emissions is most difficult to quantify because the relationships between soil moisture, vegetation cover, and turbulent shear stresses are poorly understood.

Low soil moisture combined with a lack of surface cover, strong winds and low humidity is an important factor associated with dust events (Nickling and Brazel, 1984; Lee et al., 1994; Stout, 2001). Interannual variations in dust emissions appear to be closely associated with antecedent precipitation (Nickling and Brazel, 1984) with dust emissions increasing during regionally wet El Niño events as a result of the erosion of vegetation and the deposition of new sediment (Reynolds et al., 2007). Nickling and Brazel (1984) observed that the occurrence of large-scale dust storms followed rainstorm activity but quickly dissipated. The resealing of clay crusts, which occurred after these rainstorms, was limited to the surface and consequently peel and curl to expose thin pieces of crust that are easily abraded by saltating grains. As the weaker surface crust was abraded, a strong stable clay/silt crust was left behind that was more difficult to abrade (Houser and Nickling, 2001). More recently, Stout (2001) described the annual dust cycle of the Southern

High Plains of Texas as a reflection of seasonal change in environmental factors, including surface moisture. Relationships among El Niño-Southern Oscillation (ENSO) events, dust sources, and dust composition also have recently been described by Okin and Reheis (2002) and Reheis (2006).

McKenna-Neuman and Nickling (1989) have shown that gravimetric water contents of $\sim 1\%$ create sufficient interparticle cohesion that entrainment by aerodynamic forces is all but impossible, although there is much disagreement. Furthermore, Wiggs et al. (2004) have shown that soil moisture contents of up to 1.68% do not act as a barrier to sediment flux. Field studies have shown that soil moisture contents over which transport events can occur tend to be greater than those measured in the laboratory or predicted theoretically. Hotta et al. (1984) suggests that the threshold shear velocity increases by 7.5 cm s^{-1} for each 1% increase in soil moisture up to a moisture content of 8%, at which entrainment ceases. If saltating particles are present, then sediment entrainment is dominated by impact forces. Saltation is not inhibited until soil moisture content reaches 14% (Sarre and Chancey, 1990) and Jackson and Nordstrom (1998) observed transport at surface moistures of >7% following light rains. The rate of transport increased following the rain event as the surface dried but remained greater than the transport rates measured on dry beaches. An earlier field study by Jackson and Nordstrom (1997) and a laboratory study by McKenna-Neuman and Maljaars (1997; 1998) indicated that transport rates are greater on damp surfaces due to the creation of a relatively elastic surface compared to dry, cohesion-less sediment. Drying of soil moisture is promoted by wind and is an important influence in environments where winds are competent to entrain dry but not moist sediments (Hotta et al., 1984; Jackson and Nordstrom, 1997; Logie, 1982; Sherman, 1990). Spatial variation in soil moisture and drying can lead to intermittent transport over short time periods (Davidson-Arnott et al., 2005) that can vary over an order of magnitude in the presence of a steady wind (McKenna-Neuman and Langston, 2006). Spatial and temporal variations in surface moisture can lead to the organization of the saltation cloud into streamers (Baas and Sherman, 2005). The short time required to dry a thin layer of sediment during strong winds can lead to high transport within 10–30 minutes following a soaking rain (Gillette, 1999).

The moisture content in the top sediment layer and the ability of the wind to dry the surface is dependent (to varying degrees) on the humidity of the near-surface boundary layer. Low humidity and stronger winds in the afternoon extract moisture from the surface, creating the potential for dust emissions (Stout, 2001) – most dust events on the Texas High Plains are associated with humidity levels below 30%. The humidity of the near-surface boundary layer affects particle entrainment through changes in both the kinematic viscosity (i.e. the absolute viscosity of a fluid divided by its mass density) and the density of the air (McKenna-Neuman, 2003) which, in turn, affect the critical shear velocity required for the entrainment of sediment (Belly, 1964). An increase in density reduces the aerodynamic drag force on the bed, while an increase in the kinematic viscosity increases the drag force but limits turbulence generation at both the particle and boundary-layer scale. Vapor pressures at or close to saturation can maintain high soil moisture (and vice versa), although there is a decrease in the matric potential that reduces the ability of the water to be adsorbed to the charged sediment surface (Hillel, 1998; Jury et al., 1991). Despite the change in matric potential, interparticle cohesion in moist soils is the dominant control on sediment entrainment for particles with diameters <75 μm (Greeley and Iversen, 1985). McKenna-Neuman (2003) has shown that the role of surface moisture in aeolian transport is temperature dependent. The entrainment threshold tends to be lower in cold environments due to a reduction in both the vapor pressure and matric potential, while in warm environments the high vapor pressure and matric potential leads to greater entrainment thresholds.

3 Periglacial processes

As noted by Washburn (1980), soil moisture is the sine qua non of frost action, in both seasonally and perennially frozen ground. The very definition of *permafrost* – subsurface earth materials remaining continuously at or below 0°C (i.e. the freezing point of water) for two or more years – is testament to the dominant role soil moisture plays in the geomorphic, ecological, and pedogenic processes of cold regions. A fundamental distinction in permafrost studies lies between *ice-rich* and *dry* permafrost (Bockheim and Tarnocai, 1998). Thaw of permafrost with abundant excess ice has potential for profound disturbance to ecological communities and human infrastructure at the surface through thaw consolidation and development of thermokarst terrain. In contrast, thaw of permafrost lacking appreciable water content holds little potential for disturbance at the surface.

Soil moisture plays a critical role in the long-term evolution and morphology of permafrost landscapes. Water redistributed in the soil column through freeze-thaw action creates impressive suites of landforms, including large and small frost mounds (pingos and palsas), networks of ice-wedge polygons that encompass many hectares and extend far below the ground surface, and solifluction lobes and terraces conveying vivid impressions of mass movement on hillslopes.

In medium-textured soils experiencing relatively slow freezing, moisture is attracted to freezing fronts, creating lenses of *segregated ice*. Locations at which the bottom of the seasonally thawed layer (the 'active layer') is coincident with the top of permafrost experience 'two-side freezing', a process that involves refreezing of the active layer both downward from the ground surface and upward from the permafrost table. Two-sided freezing draws moisture from the central part of the active layer to feed growing ice lenses at the upper and lower freezing fronts. Under such conditions, refreezing of the active layer can be very slow, with isothermal conditions persisting for weeks or even months, owing to latent heat effects. This 'zero curtain effect' (Outcalt et al., 1990) is characteristic of regions with ice-rich permafrost. Repeated annually over long periods (decades to millennia) these processes create thick accretions of segregated ice in the upper permafrost, just below the base of the active layer. The large amounts of energy required to thaw this extremely ice-rich layer, referred to as the 'transient layer' (Shur et al., 2005), impart buffering qualities to it that resist the deep penetration of thaw that might otherwise occur rapidly under climatic warming.

Another unusual aspect of permafrost regions lies in the key role frozen water in the soil column provides for the interpretation of Quaternary history. The continuity, arrangement, structure, crystallography, and chemistry of the various forms of underground ice (Mackay, 1972) – in soil pores, as veins and wedges, in segregated lenses, as massive bodies of injection ice, and in other forms – has given rise to a subdiscipline of permafrost science known as *cryostratigraphy* (e.g. French, 1998). Under favorable circumstances cryostratigraphic analysis can provide detailed information about local and regional climatic and geomorphic conditions extending back thousands of years.

IV Soil moisture and biogeography

Because plants are almost exclusively dependent on soil moisture to acquire needed water for photosynthesis, soil moisture and its spatial and temporal variability represent an indispensable quantity for evaluating and understanding vegetation patterns. Soil moisture recharge and utilization directly affect the distribution of vegetation and its overarching canopy structure. Vegetation directly affects soil moisture inputs at the base of plant canopies through precipitation partitioning. Precipitation partitioning is the process whereby incident rainfall and snowfall is divided into canopy interception, throughfall, or stemflow (Hewlett, 1982). The extent to which the incident precipitation is intercepted, entrained as throughfall, or routed to the subcanopy as stemflow is dependent on both biotic (canopy) and abiotic (climatological) factors, such as aboveground surface area and storm event characteristics (Levia and Frost, 2003, 2006). Precipitation intercepted by plant canopies does not contribute to soil moisture recharge. Throughfall and stemflow inputs directly affect the spatiotemporal variability of soil moisture recharge (Durocher, 1990). In fact, stemflow in temperate forests has been observed to cause the water table beneath individual tree boles to reach the soil surface, thereby accounting for drastic differences in soil moisture beneath and between trees over space and time (Durocher, 1990). More recent work by Liang et al. (2009) documents the effect of stemflow on hillslope-scale soil moisture dynamics, noting the very different influence of stemflow on vertical soil water content compared to infiltration of rainfall. In short, soil moisture controls the establishment of plant communities which, in turn, influence soil moisture recharge and its usage. This eventually further affects the establishment and expansion of plant communities as well as land-surface atmosphere interactions and variety of geomorphic processes in general.

Soil moisture extraction by vegetation is dependent upon phenological stage, stomatal resistance, vegetation type, and vegetation density. It is also known that vegetation type and fractional vegetation control transpiration rates and thus availability and variability in soil moisture (Avissar and Pielke, 1989; Barlage and Zeng, 2004; Lyons, 2002; McPherson, 2007; Mahmood and Hubbard, 2004; Narisma and Pitman, 2003; Pielke, 2001). Soil moisture availability, in turn, affects plant transpiration and related physiological activities.

Soil moisture exerts a substantial influence on vegetation, acting as a key control on stem water dynamics, stomatal regulation, and transpiration loss (Bréda and Granier, 1996; Kozlowski, 1958; Milburn, 1979). Recent work by David et al. (2004) clearly demonstrates the interplay among soil moisture, vapor pressure deficit, and sapflow for an evergreen oak in the Portuguese *montado*, sparse savannah-like ecosystems composed of evergreen green oak species (although this is a single tree, David et al. measured neighboring trees to verify their numbers were realistic). The sample tree in this study had access to deeper groundwater. Thus, soil moisture was not a limiting factor in transpiration for this particular tree (David et al., 2004). Their work demonstrated an inverse relationship between leaf water potential and sapflow. Sapflow reached a maximum of approximately 0.2 mm h^{-1} with a vapor pressure deficit of 2.0 kPa and remained at the upper limit of 0.2 mm h^{-1} with vapor pressure deficits to approximately 6.0 kPa (David et al., 2004). The upper limit of sapflow was controlled via stomatal regulation to prevent cavitation (David et al., 2004). In contrast to trees in well-watered environments, where transpiration loss is limited via stomatal control, the mismatch in water demand and supply (that vary as a function of soil type and texture) limit transpiration loss for vegetation in most soils that exhibit diurnal and seasonal fluctuations in soil moisture supply (Llorens et al., 2003). It also is important to note that interannual variations in leaf area index will have a detectable impact on transpiration loss (Bréda and Granier, 1996). Both flooding and cold soils have been found to reduce leaf conductance and transpiration for some species (Kreuzwieser et al., 2002; Teskey et al., 1984).

Research has demonstrated that transpiration differs greatly throughout the vertical profile of a forest canopy (Roberts, 2000). Although the upper portions of the forest canopy have lower proportions of leaf area compared to the midportions of the canopy, the upper canopy contributes a disproportionately large share to total transpiration (Roberts, 2000), despite generally smaller leaves and closer coupling with the atmosphere than larger leaves in the lower canopy. The greater rates and amounts of transpiration from leaves in the upper canopy can be explained, in part, by the differing leaf morphology of sun versus shade leaves (Horn, 1971).

Canopy structural characteristics, including branching patterns and bark microrelief, also affects the distribution of soil moisture by affecting stemflow inputs to the forest floor (Levia and Herwitz, 2005; Van Stan and Levia, 2010). As branching patterns change with stand age, it has been found that stemflow production can change with stand age (Murakami, 2009). Murakami (2009) reported a drastic decrease in stemflow production from ages 9 to 10 in Japanese cypress and attributed the reduction to changes in tree architecture. Therefore, it is possible that soil moisture heterogeneity may be partly accounted for by change in canopy structure and corresponding alterations in stemflow production.

As briefly indicated above, soil moisture plays a critical role in determining development and evolution of a vegetation type in a region and subsequently impacts climate. The importance of land cover (particularly vegetation) and atmospheric interactions and associated feedbacks have been well documented (Adegoke et al., 2006; Fu, 2003; Narisma and Pitman, 2003; Pielke et al., 1999, 2007; Schneider and Eugster, 2005). Carleton et al. (2008) noted changes in local atmospheric circulation by vegetation boundary discontinuity which could be determined by availability of moisture. McPherson and Stensrud (2005) have shown changes in vegetation cover impact meso-scale atmospheric circulation and development of boundary layer atmosphere. Again, establishment of a particular type of vegetation is determined by soil moisture. Adegoke et al. (2003) have also shown changes in vegetation cover along with soil moisture affect near-surface atmospheric moisture content and variety of other processes.

Whereas interception generally leads to a decrease in the input of incident precipitation to the forest floor, fog interception leads to fog drip and an increase in net precipitation inputs to forest soils (Cavelier et al., 1996; Holder, 2006). In fact, the thinning of forest in areas where fog is prevalent actually decreases fog precipitation inputs to the forest floor and, thus, soil moisture (Aboal et al., 2000). In the Canary Islands, it was found that decreases in leaf area index and basal area have led to lower inputs of moisture via fog drip (Aboal et al., 2000).

V The integrative nature of soil moisture

Soil moisture is not just a process that is integral to climate, geomorphology, and biogeography – it truly lies at the intersection of all three branches of physical geography. A complete understanding of soil moisture and its spatial and temporal variability and impact draws upon interactions among and expertise gained from all three subdivisions. Soil moisture lies at the intersection of climatology, geomorphology, biogeography, and hydrology, thereby providing true integration of the subdisciplines rather than just supplying a common theme. While the interaction of climate, soils, vegetation, and hydrology have long been recognized and analyzed (see, for example, Mather, 1978), a cross-section of some of these interactions is worth noting.

While plant growth and development is clearly directly related to soil moisture, plant responses also can be indirectly associated with the effects of soil moisture. For example, Dyer (2002) found that soil moisture, as modeled by the climatic water balance, was an excellent predictor of the occurrence of American beech (*Fagus grandifolia*). Medler et al. (2002) also evaluated the interaction between soil moisture and the spatial and temporal patterns of snowfall which, in turn, affect plant growth in the spring and the development of summer wildfires. They concluded that increases in severe wildfire resulting from decreased soil moisture are only moderately related to lowered snowfall in the previous winter. Land surface-atmosphere interactions also were found to be important in the lower Mississippi River basin by Brown and Wax (2007). In particular, they observed that differences in soil types which led to spatially variable soil moisture regimes caused significant differences in seasonal maximum and minimum air temperatures within the alluvial valley.

The highly varied spatial and temporal character of soil moisture easily lends itself to the study of its impacts on other environmental variables. Walsh et al. (1998), for example, used scale, pattern, and process with remote sensing and geographic information systems to couple geomorphic variables – including soil moisture – to biogeographic and landscape ecological processes. Bridge and Johnson (2000) found significant relationships between geomorphic principles and vegetation gradients, particularly as they relate to soil moisture and water availability. Cammeraat (2002) also focused on scale issues in geomorphology to examine how hydrological variables, such as soil moisture, are influenced by biological and climatological processes. Similarly, Western and Bloschl (1999) and Western et al. (2002) evaluated this variability in soil moisture and showed the importance of its non-linear response in environmental analyses. More recently, research has focused on a more holistic treatment of ecosystems wherein the climate, geomorphology, vegetation and soils are integrated to provide a better assessment of the overall interactions between the various components of the environment (see, for example, Abella, 2003; Botter et al., 2007; Hughes, 1997). The take-away message associated with these studies is that the entire physical system as represented by the biosphere, the atmosphere, the hydrosphere, and the lithosphere must be considered as a collective whole – not a collection of unassociated parts – if the environment is to be properly represented. Soil moisture, since its spatial and temporal characteristics are derived from the climate, land surface, and vegetative characteristics, is therefore an integrative component which summarizes and affects all components of the environment.

VI Summary and recommendations for future research

As Mather (1993) suggested in his Presidential Address to the *Association of American Geographers*, geographers should 'emphasize those aspects that bind us together rather than separate us'. Soil moisture is truly a variable that binds together the various branches of physical geography. From its impact on and the influence on it by weather and climate, geomorphology and soils, biogeography, and hydrology, soil moisture integrates all aspects of physical geography. Thus, we call on physical geographers to use soil moisture as a unifying theme in physical geography.

With that in mind, we suggest several areas of research that illustrate the integrative nature of soil moisture. For example, the WMO (2008) report on 'Future Climate Change Research and Observations' recommends that soil moisture data should be assembled, quality controlled, and harmonized because of its importance in (1) providing an improved understanding of land-atmosphere interactions, (2) the development of seasonal-to-decadal climate forecasting tools, (3) calibration, validation, and improvements in the physical parameterizations in regional and global land surface models, (4) developing and validating algorithms for determining estimates of soil moisture using satellite-based techniques, and (5) monitoring and detecting climate variability and change. Although much of this work is already underway, we anticipate and hope that more research will be focused on understanding the nature of land-atmosphere interactions and the role that soil moisture and vegetation play in influencing climate on seasonal to decadal timescales. We also foresee continued efforts to improve the accuracy of soil moisture models and the representation of soil moisture in general circulation models (GCMs) to improve the accuracy of soil energy and water fluxes to the atmosphere. But, most importantly, efforts will be focused on the development of new modeling and observational technologies, including both remotely sensed surface soil wetness products and additional in situ measurements of soil moisture. These data acquisition platforms will provide new opportunities for land surface model calibration and for developing and validating satellite-derived soil moisture algorithms.

Patch-scale temporal and spatial heterogeneity of soil moisture in forested and agricultural ecosystems is also a key element that remains inadequately understood. How do the interrelationships between and among canopy structural components, microclimates, and soil characteristics influence the timing and spatial patterns of soil moisture? A detailed understanding of soil moisture dynamics in relation to vegetative canopies will yield important insights into the exploitation of environmental heterogeneity by plants. Such knowledge at the patch scale could allow evapotranspiration models to better predict water use by plants and, ultimately, improve crop yields from precision agriculture.

From the perspective of process geomorphology, soil moisture is an important but by no means simple control on wind-blown sediment entrainment and transport, flow partitioning, mass wasting, and weathering. Contemporary research tends to be focused on spatial and temporal variations in soil moisture at a range of scale and the feedbacks therein to improve the ability of currently available models to predict sediment transport in the prototype, such as the exchange of sediment between beach and dune critical to dune recovery following storms. Moreover, the ability to discern, at high spatial resolution, variations in soil moisture and the effects of freeze and thaw over broad areas and in three dimensions is urgently needed. Methodologies for creating detailed maps of surficial heave and subsidence are under development and will prove instrumental for creating maps of hazard potential at local scales.

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