

## Chapter 2

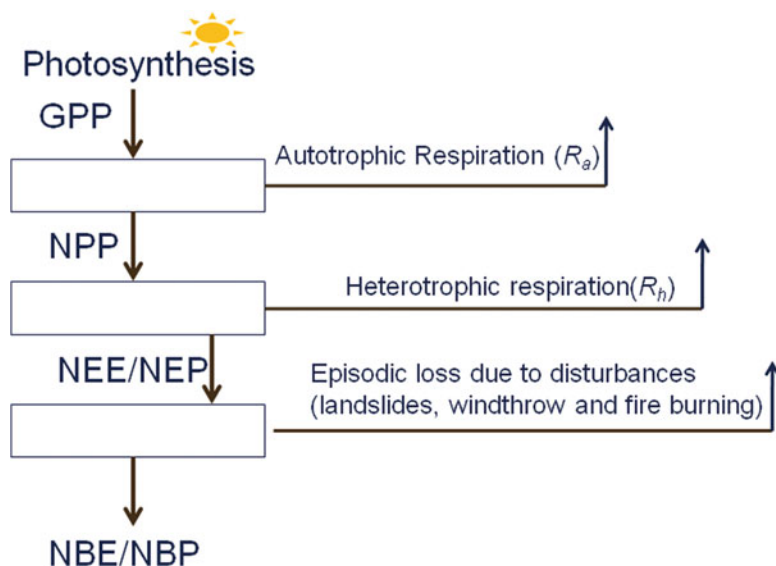
# Ecosystem of Sloping Terrain, Soil, and Vegetation

Failure of sloping earth materials falls within the general form of fatigue. However, the involved material is not a single solid specimen; rather, a multiple-body of countless degree of freedom is involved: a lump of granular material, with rocks at the coarse end of grain size and sandy loam soil at the fine end of grain size. Under the unique processes of Earth environments, the mechanical strength of the granular material is further altered by the presence of vegetation roots (fortification effects) or tunnels of subterranean animals (weakening effects). A further degree of complexity that acts on slope stability within the ecosystem of a sloping terrain is the effect on the granular material's moisture content, through slope hydrology.

### 2.1 The Biological and Physical Worlds Are Interdependent

A unique feature of terrestrial ecosystems is that vegetation acquires its resources from two very different environments; air (for CO<sub>2</sub>) and soil (for inorganic minerals of nutrients). Landslides cause disturbances to ecosystem productivity by displacing the soil mantle. In addition to being the medium in which most decomposers and many animals live, the physical soil matrix provides a source of water and nutrients to plants and microbes, and is the physical support system in which terrestrial vegetation is rooted. For these reasons, landslide displacement of the soil mantle has severe ecological consequences (Fig. 2.1).

Sloping terrain creates unique patterns of microclimates, through surface energy budgets, hydrology and availability of nutrients. For example, slopes facing the equator receive more solar radiation than opposing slopes and, hence, usually experience warmer and drier conditions. In colder or moister climates, the warmer microclimate of the equator-facing slopes provides conditions that enhance productivity, decomposition, and other ecosystem processes (including the formation



**Fig. 2.1** Diagrammatic representation of the major terms describing system carbon balances. Arrows indicate that gross primary production (GPP) and net primary production (NPP) are always positive (carbon gains by the system), net ecosystem exchange (NEE) is usually, but not always, positive, and net biome exchange/products (NBE/NEP) is the net carbon fixed and can be positive or negative. Role of landslides in the carbon cycling is as an episodic disturbance. Total global GPP is estimated to be about 120 GtC/year (Gifford 1982; Bolin et al. 2000)

of soils). Conversely, in dry climates, the low moisture levels on these slopes limit such production. Furthermore, microclimatic variations associated with slope and aspect allow stands of a particular ecosystem type to exist hundreds of kilometers beyond its major zone of distribution. These outlier populations are important sources of colonizing individuals during times of rapid climate change and are, therefore, important in understanding species migration and the long-term dynamics of ecosystems. Topography also influences climate through the drainage of cold, dense air in the form of katabatic winds that form strong near surface air temperature inversions. Inversions are climatologically important because they increase the seasonal and diurnal temperature extremes experienced by ecosystems in low-lying areas. In cool climates, inversions greatly reduce the length of the frost-free growing season. The third aspect of the impact of sloping surfaces on ecosystems is surface hydrology. The surface runoff on sloping surfaces is much larger than over flat terrain. For dry climates, this places severe water limitations on production. Before addressing the slope effects on nutrients, the soil formation process must be reviewed.

Soils are the substrate where plants roots grow and many soil animals burrow. The characteristics and qualities of soil determine its ability to retain water and to supply minerals required by plant growth. Thus, its variation provides a key to understanding the productivity of biological communities and spatial distribution of

plant species. Unfortunately, soil is difficult to define exactly. Commonly, it refers to the porous material that overlies unaltered bedrock. It includes minerals derived from the parent rock, altered minerals formed by weathering, organic material contributed by plants, air and water within the pores of soil, living roots of plants, microorganisms, and the larger worms and arthropods that dwell inside soil. Generally, soil is determined by factors such as climate, parent material (underlying rock), vegetation, local topography, and age after the formation moment from newly exposed rocks (Brady 1974). Specifically, the activities of organisms within soil affect the arrangement of particles and the size and degree of pores in the soil as well as its chemical characteristics (e.g., Oades 1993; Gonzalez-Prieto and Carballas 1995). Thus soils have vertical stratifications: soil horizons. A simplified, generalized soil profile has five major divisions (from top to bottom): O, A, E, B, and C horizons. Landslides disturb the division arrangement and cause nutrients unavailable to plants. Soil develops initially from the weathering of three types of parent rock found in the earth's crust. Igneous rock (e.g., granites) is formed when the hot magma of the earth's mantle rises to near the surface and cools. Igneous rock is composed of primary minerals, products of the original rock formation, such as olivine and plagioclase. Sedimentary rock (e.g., limestone and shale) is formed when deposits of materials in lakes and oceans accumulate and merge over thousands of years, and are pushed to the surface by geologic activity. They are composed of secondary minerals, which are the products of weathering. When either igneous rock or sedimentary rock is subjected to the intense heat and pressure of the earth's deep environment, the minerals in those rocks melt, forming new material, called the metamorphic rock. Weathering is the process whereby parent rock is broken down by physical and chemical processes. Scouring by wind, repeated freezing and thawing of water in rock crevices, and the physical and chemical actions of roots are the chief modes of weathering. Initial chemical weathering occurs when water dissolves some of its more readily soluble constituent minerals (esp.  $\text{CaSO}_4$  and  $\text{NaCl}$ ). We here leave more detailed discussion on soil formation to ecology textbooks (e.g., Stiling 2011) but emphasize that the displacement of oxides minerals by hydrogen ions is the key step and the process is a continuing one that constantly evolves. Hence, soils are dynamic, changing from the moment they begin to develop on newly exposed rocks. But even after soils achieve stable properties, they remain in a constant state of flux. Groundwater removes some material; other material enters the soil from vegetation, in precipitation (lightning produces absorbable nitrates), as dust from the air, or by further weathering of rock from below. Again because the critical role of the hydrogen bond, arid region typically have shallow soils, with bedrock lying close to surface. On the other extreme, weathering proceeds rapidly in parts of the humid Tropics, where chemical alteration of parent material may extend to depth of 100 m (Eyre 1968). Most soils in temperate climate zones are intermediate in depth,  $\sim 1.2$  m global average. At a place, soil is a result of dynamic balance of production and erosion. Thus, soils may not form at all where weathered material and detritus erode as rapidly as they form. Soil development also stops short over alluvial deposits, where fresh layers of silt deposited each year by floodwaters bury weathered

material. At this locations, soil thickness increases but it is by advection from upstream regions rather by local soil formation! In this sense, landslides also play a dual role in soil formation rate: by exposing the scarp region, increasing the weathering rate, but reducing the soil formation rate in the alluvial areas.

Under a given climatic regime, soil properties are the major form of control over ecosystem processes. Soils are the regions where geological and biological processes intersect. Soils mediate many of the key reactions within the giant global reduction–oxidation cycles of carbon, nitrogen, and sulfur, and provide essential resources to biological processes that drive these cycles. As the intersection of the terms bio-, geo-, and chemistry in the term biogeochemistry, soils play such an integral role in ecosystem processes that it is impossible to separate the study of soils from that of ecosystem processes. Soils are formed from weathered metamorphic rocks. The presence of living organisms accelerates the soil formation processes. Water is a pathway for nutrients entering an ecosystem and, also, is crucial in determining whether the products of weathering accumulate or are lost from a soil, especially the soluble minerals. Topsoils generally are more fertile because weathering rates usually are larger at the surface. Moreover, leaching processes tend to transfer soluble ions (e.g., chelated complexes of organic compounds, iron or aluminum ions from precipitation or released in the weathering of upper layers of soil) downwards. During the downward movement, they can react with ions encountered at depth under new chemical environments (e.g., increased pH value), or may precipitate out of the system when dehydration occurs (e.g., water is evaporated in semiarid or arid climate zones). Consequently, the concentrations of silica and base cations in the secondary minerals usually increase with depth, resulting in a nutrient poor, deeper soil horizon. As iron and aluminum ions dissolved in the soil water move downward, slight changes in ionic content and the microbial breakdown of the organic matter both can cause the metal ions to precipitate as oxides. The deeper soil horizon containing iron-rich minerals usually is hardened irreversibly. These layers can impede water drainage and root growth. This is the case for tropical iron-rich soils, and similar processes exist for calcium (or magnesium) soils of arid and semiarid temperate climate zones. The hard calcic horizon at depth is formed when calcium carbonate precipitation occurs under conditions of increased pH, or under saturation concentrations of carbonate with evaporation of soil moisture. If a debris flow removes the fertile topsoil, then the deeper horizon is exposed and this layer has poor water retention ability and also is nutrient-poor. Moreover, roots cannot develop within it and thus cannot support regrowth. Even for the depositional alluvial fans, the exposed deep soil and deep buried top soil is a nutrient sink for the ecosystem, as the majority of the roots can use nutrients only in the upper one or two meters. Thus, landslides remove nutrients from the rhizospheric layer by burying nutrient-rich soil and unearthing nutrient-poor deep soil.

Following sections intend to build up proper background for understanding root reinforcement of slopes and their unique role in slope hydrology. Distribution of roots in soil represents the plants' strategy to maximize the use of available soil moisture under climatologically normal condition.

## 2.2 The Ability of Soil to Retain Water Is Related to the Size of Soil Particles

Most terrestrial plants obtain the water they need from the soil. The amount of water that soil holds, and its availability to plants, vary according to the physical structure of the soil particles. Soil consists of grains of clay, silt, and sand, as well as particles of dead and decomposing organic matter, called “detritus.” Grains of clay (particles smaller than 0.002 mm according to USDA classification), produced by the weathering of minerals in certain kinds of bedrocks, are the smallest; grains of sand (particles larger than 0.05 mm), derived from quartz crystals that remain after minerals more susceptible to weathering dissolve out of rock, are often the largest; silt particles are intermediate in size. Collectively, these particles make up the soil skeleton. The soil skeleton is an imaginary stable component that influences the physical structure of the soil and its water-holding ability, but does not play a major role in chemical transformations.

Plants obtain water from the soil. The availability of water in the soil is only partly determined by the amount of water present. It is also determined by how tightly the water is held in the soil. The concept of water potential (to be detailed in Chap. 5, e.g., Sect. 5.1.3), which is central to the dynamics of water, plants, and soil, needs to be established to understand water movement within the soil–plant–atmosphere. The water potential of a system is a form of Gibbs free energy of solvent water in the system. It is usually measured in units of pressure (e.g., MPa, KPa, and GPa). In case of solutes diffuse, water moves down a gradient of water potential (moving from higher water potential to lower water potential) to arrive a uniform solute concentration. Apparently, pure water has the highest water potential and adding in impurities lower the water potential. Since water potential is a form of compressive tensor, there apparently are gravitational potential components (generally compressive pressure components) in the total water potential, in addition to the component determined by solute concentration (osmotic component for plant cell). Thus, a cell surrounded by pure water will gain water through osmosis. On the other hand, if it is surrounded by water of higher ions concentration, it may lose water. By convention, the water potential of pure water at 1-atmospheric pressure is zero.

A comparison of the water potential of the soil, the atmosphere, and various parts of the plants help us understand how water moves from the soil to the upper portions of a plant, a topic that we will discussed more in Sect. 5.1.3 below and have direct influence in slope hydrology for vegetated slopes.

### 2.3 The Movement of Water from Soil to Plant to the Atmosphere Depends on Transpiration and the Cohesive Properties of Water

Typically, water potential is lowest (most negative) in the atmosphere and highest in the soil. Leaves, stems, and other parts of a plant usually have water potentials in between. This difference creates a downward water potential gradient from the soil to the leaves and out to the atmosphere, which helps move water through the plant. The water potential of a plant is affected mainly by the concentration of solutes inside and tension applied to some parts of the plant. Water potential in the soil, at least for parts of the soil that are above the water table, is usually not affected as much by pressure components. Water is held in soil by capillary action resulting from adhesion of the water to the elements of the soil skeleton. This capillary action holds water in the soil with a force equivalent to a pressure of about 0.01 Mpa (~1 m water column). Water that is draw to soil particles with a vertical *continuous* column length greater than 1 m will drop the extra as ground water. Water within the spaces between soil particles is held by cohesion, which generates pressures of about  $-15$  KPa (field capacity tension). Water in large pores inside the soil, at a distance from the surfaces of soil particle, is held with pressure less than  $-15$  KPa (e.g.,  $-17$  KPa), and usually drains through the soil under the pull of gravity. The tendency of soil to hold additional water molecules is referred to as its matric potential. The matric potential equals to the average strength with which the least tightly held water molecules are held. The matric potential of a soil contributes to its total water potential. For example, if the soil is very dry, the matric potential may be extremely low (e.g.,  $-200$  MPa or lower). This will lower the water potential of the soil, thereby making the water potential gradient from soil to plant weaker.

As soil water is depleted, the remainder is held by increasingly strong forces, because a greater portion of the water lies close to the surfaces of soil particles. There are empirical relationship between water content and water potential (Brady 1974). For a soil of porosity 45 % (loamy soil), the saturation moisture content is 45 %. The field capacity of this soil may be only 34 %. Thus, at field condition, when the loam soil is saturated, about 11 % of the water will be lost to ground water by gravity. The wilting point—the minimum water content of the soil at which plants can no longer obtain water—may be 7 % volumetric soil moisture. The difference between the field capacity and the wilting point, about 27 % for this loam soil, measures the water available to plants. Of course, plants obtain water more readily when soil moisture is close to the field capacity. In clayey soils with predominantly smaller particles, the soil skeleton has a relatively large surface area; such soils hold a larger amount of water at both the wilting point and the field capacity, and a correspondingly larger proportion of soil water is held by forces greater than  $-15$  KPa. On the other hand, sandy soils with predominantly larger skeletal particles have less surface area and larger interstices between particles. Most of the soil water is held loosely and is thus available to plants, but such soils

have lower field capacities due to higher drainage. Plants can obtain the most water from soils having a variety of particle sizes between sand and clay.

In order to live, terrestrial plants must obtain water from the soil and transport it to all areas of the plant where cellular function is ongoing. This transport mechanism must include a way to get water from the soil into the roots, and a means to move that water from the roots to the topmost parts of the plant, all against the gravity and the resistance exerted by the structures through which the water moves. Xylem is the tissue primarily responsible for the transport of water in plants. Xylem is composed of dead cells in the stems of the plant. In addition to water transport, xylem also provides support for the plant and is the major contributor to root tensile strength. We are not going to discuss the details of the upward water transfer here but would like to emphasize that active transpiration (“transpiration pull”) is critical for sending water to tree tops over 50 m tall. Xylem sap’s concentration changes also are responsible for maintaining the downward water potential inside stems. Thus, the cohesive properties of water, and the fact that the xylem tissue creates a continuous column of water from root to leaves, explain the movement of water. When tension is applied to the top of the column by transpiration, the entire water column is pulled upward.

Plants obtain water from soil by osmosis, so the ability of their roots to take up water depends on their osmotic pressure. Osmotic pressure, in turn, is a function of the concentration of dissolved molecules and ions within the root cells. By manipulating the osmotic pressure of their root cells, plants can alter their ability to remove water from the soil. Plants growing in deserts and in salty environments can increase the water potential of their roots by as much as  $-6$  MPa by increasing the concentration of amino acids, carbohydrates, or organic acids in their root cells. There certainly is a metabolic price to pay to maintain such high concentrations of dissolved substances. Soil to root water transfer also is necessary because life requires inorganic nutrients and the mineral nutrients (nitrogen (N), phosphorous (P), sulfur (S), potassium (P), calcium (C), magnesium (M), and iron (I)) must be obtained from water as dissolved forms (Chapin 1980). For low level concentration nutrients that limits growth (e.g., potassium), active uptake of that nutrient by increasing the extent of the root system, or the absorptive surface of the roots. The active absorption requires the expenditure of energy as the root tissue moves ions against a concentration gradient. Plants may also respond to decreased soil nutrient availability by increasing root growth at the expense of shoot growth—allometrically.

## 2.4 Plants Can Control the Energy and Material Fluxes Between Their Internal and External Environments

Crops and wild species growing on fertile soils have greater capacity to absorb nutrients across their root surfaces, and their growth rates vary in response to variations in soil nutrient levels. Species adapted to nutrient-poor soils are much more conservative in increasing their rate of growth (Chapin 1980) and cope with nutrient-limitation by allocating a large proportion of their biomass to roots; by growing slowly and retaining leaves for longer periods, thereby reducing nutrient demand; or even establishing symbiotic relations with fungi, which enhance mineral absorption. In response to nutrient flush, their roots absorb more nutrients than the plant requires and store them for subsequent utilization when the nutrient status of the soil decreases. Different species relate differently to their environments because many physical and physiological processes vary out of proportion to size. In ecology (Ricklefs and Miller 2000), this is referred to as allometry. The above adaptation to environments by roots can be described by allometric relationships.

Water is the basic medium of life. The chemical, physical, thermal, and mechanical characteristics of water result from the nature of the covalent bonds between hydrogen and oxygen and the weak hydrogen bonds between water molecules. This also explains its “lubrication effects on granules.” Live vegetation, by transpiration, alters the soil moisture level and indirectly affects slope stability.

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