TROPICAL SOILS

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Contents

Arid and Semiarid

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Introduction

Arid and semiarid soils occupy about one-third of the Earth's ice-free land surface. They are sources and sinks of atmospheric CO_2, sources and sinks (mainly sources) of global dust, and substrate that support high biodiversity of plants and animals. Arid and semiarid soils uniquely accumulate secondary minerals, such as calcite and gypsum, as the result of low rainfall and limited leaching. Because of sparse vegetative cover and high susceptibility to wind and water erosion, many arid and semiarid soils have low resistance and low resilience to disturbance. Hence land degradation (i.e., desertification) is common on most continents with arid and semiarid soils.

These dryland soils have been a factor of primary importance in human history. The oldest hominid fossils are found in east Africa in sediments with paleosols containing pedogenic carbonate indicating an arid or semiarid climate. The transition from hunting-and-gathering to agriculture took place in arid and semiarid Mesopotamia about 10 000 years ago. The production of surplus food on the floodplain soils of the Euphrates and Nile gave rise to early civilizations in Sumeria, Babylonia, and Egypt. Today several large urban centers are located on arid and semiarid soils around the world that have adequate groundwater or river water supplies. If irrigated, arid and semiarid soils are an important source of local and global food production. Still, most arid and semiarid land is sparsely populated, open, and often wilderness land.

Climatic Controls

The terms arid, deserts, semiarid, and steppes are used variously to describe dryland conditions. Arid (an adjective) describes a climatic condition of low rainfall – commonly taken to be less than 250 mm (10 in.) of mean annual precipitation (**Figure 1a**). Desert (a noun) is a region of the Earth's land surface within an arid climate. Likewise, semiarid is a climatic condition characterized by a mean annual precipitation between 250 and 500 mm (**Figure 1a**). A region of the Earth's surface within a semiarid climate is a steppe.

Closely linked to annual precipitation, and especially to soil moisture, is vegetation. The driest deserts are often barren of plant cover, but most deserts have scattered shrubs, cacti, forbs, and grasses. Though some steppe vegetation can occur in areas like the Badia of Jordan that receive as little as 100 mm of rainfall, generally steppe vegetation is characterized by higher amounts of rainfall in which short-grass prairie is bordered by desert vegetation on the arid side and tall-grass prairie, savanna, or woodlands on the subhumid side. Thus, by these definitions arid soils are synonymous with desert soils and semiarid soils are synonymous with steppe soils.

But to define deserts and steppes by precipitation alone is to ignore other important climatic variables, mainly temperature. One expression of the combined influences of both precipitation and temperature is the de Martonne aridity index based on the formula:

$$I_a = P_{mm}/(T^\circ C + 10) \quad [1]$$

where the aridity index (I_a) is equal to the mean annual precipitation in millimeters (P_{mm}) divided by the mean annual temperature in degrees Celsius ($T\,^\circ C$) plus 10. According to this index, values below 5 characterize true deserts, values of approximately 10 demarcate dry steppes, values of about 20 represent prairies, and values above 30 typify forest. The boundary for the Chihuahuan desert of Mexico and the USA, for example, is based on an aridity index of 10 or lower.

The Köppen system also demarcates deserts and steppes as a function of both precipitation and temperature (**Figure 1b**). For example, some cold regions in the high latitudes of North America and Eurasia that get semiarid-amounts of precipitation are coniferous forest instead of steppes, and many cold

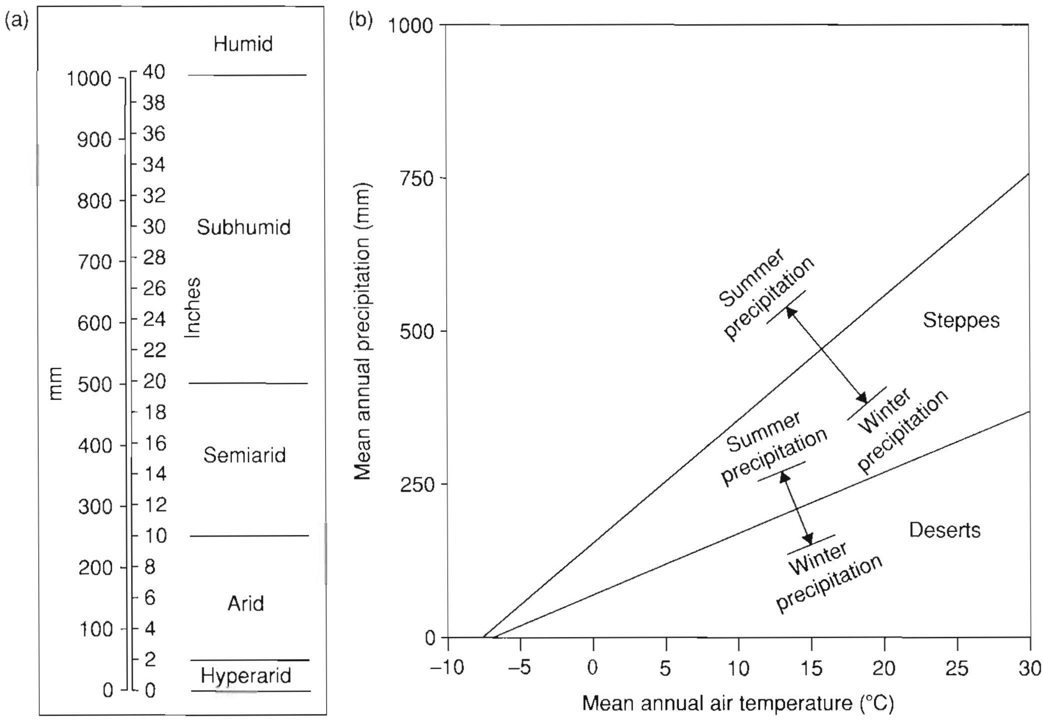

Figure 1 (a) Climate categories based on mean annual precipitation. (b) Desert and steppe boundaries as a function of both mean annual precipitation and temperature according to the Köppen system. Arrows show how boundaries shift according to whether precipitation falls mainly in the summer or winter.

areas that receive arid-amounts of precipitation are steppes instead of deserts.

Seasonality of precipitation is another climatic factor that affects desert and steppe boundaries. For a given mean annual temperature, the boundary of a steppe will extend into wetter climates if its precipitation falls mainly in the summer (**Figure 1b**). In other words, if precipitation falls in summer, the area of a steppe will be larger because summer evapotranspiration depletes soil moisture more thoroughly than winter evapotranspiration. Similarly, the size of a desert will be larger if its precipitation falls in the summer rather than in the winter.

Soil water potential is another way of defining boundaries of arid and semiarid soils. Soil moisture measured as soil water potential, which includes the influence of particle size and salts, is more important to vegetation than annual precipitation alone. The Soil Taxonomy system, for example, uses soil water potential to define moisture regimes as a criterion for classifying soils. The aridic moisture regime, for example, includes soils too dry to support nonirrigated crops, and is defined as soil that is moist (i.e., water held at tensions greater than −1500 kPa) for no more than 90 consecutive days when the soil temperature at a depth of 50 cm is above 8°C. Soils with the ustic and xeric moisture regimes are transitional between the aridic moisture regime and soils of humid climates that have the udic moisture regime. Semiarid soils occur within ustic and xeric moisture regimes, their drier subdivisions, and wetter subdivisions of the aridic moisture regime, namely, the aridic ustic, aridic xeric, xeric aridic, and ustic aridic regimes.

Processes of Soil Formation in Arid and Semiarid Soils

Water – its amount and depth-of-wetting – is the major driver that gives rise to differences between arid and humid soils. In humid soils >50% of the water entering the soil drains downward through the profile to groundwater. In arid soils, <10% flushes through the soil profile to the groundwater. A humid soil receiving 1300 mm of rain, for example, would have about 650 mm that percolated through its profile in a year. An arid soil receiving 200 mm would have <20 mm that percolated through its profile. Thus, nearly all water in arid soils and much water in semiarid soils enters and leaves via the soil surface. Notable exceptions are low-lying areas that receive runoff water (e.g., playas). In these topographic lows, soils are nonsaline because of deep leaching, if the water table is deep and the soils have high permeability. However, if the water table is shallow or soils have slow permeability, these topographic lows are zones of salt accumulation

As with humid soils, the processes of soil genesis (i.e., gains, transfers, transformations, and losses) operate in arid and semiarid soils, but the magnitude and direction of these processes are different. The shallow depth-of-wetting and incomplete leaching have a major impact on gains because authigenic minerals, such as calcite, silica, and gypsum, accumulate in the profile and give rise to the formation of calcic, petrocalcic, duripans, gypsic, and petrogypic horizons. Gains of dust are also important. Silicate clay dust, for example, contributes to the formation of argillic horizons, carbonate dust to the formation of calcic horizons, and gypsum dust to the formation of gypsic horizons. Gains of photosynthetic carbon in the form of soil organic matter are lower than in humid soils. But gains of photosynthetic carbon released as respired soil CO_2 that leads to HCO_3^- and $CaCO_3$ formation are higher than in humid soils.

Transfers of material down the profiles of arid and semiarid soils include illuvial clay, carbonate, and salts. Arid soils typically display a chromatographic pattern of an argillic horizon overlying a calcic horizon. If gypsum and soluble salts are also present, the profile can contain an argillic overlying a calcic overlying a gypsic overlying a salic horizon. Transfers of materials also occur up the profiles of some arid and semiarid soils. These include capillary rise of soluble material and particles moved upward by ants and termites. In some cases, desert pavements are formed by the upward movement of coarse fragments lifted by silts and fine sands that accumulate beneath them.

Important transformations in arid and semiarid soils include rock disintegration resulting from the crystallization of salts, thermal fluctuations, and chemical weathering. Other transformations involve the decomposition of organic matter and formation of clay minerals, such as palygorskites and sepiolites. The formation of kaolinite is common in parent materials containing feldspars. Losses are mainly in the form of erosional truncation of soil horizons.

Factors of Soil Formation in Arid and Semiarid Soils

The five soil-forming factors interact in assorted ways to produce arid and semiarid soils (Figure 2). Climate, especially water supply, is the defining factor. Water is not only the agent for mineralogical gains, transformations, and transfers, it is also essential for nutrient supply and direct use by vegetation. Vegetation, in turn, has a feedback link to soil by adding organic matter, translocating ions via bioaccumulation, and providing ground cover that protects the soil from erosion. Vegetation is also linked to animals by being their food supply, while animals are linked to vegetation by herbivory and seed dispersal (Figure 2). Animals affect soil by bioturbation – humans alone move about 40 GT of soil per year. Soil, in turn, affects animals by providing habitat, which is important for nematodes, gastropods, earthworms, crustaceans, mites, spiders, ants, termites, mice, moles, rabbits, gophers, birds, foxes, badgers, deer, bear, and even humans in some places of the arid world.

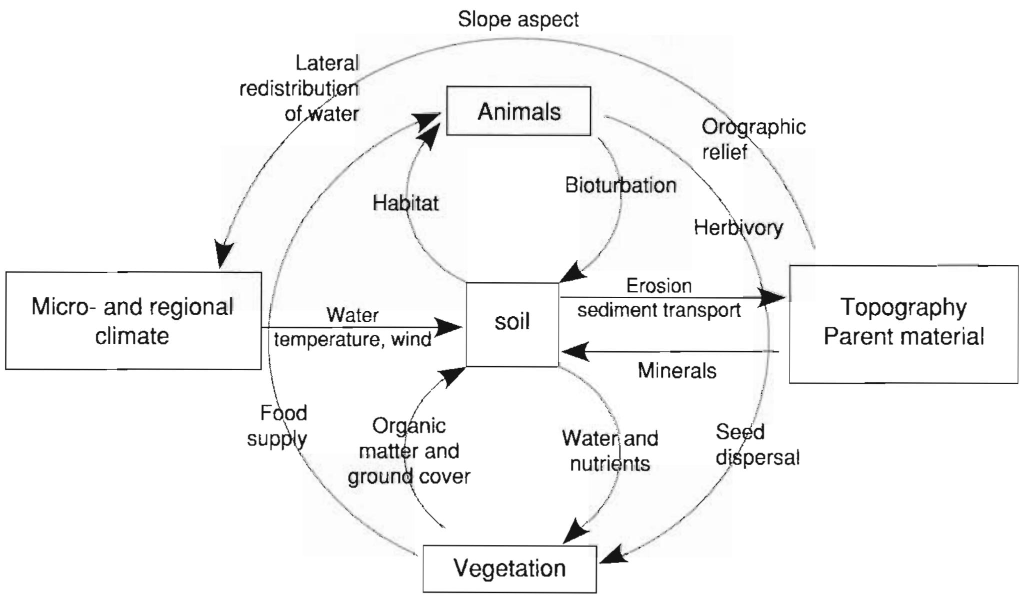

Figure 2 Illustration of the links among the soil-forming factors of climate, biota (vegetation and animals), topography, and parent material. The fifth factor, time, affects all of the illustrated links in proportion to the duration that the factors operate.

Parent material and topography are the main factors of the geologic setting that affect arid and semiarid soils. Parent material has a direct link to soil as a supplier of mineral detritus. Topography has its link to soil by its influence on regional climate at the orographic scale and by its influence on microclimate (resulting from slope aspect and laterally redistributed water) at the local scale. Over the long term, climate through its effects on soils alters the configuration of the landscape by erosion and sediment transport (**Figure 2**).

Properties of Arid Soils

Arid soils have surface horizons with several unique characteristics. Many arid soils, for example, are covered by desert pavement that overlies vesicular A and E horizons. Other arid soils are covered by salt efflorescence in areas where shallow groundwater has risen by capillarity and evaporated at the surface. Still other arid soils are covered by microbiotic crusts or by blankets of aeolian sand or silt. Nearly all arid soils have lower amounts of organic matter than their more humid counterparts. For classification purposes, the surface horizon (i.e., epipedon) that is ubiquitous for arid soils is the ochric epipedon. Other epipedons of arid soils with much smaller occurrences are the mollic, anthropic, and in very rare cases of grass sod over shallow basalt, the histic.

Subsurface horizons of arid soils are uniquely different from subsurface horizons of humid soils in some instances, yet similar in other instances. Subsurface horizons in arid soils that are uniquely different include horizons dominated by calcium carbonate, secondary silica, gypsum, and soluble salts, while horizons common to both arid and humid soils include those with weak structural and color development and accumulations of illuvial clay and sesquioxides. Diagnostic horizons unique to arid soils include the calcic, petrocalcic, duripan, gypsic, petrogypsic, natric, and salic horizons (**Figure 3**). Diagnostic horizons found in both arid and humid soils include the cambic, argillic, and in rare cases, the oxic.

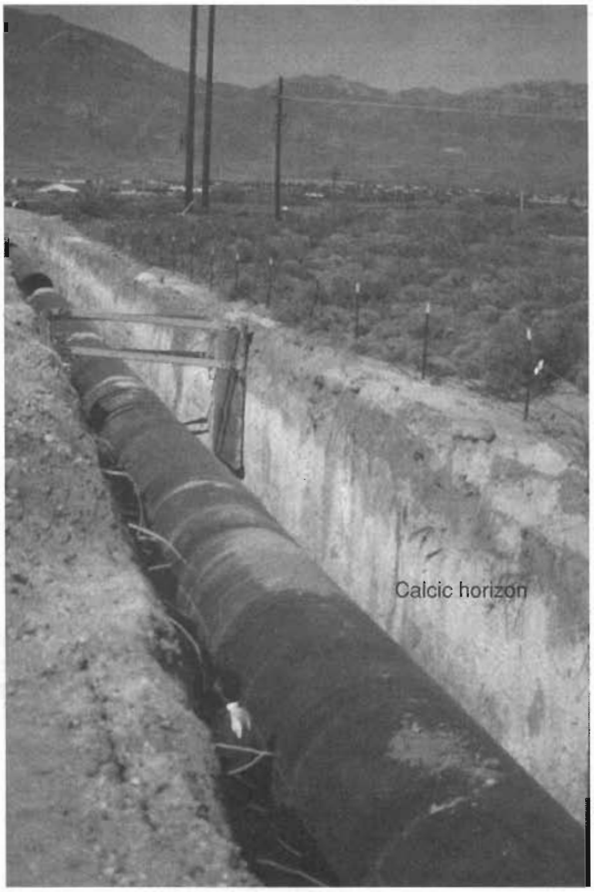

Figure 3 Calcic horizon in an arid soil in the Chihuahuan desert of North America. This site has an annual rainfall of 250 mm and an annual temperature of 16°C.

In addition to diagnostic horizons, other soil properties, such as vertic, andic, lithic, climatic, anthropogenic, depth to groundwater, and particle-size characteristics are used to make taxonomic subdivisions in arid soils. At the highest taxonomic levels, arid soils include Leptosols, Gypsisols, Durisols, Calcisols, and Solonchaks in the World Reference Base (WRB) system; Desert gray brown, Desert takyr-like, Desert sandy, and Meadow desert soils in the Russian system; and Halosols and Aridisols in the Chinese system. In the Soil Taxonomy system, arid soils are classified as, in order of abundance, Aridisols, Entisols, Vertisols, Oxisols, and Andisols (**Table 1**). Moving dune fields also occupy large areas of deserts, especially in North Africa.

Properties of Semiarid Soils

Semiarid soils, owing to more rainfall and the homogenizing effects of greater vegetative cover, have surface horizons with more organic matter than arid soils and fewer unique features like desert pavements, vesicular horizons, and efflorescence. Although the ochric epipedon is still a common horizon of semiarid soils, the mollic epipedon is widespread and dominates the steppe areas that border tall-grass prairies.

Being transitional between arid and humid soils, semiarid soils have a large variety of subsurface horizons. As with arid soils, semiarid soils might have calcic, petrocalcic, duripan, gypsic, natric, and salic horizons. Yet, as with humid soils, semiarid soils might have albic, argillic, and kandic horizons as well as fragipans and plinthite.

Table 1 Global extent of arid and semiarid soils (km^2) based on the Soil Taxonomy system[a]

Soil order	*Suborder*	*Africa*	*Asia*	*Australia/ Oceania*	*Europe*	*South America*	*Central America*	*North America*	*Global*
Arid soils									
Aridisols									15 798 100
	Cryids	653	417 587	–	103	165 909	–	499 351	1 083 601
	Salids	95 249	595 400	919	130	59 756	–	17 698	769 152
	Durids	–	–	–	–	–	–	–	–
	Gypsids	347 458	326 137	–	3454	–	–	–	677 050
	Argids	450 884	1 635 130	1 710 271	1218	520 175	1111	1 093 291	5 412 080
	Calcids	1 818 639	2 204 270	613 547	1013	98 680	–	202 235	4 938 384
	Cambids	842 681	1 125 259	346 253	5573	422 429	2259	173 378	2 917 832
Vertisols	Torrerts	196 570	65 210	602 630	–	6233	1754	42 435	914 832
Oxisols	Torroxes	9346	–	4247	–	16 550	–	–	30 143
Andisols	Torrands	834	–	–	–	95	–	150	1078
Entisols[b]	In aridic (torric) moisture regimes								12 600 308
Total arid soils									29 344 460
Semiarid soils[c]									
Mollisols									
	Ustolls	4371	1 587 526	21 689	303 635	409 796	–	1 744 438	4 071 455
	Xerolls	72 125	403 161	55 502	236 656	769	–	165 132	933 346
Vertisols									
	Usterts	722 630	600 544	14 863	29 001	38 107	18 247	114 387	1 763 776
	Xererts	11 692	47 348	20 258	17 105	1050	–	969	98 423
Oxisols	Ustoxes	1 718 701	18 457	39 249	–	1 338 805	1295	360	3 116 866
Andisols									
	Ustands	11 235	12 308	–	1975	11 414	11 004	7750	55 686
	Xerands	–	–	–	8937	2098	–	17 840	28 876
Alfisols									
	Ustalfs	2 470 581	1 084 231	501 676	253 839	998 870	22 555	346 868	5 678 621
	Xeralfs	80 071	209 377	270 520	118 833	25 340	–	176 034	880 174
Ultisols									
	Ustults	1 649 310	824 575	101 301	–	1 091 366	58 903	131 048	3 856 502
	Xerults	933	2672	–	–	22	–	15 958	19 586
Inceptisols									
	Ustepts	1 675 118	832 200	257 463	377 338	611 443	83 255	331 262	4 168 080
	Xerepts	163 793	178 312	264	310 697	8342	–	9246	670 654
Entisols[d]	In ustic moisture regimes								4 620 113
Entisols	In xeric moisture regimes								840 021
Total semiarid soils									30 802 179
Total ice-free land area									130 268 185

[a]Courtesy of USDA–Natural Resources Conservation Service, Soil Survey Division, World Soil Resources, 2002.
[b]Entisols with the aridic (torric) moisture regime are designated at the great group level (e.g., Torripsamments and Torriorthents).
[c]The semiarid soils category contains some soils of subhumid climates (500–1000 mm annual precipitation) in cold regions and along coasts.
[d]Entisols with the ustic and xeric moisture regimes are designated at the great group level (e.g., Ustorthents and Xerofluvents).

Other diagnostic properties used to subdivide semiarid soils include redox, petroferric, vertic, andic, lithic, climatic, anthropogenic, particle-size, and groundwater characteristics. Classification of semiarid soils includes the Kastanozems, Chernozems, and Phaeozems in the WRB system; Meadow Chernozem-like, Meadow Chestnut, Semidesert Brown, and Semidesert Meadow Brown soils in the Russian system; and Isohumisols and Ferrallisols in the Chinese system. In the Soil Taxonomy system, semiarid soils are classified as, in order of abundance, Alfisols, Entisols, Mollisols, Inceptisols, Ultisols, Oxisols, Vertisols, and Andisols (Table 1).

Human Land Use of Arid and Semiarid Soils

Early civilizations arose in arid and semiarid Sumeria in the fourth millennium BC as irrigated agriculture on floodplain soils encouraged stable settlements, led to surplus food, and freed people to pursue specialized trades and to develop social order and cultural creativity. Similar cultural developments arose along rivers in other arid and semiarid climates, such as the Indus of ancient India and Hoang-Ho of ancient China. In the western hemisphere as well, societies developed in arid and semiarid climates, such as the Inca, Aztec, and Hohokan cultures.

Grazing of domesticated cattle, sheep, and goats has been the traditional land use of arid and semiarid soil away from the irrigated floodplains. Today, in addition to grazing, arid and semiarid soils have ecological and global biogeochemical properties important to humans. Arid and semiarid ecosystems have some of the highest biodiversity on Earth as grasses, cacti, shrubs, reptiles, birds, and mammals have adapted to wide and rapid shifts in temperature and moisture. Much of the carbon in the global carbon cycle, at least 800×10^{15} g, is stored as soil carbonate in arid and semiarid soils. The source of much of the local, regional, and global dust is from arid and semiarid soils.

Desertification, which is defined by the United Nations Convention on Desertification as 'land degradation resulting from climatic and human activities,' is a major issue of importance in arid and semiarid climates because desertification directly affects about one-sixth of the world's population in both developing and developed countries. Increasing human population and livestock pressures have accelerated desertification and caused shrubs to invade grasslands with subsequent erosion of exposed topsoil. Wind erosion is a major agent for desertification in arid and semiarid regions because it removes organic matter and fine mineral particles in A horizons that have important water and nutrient storage properties. Water erosion is also important, especially at the arid–semiarid boundary of about 250 mm of precipitation where erosion rates are commonly at their greatest.

Limited water supply is of paramount importance to expanding populations in arid and semiarid regions of North and South America, Australia, Africa, Asia, and the Middle East. In the western USA, for example, the drought did not move to the people, the people moved to the drought. While the lack of water threatens population growth in arid and semiarid regions, the lack of water is the natural state, and the state that imparted the unique properties to arid and semiarid soils. It is also the lack of water that makes arid and semiarid places some of the most open, least developed places on Earth, and some of the last 'wild' places for future generations to enjoy and study.

See also: **Classification of Soils**; **Desertification**; **Factors of Soil Formation:** Climate

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Humid Tropical

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Introduction

Soils are the physical, chemical, and biological media at the upper surface of the Earth's land areas capable of accepting plant roots. A wide range of geologic materials, soil moisture, and temperature conditions that differ regionally and among adjacent soils on local landscape positions provide for diverse suites of contrasting soils that interact differently with biological communities and human attempts to sustain food production within the humid tropics.

Humid Tropical Setting

Many climatic classifications have been published. The parameters of soil temperature and moisture regimes used to classify soils do not conform to general concepts of humid tropics. The following criteria, adopted by the National Cooperative Soil Survey in the USA, are most universally used when classifying soil.

Soil-Temperature Regimes of the Tropics

Mean annual soil temperatures are 2–4°C warmer than mean annual air temperatures. Soil-temperature regimes (STRs) are defined by two criteria, mean annual soil temperature and seasonal temperature difference (**Figure 1**). Seasonal soil-temperature difference is determined as the mean soil temperature of June, July, and August compared with the mean soil temperature of December, January, and February. Almost all of the soils within the geographic tropics have soil temperatures that seasonally differ by less than 6°C and are identified by the prefix 'iso' placed before the name of the mean annual soil-temperature regime. Except for a few soils near the northern and southern extremities of the geographic tropics in Africa, this one characteristic is the only soil property that is nearly universal with the concept of tropical soil. The practical aspect of this soil property is that seasonal soil temperatures seldom have to be considered when planting food crops.

Soils with mean annual soil temperatures of 22°C or higher are classified as isohyperthermic; soils with mean annual soil temperatures of 15–22°C are identified as isothermic. Freezing conditions are seldom a problem in the isothermic and isohyperthermic STRs. Higher elevations in tropical areas have isomesic STRs, with mean annual soil temperatures less than 15°C; crop growth is slow, night-time freezing is common, and even cold-tolerant crops such as potatoes seldom grow well where mean annual soil temperature is below 10°C.

Soil-Moisture Regimes of the Tropics

Soil-moisture regimes (SMRs) are defined to classify a soil's ability to supply water to plants without irrigation (**Figure 2**). In soils where the groundwater table is not reached by the roots of most crop plants, the SMR is determined by the seasonal distribution of rainfall in 'normal' years. Normal years are ±1 standard deviation of long-term means. Most food crops require a reliable supply of water for at least 90 consecutive days. To calculate SMRs, the mean monthly precipitation is compared with the calculated potential evapotranspiration. A soil-water balance is then constructed for the mean rainfall in the area. The duration of time during which water is normally available either from average rainfall or as stored available water in the soil during a period when soil temperatures are warm enough to grow the crop determines the SMR.

The perudic SMR has precipitation that exceeds potential evapotranspiration every month of normal years. Although this may seem desirable, these areas present weed, insect, and disease problems, and the constantly humid conditions make it difficult to harvest mature grain crops.

The udic SMR has fewer than 90 cumulative days when water is not available in the rooting zone in normal years. It is possible to grow food crops any time of the year without irrigation when the temperature is warm enough for that crop. Available water is less reliable during some part of the year, and farmers often select more drought-tolerant crops or may choose not to plant during that period, but perennial plants are adequately supplied with water throughout most years in most of the udic SMR areas.

The ustic SMR is borderline to the common concept of humid. In normal years, soils with an ustic SMR have at least 90 consecutive days when moisture is available, but more than 90 cumulative days when water is not available in the rooting zone. Natural vegetation is either seasonal rain forest or savanna. At least one crop can be reliably grown each year, and it is possible to grow two crops per year on some soils, but there is a seasonal dry period of 90 days or more when crop production is not possible without irrigation. The reliable dry season of the ustic SMR is a distinct advantage for weed and disease control and grain-crop harvest in isohyperthermic and isothermic STRs.

Soils that have a reliable moisture supply for fewer than 90 consecutive days in normal years have an aridic SMR and are excluded from the concept of humid tropics.

The above SMRs are used to classify only the well-drained upland soils. Groundwater often saturates the rooting zone of some soils within all areas of the humid tropics. These soils are identified as having an 'aquic soil moisture condition' and are commonly referred to as poorly drained soils. Soils with aquic soil-moisture conditions most often occur in areas adjacent to rivers and lakes or in broad, level