SOILS: THE MIRACLE OF ORDINARY DIRT

Just what are soils? Tiny rock fragments comprise their framework. Interpolated betweep these bits of rock are dead and decaying organic materials and complex interacting societies of small, tiny, and microscopic organisms, including densely intertwined fungal threads, teeming bacteria and blue-green bacteria (formerly known as blue-green algae), wormlike nematodes, legions of varied, single-celled protozoans, and myriad insect larvae. Of course, some soils are sterile and lack these essential, hidden life forms, but the frozen tundra, the salt pans of deserts, and the blowing sands of dunes are the exceptions rather than the rule.

Soils are dynamic ecosystems. The patterns of life and framework shift constantly, for the tiny inorganic fragments alter their physical and chemical natures over time. To understand soil evolution, start with their parent rock, consider the amount of time the soil has been developing, and factor in the climatic and biotic conditions influencing the soil. Climate includes the ever-present forces of wind, precipitation, and temperature. Biotic factors include the microorganisms in the soil, the roots of the plants and trees, the droppings and carcasses of the animals, and the plant debris. All these components interact chemically, changing the physical size and shape of soil particles and altering their chemical composition and reactivity.

A full representation of a soil includes its soil profile: a core taken from the surface down to bedrock gives you a clear view of this progression. The closer you come to bedrock, the closer you approach the beginning of soil evolution; the closer you are to the soil surface, the longer the soil has been under development. Old soils are generally deeper--with more layers--than new soils. Each horizon has its own Story to tell,

The types of plants that grow in a particular place also influence how soils form. Plant litter is a major source of carbon-rich material that breaks down to form humuns. Some humus, such as pine and fir needles, decomposes into litter that helps create acid soils. The resulting humic acids consist of complex macromolecules that contain polymeric, phenolic structures that can bind to metal ions to varying degrees. The degree to which these ions remains available to plants determines how nutrient rich a soil may be. Some humus, such as pine and fir needles, decomposes into litter that helps create acid soils.

Soil particles may be large enough to see and feel (they are "gritty")--as with coarse sands—or they may be minuscule and feel smooth- The three general categories of particle size are sandy soils, silts, and clays, silt.s having sizes between those of sand and clay. Clay soils and sandy soils each have their benefits and shortcomings, and ideal garden soils are mixtures that combine their best attributes. We call healthy garden soils loams. To understand characteristics of soil texture better, let's take a look at the extremes.

Clays consist of numerous tiny particles--micelles—each Of which carries a small negative electrical charge. The positively charged mineral ions that are essential for plant nutrition, such as potassium, magnesium, and calcium ions, are electrostatically attracted to these clay particles. They form an ionic bond with these micelles. Because of these strong bonds, nutrients minerals are not readily available to plants.

Mineral ions can be detached from clay micelles, to a limited extent, by reacting with carbonic acid.(H2C03). This acid is almost universally present in soils, because of the interaction of carbon dioxide in the atmosphere with water in the soil. Let's take a closer look at this interaction. Some carbon dioxide moleculees react with water in the soil to form carbon acid. Some of these carbonic acid molecules may decay back again to water and carbon dioxide in a continuous, back-and-forth process. Equations with such back-and-f01th motions are indicated with a double arrow, and the process is called a dynamiC equilibrium.

Sandy soils Sandy soils feature large particles with equally large air spaces between. Their angular fragments consist of quartz (silicon dioxide, Si02), and carry little electrical charge, so mineral ions seldom adhere to their surfaces. The large spaces (pores) allow water to pass freely between fragments and to run off rapidly. Thus, little water is available and less is retained. Sandy soils are well oxygenated. Oxygen is necessary for respiration and promotes the healthy growth of roots. Think of sandy soils as sieves, for they retain water poorly. To compensate, plants have evolved ingenious adaptations to cope with these challenging circumstances. Where sands accumulate they form desert and oceanic dunes and beaches, places that also impose additional environmental sa-esses. Although ocean and desert dunes might seem very different--as they are in overall rainfall and summer temperatures--they share the same difficult soils along with strong, drying winds. Winds whisk moisture away from leaf surfaces, forcing more water to be drawn up from the roots to replace what has been lost. Sands and winds present plants with a killer combination. Plants form extensive carpets, mats, or cushions close to the ground, where winds are far less severe. Plants send down roots to stabilize the shifting sands as they creep along. Roots also probe deeply_to tap unseen water and anchor plants securely in place. Leaf adapations are designed to slow water loss. For example, succulent leaves store extra water in specialized tissues to draw on in difficult times. Sand verbena (Abronia spp.), various beach morning glories (including Calystegia soldanella and Ipomoeapes-caprae), and sea-rocket (Cakile spp.) all exhibit fleshy leaves. Testimony to the effectiveness of this adaptation is shown by howwidely distributed these plants are on the world's sand dunes and beaches. Leaves may also be covered with intricately interwoven, white or silvery hairs that reflect away excess light. (White sands intensely radiate and reflect sunlight.) When leaves receive less light they don't heat up as much and so water loss is slowed. Dune sagebrush (Artemisia pycnocephala), beach lupine (Lupinus chamissonis), and beach sweetpea (Inthyrus littoralis) all use this ploy.

Leaves are often shiny because of their covering of an extra thick, waxy cuticle that assures that little water passes through to evaporate. Beach strawberry (Fragaria chiloensis) and dune gumweed (Grindelia stricta venulosa) provide examples.

Vertically oriented leaves cut down on the angle of impact of the sun's rays, so that leaf surfaces don't heat up so much. This adaptation works best on plants with tall stems, such as bush lupines (Lupinus spp.), willows (Salix spp.), and the turkey oak (Quercus pumila), from the Atlantic seaboard.

pH. The measure of the sweetness or sourness of soils Soil pH reveals yet another aspect of soil chemistry. pH is a measure of the acidity or alkalinity of soils- The pH scale stretches from 0 to 14. pH 7 is the pH of pure water and stands for a neutral medium (this may be a soil sample, plant sap, water from a pond, or any other water-containing mixture). If the pH is above 7, it represenß an alkaline or basic medium; values below 7 are increasingly more acidic. A revealing aspect of the pH scale is that it is not a linear measure: a slightly acidic soil with a pH value of 6 is actually ten times more acid than a soil with a pH of 7. Every unit on the scale differs by a factor of 10! The values represented are exponential rather than linear. To understand this a bit better, let's backtrack to the compound water, which is so essential to living cells.

In pure water, the concentration (which is the amount per volume) of hydrogen ions is equal to the concentration of hydroxide ions, and we say that pure water is neutral. Any water-containing medium, be it in the soil or inside plant cells, is neutral if it contains equal concentrations of H+ and OH--ions. Since water is the all-imponant solvent in and around living cells, the specific concentration of its ions affects life as a whole. So when cell sap contains a surplus of H+-ions, making it acidic, or a higher concentration of Off-ions, making it basic or alkaline, it changes the equilibrium of cells.

Acids are compounds that give off hydrogen ions into a watery medium such as the sap of plant cells or moist soil. Examples of acids include citric acid in lemons; oxalic acid lends its sour taste to rhubarb and sorrel. The sour taste of unripe fruit is due to yet other acids. Most acids in living cells are weak acids. Some of their hydrogen ions recombine with negative ions to reform an acid in a dynamic equilibrium, so that there is seldom a large concentration of available free hydrogen ions. This is illustrated by acetic acid (here abbreviated as Hac), the acid found In Vinegar:

With Strong acids, by contrast, such dynamic equilibria do not occur, and a high concentration of free hydrogen ions remains, leading to high acidity. (Hydrochloric acid, HCI, is an example of a strong acid; it does not occur in plants!)

Bases, the opposite of acids, pick up H+ -ions from water molecules, creating an excess of Off-ions. Ammonia—an important fertilizer—is a base. [(aq) means "surrounded by water molecules".] Once again the equation shows a dynamic equilibrium between ammonia molecules and water, indicated by the double arrow. Thus, ammonia is a weak base.

Soils high in calcium carbonate (lime) and other minerals are alkaline. A weakly basic or alkaline soil would have a pH of 8. Acidic soil is frequently found in areas with cool temperatures and heavy rainfall. Water in a bog may go down to a pH of 4. Acid rain, produced by the reaction of rain water with automobile exhaust and smoke from factories, often has a pH of 3, which means its concentration of hydrogen ions is 10^4 or 10,000 times higher than the concentration found in neutral water.

Soil pH strongly affects plants, and growth of specific •plants affects soil pH. The two are interactive. Most plants flourish in soils with values close to 7. If a soil deviates greatly from pH 7, special growth problems occur which relate to the availability of mineral nutrients.

How plants affect soils Soils that are rich in exchangeable positive ions of minerals (EXAMPLES?) provide plants with large amounts of extractable mineral nutrients. When these plants die and decay, they form a rich, alkaline humus. On nutrient-poor soils, on the other hand, plants can extract fewer minerals; less ion exchange can take place, and the plant litter formed in these areas will create acid soils, higher in H* -ions. Conifers, in particular, produce this type of soil.

After hundreds of thousands of years most of the exchangeable mineral nutrients are leached from the soil or are extracted by plants. Such truly ancient soils are found in large areas of the tropics and subüopics, aside from volcanic areas. These tropical soils are useless for agriculture unless they are heavily fertilized. Yet, in their natural state, unmanaged, these soils support lush vegetation in areas of high rainfall. How is this possible? How can the incredible diversity of flowers, trees, lianas, epiphytes, birds, mammals, herps, insects, and fungi be fostered in rainforests with such deficient soils? The answer lies in the intricate ecological web that connects all the denizens of the forest. Instead of the soils containing high levels of nutrients, these essential substances are part and parcel of the living fabric of the forests' organisms. The immense hardwood trees, because of their great bulk, harbor vast mineral resources.

When eventually a giant tree falls to its death, the millions of microorganisms in the soil immediately go into frantic action, recycling wood, bark, and leaves to feed the roots of living trees and flowers. So efficient is this process that the nutrients recycled barely penetrate the upper layers ofsoils before they're reabsorbed by roots. Temperature affects the speed of chemical processes: the higher the temperature—within certain strict limits--the faster the process. High temperatures at the soil surface promote rapid processing Of plant and animal debris.

The consequences Of squandering tropical soils due to agricultural activity are felt throughout the world, with profound repercussions. Formerly, small bands of indigenous peoples practiced slashing and burning the rainforest. After burning, crops were raised for two or three years then abandoned, and the group moved to a new site. Because the cultivated plots were small, the tropical rainforest could quickly encroach on the abandoned plots and begin regeneration. But with large-scale agriculture—where huge tracts of land are cleared--such recovery is impossible,

• and the soils soon lie degraded and useless. Areas that were formerly home to vast tracts of rainforest are exploited to support the wasteful practice of grazing cattle in order to provide the world with cheap hamburgers!

How Soils Affect Plants

Plants that five on sour, acid soilsNitrogen-fixing bacteria do not survive in soils with a pH below 6. Such soils are common to cool, damp climates where coniferous forests thrive. So the plants that grow there adapt in amazing ways. Many

depend on mycorrhizal fungi for their nitrogen source. Others parasitize mycorrhizal fringi for all their nutritional needs.

Mycorrhizal fungi evolved from fungal ancestors that, first parasitized plant roots for food. As time went on, plant roots evolved defenses that killed the fungus when it penetrated too far into the root. Plant roots actually came to engulf and absorb parts of their invaders. The digested ends of fungal strands contain nitrogen, phosphorous, sulfur, and other minerals that roots usually extract directly from the soil. Most mycorrhizal fungi are decomposers, and their branched strands break down dead animal detritus and plant litter into simpler substances for their own nutritional needs. Some of this gets passed on to tree roots. In return, tree roots nourish the fungus by providing the sugar glucose.

Mycorrhizal fungi are associated with the roots of most plants, but the relationship is a general one. For trees and shrubs adapted to acid soils, the relationship has become highly specialized, with only one particular kind of fungus associated with the roots of one particular plant group. These fungi have become of paramount importance as a steady source of nitrogen, ordinarily supplied by soil bacteria.

Certain flowering plants that live in the depths of shaded forests--where light levels are critically low--have lost their green, chlorophyllcontaining leaves and so cannot photosynthesize. Without the benefit of the primary building blocks of the glucose molecule, these plants are as helpless as animals and must be fed. They have become totally dependent on their fungal partners for food. Although most books refer to such plants as saprophytes, (that is, organisms that live off dead animal and plant remains) such plants are really mycoparasites. The vivid red snowplant (Sarcodes sanguinea), the ghostly white Indian pipe (Monotropa uniflora), or the purplish-tinted coralroot (Coralorrhiza maculata) all obtain their nutrients from dead animals and plants by parasitizing their fungal partners, which are the actual saprophytes. These same fungi also depend on their mycorrhizal relationships with tree roots. So we have a three-way dependency between tree, fungus, and parasitic flowers.

An even more bizarre twist is seen in plants that live in extremely acid places such as bogs, which are carpeted with layer upon layer of special sphagnum mosses. Sphagnum moss holds massive amounts of water in its highly complex branch systems and, because of its acid cell sap—comparable in pH to weak vinegar--it's able to kill off competing plants and keep all the water, space, and light for itself.

Some flowering plants have learned the trick of surviving in these bogs. Cermin species are associated with highly specialized mycorrhizal fungi. Others have invented an unexpected wrinkle: they trap their food and digest it! Such carnivorous or insectivorous plants are among the strangest looking vegetable creations on the planet. Although carnivorous plants bear ordinary flowers, their green leaves are modified into traps that snare animal prey. Some species, like the pitcher plants (Sarracenia and Nepenthes spp.), build hollow tubes; others, like the Venus fly nap (Dionaea muscipula), produce leaves with rows of interlacing spines at the top; others, others, like the sundews (Drosera spp.), cover their leaves with sticky jewel-like hairs; still others, like the bladderworts (Utricularia spp.) make tiny bladders with trap doors underwater. Each kind goes about the business of trapping in its own special way, but all offer the enticement of color, odor, or nectar to lure potential victims. All digest their victims either by secreting enzymes or by creating pools filled with bacteria in which their victims drown. Some carnivores have active traps where the leaves move to do the trapping; for example, the Venus fly trap has sensitive hairs at the bottom of its leaves that trigger the leaves to snap shut around their victim. Many other carnivores have motionless leaves (passive traps), and simply catch their victims by design. Most passive traps use pitchers of water into which the prey slips and drowns.

Soils that don't breathe

Although oxygen is generally not considered a soil nutrient, it is essential to aerobic respiration. Oxygen is a gas in the atmosphere, so we seldom think about its importance to healthy roots in soils. But just as stem and leaf cells use oxygen to produce energy for their metabolic reactions so, too, do root cells. The pores of sandy and loamy soils favor oxygen exchange with the aunosphere. Badly compacted soils--clays, and waterlogged soils, by contrast--are oxygen deprived. Little oxygen dissolves in water. How do plant roots survive in these oxygen-poor soils?

Plants may have spongy chambers or air canals inside their stems and leaves. Chambers and canals connect directly to roots, allowing oxygen from the air to diffuse down and aerate roots. Internal air chambers are especially common in marsh plants, such as rushes (Juncus spp., with pithy stems); cattails (Typha spp., with honeycombed leaves); and horsetails (Equisetum spp., with hollow stems). All are small, nonwoody plants.

Striking examples of trees that have adapted to these stringent conditions occur in the bayous of the southeastern United States, where broad .flood plains are periodically and systematically inundated with water. Here the bald cypress (Taxodium distichum) creates spacious, open woodlands. The strange "knees" of these deciduous conifers, like so many twisted gnomes, not only add to the picturesque landscape but also allow the flow of oxygen into the vast root system that stretches out just below the mud.

Soils laced with heavy metals   Although plants need certain heavy metal ions (e.g- Cu^{2} +, Zn^{2} + Ni^{24}) in very low doses, higher concenffations of these same metal ions are poisonous to most plants. Places where such concentrations occur include natural outcrops of serpentine rocks and man-created mine tailings. Such places are environments that are hostile to the growth of most plants. Yet these habitats are seldom barren, for some plants have learnt how to cope with this challenging environment. Serpentine soils provide an outstanding example.

Serpentine is the general term that describes serpentinite rocks and soils derived from them. The name actually represents a series of minerals that were dredged up from the earth's mantle when continental plates collided. Subduction of one plate under another causes substances from the deep oceanic trenches to get squeezed up, during which time they're heated or compressed. Yet some material remains little changed, while other similar material has been altered through heat or pressure. Changed or not, these materials share a similar chemistry and are called ultramafic, meaning they're high in magnesium and iron, both of which are key components in plant nutrition.

Serpentines also are low in the main elements found in fertilizers: nitrogen, phosphorous, and potassium, as well as the macronutrient calcium. Yet serpentines are especially rich in such heavy metals as nickel, molybdenum, and chromium. Such a specialized chemistry strongly hints that serpentine soils are not good for most plants. The low amounts of nitrogen, phosphorous, potassium, and calcium are serious obstacles to healthy growth.

Somehow plants adapted to serpentine soils must suffer these deficiencies, survive, and reproduce. One predictable response is slow growth, resulting in dwarfed plants: we see this, for example, in serpentine races of otherwise widespread species such as chamise (Adenostoma fasciculatum), Klamath weed (Hypericum perforatum), and scarlet oak (Quercus coccinea).

Other plants adapt by their high efficiency in absorbing all available traces of needed nutrients or by recycling these nutrients with speed and thrift. The high amounts of iron and magnesium in serpentine are another obstacle to healthy growth. Both are essential in small amounts but toxic in large helpings. Many plants simply can't cope with these generous portions of magnesium and iron. High doses of magnesium ions seem to be an obstacle to calcium uptake. Finally, serpentines contain nickel and chromium which are used in only the most minute amounts by ordinary plants, usually to catalyze (DEFINITION OF CATALYSIS?) enzyme activity. In large amounts, however, these metal ions attach themselves to amino acids and proteins, changing their abilities to function.

Studies are just beginning to explain how serpentine-inhabiting plants deal with those elevated levels of magnesium, iron, nickel, and chromium. Some plants simply don't allow these metals across their root membranes and so remain unaffected. Others, such as the milkwort jewelflower (Streptanthus polygaloides), accumulate large amounts of nickel in special tissues where these heavy metals can be safely stored. Jewelflower is called a hyperaccumulator.

How does serpentine affect plant life? Besides the several species that are broadly adapted to a wide variety of soils including serpentine, many generalist species have specific serpentine races. While these races grow well on serpentine, their sister races, adapted to ordinary soils, are unable to survive on serpentine. Generalist species with serpentine races include yarrow (Achillea millefolium), a perennial wildflower found from the seashore to the alpine tundra; self-heal (Prunella vulgaris), an herbaceous member of the mint family broadly distributed across North America and Europe; and mat pink (Silene acaulis), a sprawling alpine wildflower widespread in the high mountains of Europe and North America.

Other plants are endemic--that is, restricted—to serpentine. These plants serve as serpentine indicators, being ever faithful to serpentine soils. Some are narrow endemics, occurring only in limited, closely circumscribed areas. For example, the black jewelflower (Streptanthus niger) is found only at the east end of the Tiburon Peninsula in Marin County, California, an area of, at best, a few hundred acres; while the Tiburon mariposa (Calochortus tiburonensis), is confined to the other end of the same peninsula! Other serpentine endemics show a broader distribution. The picturesque Californian Sargent's cypress (Cupressus sargentit), the northwestern, early spring-blooming, subalpine Drummond's anemone (Anemone drummondit), and the slashed-leaf foxglove from the Iberian Peninsula (Digitalis laciniata) all occupy many acres of serpentine habitat in several different locales.

Why some plants are so narrowly confined while others are wide-ranging opportunists is poorly understood, although the distribution of serpentine soils in patterns resembling islands adrift in vast seas of ordinary soils, separated from one another by many miles, may help explain why some species are so limited. New species that have evolved on these islands may not have had the time or means to reach other islands because of inefficient, long-range seed dispersal. Or perhaps the chemistry between serpentines of different islands varies enough that the most highly specialized species can't grow on the soils of other islands.

Many serpentine endemics actually grow well or better on ordinary garden soils with their normal complement of nitrogen, phosphorous, potassium, and calcium. Yet under natural conditions competition--that unceasing struggle between plants for mineral nutrients, light, and water— prevents serpentine ehdemics from moving onto nutrient-rich soils, because they're such poor competitors with "normal " species. Serpentophiles may exhibit slow growth--roots that don't absorb water fast enough or leaves that don't photosynthesize as effectively as plants from ordinary soils. Much remains to be learned.