Chapter 7: Site Assessment and Soil Improvement

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Abstract
The first step in any restoration project is to gain an appreciation of the site. The site needs to be defined, delineated, inventoried, and assessed for the restoration goals and objectives to be successfully accomplished. A key component in assessing sites for ecological restoration is determining the site context. Each site should be assessed for its ecological and societal context. An ecological management unit (EMU), the smallest treatable unit—smallest restorable unit—must be the focus for restoration management activities. Through the assessment process, the primary concern is the ecological restoration of the EMU. An initial site assessment should include inventory of resources, space, size, diversity, temporal changes, disturbances, stress, natural cycles, organic matter, management, form, and development of a final action-list. However, it is just as important to the success of any restoration project to include the stake holders, decision-makers, and social systems in all phases of the project. Assessment is a part of the planning and management process, not a disjunct and separate piece. Remember that every site and situation will be different.

Another decisive step to be considered in a restoration project is soil health evaluation and improvement. Soil health management is essential for (and a part of) healthy and sustainable ecological systems. A number of soil features become degraded or destroyed over time in highly stressed environments. An average urban soil usually has few essential elements, poor drainage, erosion, soil compaction, a heavy texture, little organic matter, and a low diversity and small number of beneficial organisms. Restoration activities need to be prescribed carefully in trophic level order to assure success—in other words, truly start at the bottom and restore upward. The soil is the foundation upon which we restore ecosystem functions and structures. The soil attributes to be restored successfully include texture, structure, bulk density, water, aeration, element holding capacity, essential elements, organic matter, contamination, and trophic enrichment.

Introduction
The urban forest is the tie that binds humans to life sustaining ecological systems. Beyond the urban forest are the rocky and barren hardscapes of paved and roofed deserts. We have interspersed these buildings and roads with a few parks and road-side trees that are often maintained with too many resources and much energy. It is time to take back a heritage of forest and field, and live more gently among the trees. Restoration of these altered and often exhausted ecological systems will not be quick or easy. Yet the results and rewards are important to the future health of our cities and communities.

A restoration process includes an understanding of basic rules and perceptions regarding a community's ecological resources and how to plan and make decisions which impact these resources. Other chapters in this CD-ROM review the ecological principles and processes as well as the development of a management plan. However, one of the


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first steps in the restoration process is assessing the site’s resources. The soil is probably one of the most damaged parts of the ecosystem in the urban forest; therefore, restoring soil health of a site is a critical step to successful restoration. The first part of this chapter, Site Assessment, is concerned with the steps involved in this assessment. The second part of this chapter, Soil Improvement, presents the principles of soil health and methods for its restoration.

**Site Assessment**

Every surface and space in the urban forest is a resource containing site. Most sites are severely lacking in many resources, either through a lack of quantity or quality. Many sites have experienced disturbances such as hydrological alterations, invasion of exotic species, compaction from recreational activities and fragmentation. In restoring these sites, urban foresters seek to restore resources and processes. The first step in any restoration project is to gain an appreciation of the site. The site needs to be defined, delineated, inventoried, and assessed even before the goals and objectives for restoration are developed. Having a clear picture of the site is essential to describe and defend restoration options and plans to peers, stake-holders, decision-makers, site workers, and resource owners/controllers (Figure 1).

Site components include:

- life resources
- life connections,
- biological units,
- climate,
- topography,
- geology, and
- past history (disturbances, stresses, and mechanical damage).

What were the past historic ecosystems like on the site? Using maps, interviews, GIS and other resources, the historic ecosystems on the site need to be described with their flora and fauna and natural disturbances. Then the current ecosystems need to be described; what is there now and why? And finally how does this site fit into the landscape and the master plan for the region? Does it have regional significance, ecological significance, and/or social significance (Figure 2)?
Site Context

A key component in assessing sites for ecological restoration is developing, both for your own reference and others, a story of site development or a site picture. This is called determining the site context. How did the site arrive at its current condition? Included in this assessment is determining what it was like in the past, and, finally, an evaluation of the possibilities for restoration. Developing a full description of the site, its attributes and processes, is critical for identifying the possibilities and constraints to restoration. Practically speaking, a restoration site might be a perfect biological or ecological candidate, but socially unacceptable for restoration. Each site should be assessed for its ecological and societal context.

The ecological story of a site must be determined in any assessment process. The ecological context of a site includes, but is not limited to:

- **Anthropogenic changes** to the ecosystems on the site.
- **Site history** (biological, physical, chemical), including presence of toxins, hydrological alterations, substrate changes such as impervious layers, soil interfaces, and past abuse.
- **Soils**, including fill, compaction, interface problems, depth, drainage, aeration, contamination, and flooding regimes.
- **Topography/slope**, including cold pockets, soil depth, water relations, and wind impacts.
- **Energy balance**, including incoming radiation and its distribution/dissipation, urban heat island effects, wind and direction, light quality and quantity, and night lighting.
- **Water balance**, including relative humidity, precipitation, evaporation, irrigation, and site water demand.
- **Biological components** (animals, plants, microbes, etc.) and their interactions, including pests, competition, allelopathy, disturbance, succession, and mechanical damage.
- **Genetics**, including cultivars, natives, exotics, and genetic interactions with the environment (response to stress, strain, abuse, and pests).
- **Space**, including space for growth, expansion, crowding, stagnation, and space to structurally support life-forms.
- **Climate**, including precipitation, temperature, wind, pollution deposition, wind/pest interactions, variability (winter to summer or day to night), drought concerns in summer and winter, lag effect (e.g., time delay) of symptom expression, and problems of scale.

Climate is a critical feature of the site to understand. In general, urban climates (local to meso-climate scales) are significantly different than average climate data collected at regional weather stations. Urban climates, when compared to national/regional averages, have 25% lower wind speeds from obstructions; 12% greater calm days (air mass stagnation); 1.5°F greater annual temperature; 2.7°F greater minimum winter temperature; 7% greater precipitation events (more precipitation events but less per event); 5% lower relative humidity (geometrically increased site water demands); 7% greater cloudiness; 17% less incoming radiation (clouds and pollution); and, 10 times more common pollutants (Craul 1992). For further information check Craul's urban soils books listed in the Suggested Readings section.

In general, the urban climate is drier and hotter, with less usable water, more pests, and more pollution than normal. All these climate factors combined lead to greatly increased stress on ecosystems.

The societal context or story of a site must be determined in any assessment process. The societal context of a site includes, but is not limited to:

- **Anthropogenic changes of management**, such as changes in ownership from private to public with different management goals, objectives and implementation.
- **Historical significance**, including archaeological importance as well as more recent cultural significance.
- **Social significance**, including public/private ownership, emotional attachment, and pride or remorse of ownership.
- **Aesthetics**, considering the interaction between ecology and aesthetics. In the past we have accepted great architectural and aesthetic trade-offs disregarding local site ecology and biological functions.
- **Political significance**, including delineating who takes credit, pays bills, and is included.
- **Economics**, including analysis of values produced versus costs.
- **Site circulation and access**, including movement around and across the site, how access is allowed, and security issues.
- **Liability and environmental vandalism**, including safety, noise pollution, traffic control, and asset loss.
• **Regulatory environment**, including zoning, endangered species, wetlands, and erosion.

• **Cultural practices and public awareness** including herbicides, tree removals, topping, and perceptions of existing programs.

Once a site can be viewed in its ecological and societal context, an ecological restoration process can be fitted within the identified constraints to maximize ecological and biological values in a sustainable manner. An urban forester should list site constraints in a carefully prepared management plan by prioritized order from the most limiting to least limiting. For each constraint identified in the management plan, plans for dealing with the constraint need to be included.

### Management Units

In our assessment system for identifying and prioritizing process and site constraints, a management unit must be identified and delineated. Without mapable management units, discrete boundaries for treatments, and accurate planning edges, management confusion can exist as well as administrative accountability problems. What is the space and its dimensions for your restoration plan? What is the ecological management unit?

An ecological management unit (EMU), the smallest treatable unit—smallest restorable unit—must be the focus for restoration management activities. An EMU is a human-defined, limited area which can include one or more ecosystems. Site assessment requires identification, delineation, and declaration of an ecological management unit (EMU). In natural resource management, a written management plan cannot be fulfilled without understanding what is being managed, for what purpose, and its size, shape, or form. From an ecological restoration standpoint, the criteria we must use to apply, maintain and evaluate our actions depend upon our abilities to delineate an ecological management unit.

The necessity for setting boundaries and management limits is self-evident for any restoration manager. Unfortunately, many academic concepts of ecosystems fail to provide walls, limits or boundaries. The landscape includes many interconnected smaller ecosystems of various spatial scales, overlapping with each other and the restoration site. The conceptual problems with these ideas of ecosystems is which one you are trying to restore? What sub-division? What portion? How do you declare victory, evaluate actions, or prepare budgets if the spacial extent of the ecological restoration area is nebulous? Discrete boundaries for the restoration project are critical to planning, implementing and the success of the project.

### Politics and Science

Through the assessment process, the primary concern has been the ecological restoration of the EMU. However, it is just as important to the success of any restoration project to include the stake-holders, decision-makers, and surrounding social systems in all phases of the project (Figure 3). It is also critical to the project that science and politics remain separated. An ecological restoration project needs to compartmentalize and keep separate ecological science from social, cultural, and economic-based decision making. Physical, chemical, and structural facts need to be clearly separated from human feelings, needs, and value judgements. Ecology is apolitical in the natural world.

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**Figure 3.1.**
Credits: Rob Buffler

**Figure 3.2.** It is important to the success of any restoration project to include stake-holders, decision-makers and surrounding social systems in all phases of a project.
Credits: Mary Duryea
The Assessment Process

There are many tools and methodologies for assessing damaged and exhausted EMUs to determine whether they are viable candidates for restoration, and to identify the magnitude of efforts required for a restoration project. Presented here is a basic checklist for an assessment process. It is assumed you have already set goals and objectives, and identified a number of constraints (see Chapter 5—Developing a Management Plan). Assessment is a part of the planning and management process, not a disjunct and separate piece. Remember, every site and situation will be different. You are encouraged to develop assessment systems that best serve your ecological and political situations.

The following assessment process has been used successfully for urban and community forest sites, land development interface sites, and for damaged or abused environmental management sites in Europe and North America. This assessment process is presented as a guide to collecting information for planning restoration activities in an ecological management unit. The following information must be determined:

1. Quantify

The first step is to define and delineate (on maps and on the ground) the EMU and its context in the landscape. This step is an inventory of resources, processes and rates of change, and a classification or analysis of what exists (quantify and graphically classify).

2. Size

Assess the EMU and determine if it is large enough to sustain the values and outputs expected. This step is an assessment of scale problems including biodiversity, genetic variability, reproductive spheres, and colonization potential.

3. Space

Assess the spatial relationships between the EMU and other ecosystems in the landscape for current and future connectivity, fragmentation, and ecological integrity. Record quality and quantity of information on ecological gaps, fragments, corridors, and ecotones.

4. Diversity

Assess the variability, density, and diversity of species and their habitat. Included should be information on natives, exotics, and habitat composition for key species.

5. Time

Temporal changes across a site will be many. Assess the pattern and timing of when individuals and species are expected to age and die, and successional patterns for the site (See Chapter 4 - Plant Succession and Disturbances). Considerations are life-spans of key and dominant species, current age classes and structures, and how life-forms are removed or enter a site.

6. Disturbance

Assess historical and present disturbance regimes including the type, intensity, and frequency (see Chapter 4—Plant Succession and Disturbances).

7. Stress

Assess historic and present stress components of the site. Stress includes anthropogenic problems, competition, allelopathy, pests including invasive species, and environmental constraints to survival and growth (see Chapter 9—Invasive Species).

8. Natural Cycles

Assess the effort and consequences of activities to recover historic material and energy cycling processes. Assess how to restore the natural cycles such as nutrient cycling to encourage a more natural support (lower maintenance) of site functions and move away from human-centered support. Take special care in observing energy flow, the hydrology on the site, and nutrient status and processing (see Chapters 2 and 6—Ecological Processes and Restoring the Hydrologic Cycle)

9. Organic Matter

The presence of organic matter on the site is critical to the nutrient cycle and the health of the site. Special concern should be targeted at large woody debris and soil organic matter.

10. Management Resolve

Assess on-site and within the management system the appreciation of ecological realities (sometimes natural ecosystems may appear messy, unkept, or chaotic compared to sites with single species or grassy parks) and acceptance of change.
11. Action Check-List

The principle means of restoring the EMU can include:

- Re-instituting successional processes.
- Re-instanting disturbance regimes.
  - Enriching the genetic resources (living things), including:
    - Adding and/or replacing “key” organisms (trees, vertebrates, fungi, arthropods, worms, etc.)
    - Modifying native systems to include more trophic levels.
  - Improving site resources, including:
    - Increasing organic matter (woody biomass, soil and litter).
    - Improving soil exchange capacity (element cycling and holding).
    - Improving soil health (pore space and structure).
    - Increasing water availability (cycling, use, flow).
    - Modifying or enriching nitrogen cycling.
    - Altering site light resources (light and shade management).
- Minimizing stress on key species.
  - Contain or eliminate heavy metals.
  - Control pollution.
  - Control heat.
  - Control exotics.
  - Physically protect site from mechanical and chemical damage.
  - Control oxygen availability and water drainage trade-offs in soil.

**Soil Improvement**

**Introduction**

Soil health management is a very critical portion of a renovation process to sustain ecological functions. Soils are the primary contact point between living organisms and are a biologically, chemically, and physically active portion of the environment. Soils are the ecological interface for materials and energy exchange, and a matrix that supports, houses, and stores essential elements and living things. Mineral, dead, near-dead, and living things are all held in a thin layer of ecological volume called soil. Conceptually, a soil for restoration can be considered a matrix of living things rather than an engineering material. Soil is the basis for urban ecosystem productivity.

The resources soil provide to support ecosystem productivity include:

- growth materials (15 of 18 essential elements plus water from the soil,)
- transport and storage of growth materials,
- buffer change and variability,
- physical and chemical protection,
- structural growth matrix, and
- primary energy exchange surface.

Good soil management is essential for (and a part of) healthy and sustainable ecological systems. A number of soil features become degraded, destroyed or exhausted over time in highly stressed environments. Soil assessments concentrate on those chemical, physical, and biological features of soil resources that can limit colonization, survival, and growth of living things. Restoration activities need to be prescribed carefully in trophic level order to assure success—in other words, truly start at the bottom and restore upward. The soil is the foundation upon which we restore ecosystem functions and structures (Figure 4).

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*Figure 4. Soils form the basis for urban forest ecosystem productivity.*

Credits: Larry Korhnak

**Ideal Soils**

Ideally a soil is composed of materials and space in roughly equal proportions. A "perfect soil" for ecological development is considered to have 45% mineral materials and 5% organic materials (living and dead), and 50% pore space.
divided equally between large air-filled pores and small water-filled pores. A perfect soil has horizontal layering developed through an assortment of genesis processes. These layers are called “horizons” (Figure 5). Horizonation requires time to develop from the last major disturbance on the site. As such, most urban soils have little horizonation, but do develop these characteristics if allowed to remain relatively undisturbed.

An ideal soil profile (from the surface downward) would have four horizons as seen in (Table 1). Most urban soils deviate wildly from ideal soil features, but by knowing theoretical limits, restoration changes can be judged for value.

**Urban Soil Features**

Urban soils have many unique features. Urban soil features which are most limiting to a restoration process are listed below:

- great vertical and horizontal variation,
- compacted structure,
- modified infiltration, percolation and water holding capacity,
- crusting or water repellent surface,
- pH changes (usually increasing pH),
- restricted aeration and drainage,
- impotent or disjunct element cycling,
- modified ecology of soil organism activities (no organic material),
- toxins and contaminants,
- soil temperature changes, and
- reduced mineralization rates (from organic matter) and accelerated nitrification.

An average urban soil is disturbed and highly variable caused by digging, cutting, filling, trenching, and scraping (Figure 6). The average urban soil has few essential elements, poor drainage, and a compacted, heavy texture. Within the soil are many blatant, sharp interfaces between layers and parts. The average urban soil has little organic matter and surface litter with a low diversity and small number of beneficial organisms. Erosion remains a terrible problem.

**The Manageable 10**

The soil attributes that affect and control soil resources, and present the most potential for ecological restoration success are:

1. texture
2. structure
3. bulk density
4. water
5. aeration
6. element holding capacity
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7. essential elements
8. organic matter
9. contamination
10. trophic enrichment

Each of these restoration attributes represent opportunities for a manager to be successful.

**1. SOIL TEXTURE**

Texture is the relative percentage of sand, silt, and clay-sized particles in the mineral portion of the soil. Most soils are a mixture of various particle sizes and distributions. Texture directly affects water and oxygen, and indirectly affects essential elements. The clay component of a soil dominates soil activity. As clay contents approach and exceed 20–25% in the soil particle mixture, the chemistry and limitations of the clays control soil attributes (Figure 7).

Soil texture can be modified by amendments, but it is not practical for large scale projects. For example, on an average house lot the top foot of soil weights 400 tons. To convert soil texture in this zone from a clay soil to a sandy clay loam requires the removal of 120 tons of the clay soil and its replacement with 120 tons of sand. At the one-foot depth mark, the interface between the first foot and second foot of soil would be limiting to tree growth. The texture change provided by this amendment process successfully increased aeration pore space. It is clear from this example that soil texture changes are of little practical importance other than in beds, containers, or planting holes.

One area where texture is critical to understanding restoration processes is at textural interfaces. An interface is where soil texture changes over short distances (less than 1–4 inches). These interfaces are most often horizontal layers, but can be lens or vertical layers that texturally vary from adjacent layers. Textural interfaces below the soil surface can provide many gas and water exchange limitations.

There are four primary texture interface types:

**Type 1 Interface** = finer texture soil to coarser textured soil (small pores to large pores)—water cannot move from one layer to the next until the upper fine-textured layer is saturated (water will remain in the fine soil if it is at less-than-saturation). Bathtub effect!

**Type 2 Interface** = coarser textured soil to finer texture soil (large pores to small pores)—water movement is away from coarser textured soil and limited by water movement into finer soil (water can build-up at the interface if in excess, but continues to move into finer soil.) Drought effect!

**Type 3 Interface** = coarse horizontal or vertical layers of gravel, large sand, organic materials, etc.—water must saturate soil above the coarse layer before moving into the coarse layer (water will perch above the coarse layer). Because of hydraulic conductivity processes, the tree depends upon local water and local essential elements. This interface limits rooting area from the bottom. Perched water, limited oxygen flow!

**Type 4 Interface** = gradual texture changes where mixing or incorporation has spread out the interface distance—good interface width for minimizing water problems is 1 foot (1–4 feet depending on texture changes).

Working examples utilizing trees showing the importance of interface problems to restoration work follow. Tree #1 is planted in a native coarse soil with a root ball composed of fine textured soil. Water is added immediately above/over the root ball. Because of the interface (rapidly changing average pore sizes), water cannot move across the interface until the soil in the root ball saturates. The result is the tree sits in a near-saturated soil much of the time. (Type #1 Interface). An additional result is water applied to the site will not necessarily enter the root ball leaving the tree drought stricken.

Tree #2 is planted in a native fine soil with a root ball that is composed of coarse textured soil. Water added directly above the root ball will move across the interface, although slowly. Water will be drawn into the surrounding fine
textured soil from the large pore spaces of the root ball soil. The result is a tree under low soil water conditions much of the time. (Type #2 Interface).

Tree #3 is planted in native fine soil with a root ball composed of fine textured soil and a layer of gravel in the bottom of the planting hole. Water will be perched above the coarse layer and move through only as the soil above saturates. The result is water and oxygen movement through the soil is disrupted. (Type #3 Interface). A tree will have a limited rooting area until it breaks through the coarse layer. Depending upon the scale and duration of water and oxygen movement disruption in the soil, roots may never escape soil constraints.

2. SOIL STRUCTURE
Structure in soil is represented by aggregates of the basic texture particles in specific shaped structures. The primary types of soil structure are platelike, prismlike, blocklike and spheroidal. Soil particles are held in these structural aggregates by adhesive forces from organic, colloidal, or metal oxide coatings. Soil structure can be modified by amendments.

Organic matter amendments (composted organic material not merely organic mulch) promote granulation in both sandy and clay soils. Organic materials added to sandy soils generate more small pore development, which sandy soils lack. Organic materials added to clay soils generate more large pore development, which clay soils lack. In both coarse and fine soils the improvement in structure from organic matter additions improves the availability of water and oxygen (Figure 8). Care must be exercised when working with clay soils because they are very susceptible to compaction of pore spaces and destruction of structural units when wet.

An example of soil improvement through structural change could be compared to the attempted textural change example given above. The example cited modifying water and oxygen availability in the top foot of an average house lot. Adding 1.2 tons of composted organic material to the soil will have a similar effect as replacing 120 tons of soil with sand. A simple conclusion is restoration can be successful and cost-effective by concentrating on soil structure changes rather than soil texture changes. A critical feature of organic matter additions is do not allow sub-surface layers to develop.

3. BULK DENSITY AND PORE SPACE
Bulk density is the relative density of a soil including its pore space volume. It is measured by dividing the dry weight of a soil by its volume. If soil was just mineral material, an average density of common minerals would be 2.65 g/cc. As we discussed earlier, half of an ideal soil should be pore space (voids or spaces between solid soil materials)—which makes ideal bulk density 1.3 g/cc (50% pore space.)

The characteristics of pore space varies by soil texture. Sands have many large pores filled with air. Clays have many small pores filled with water. Clays have greater total pore space than sand, but it is filled with tightly held water. For example, the typical air filled pore space of a drained soil would be 35% for sand, 25% for silt, and only 15% for clay.

Unfortunately, urban soils are moderate to heavily compacted by footsteps, light vehicles, and heavy construction vehicles. This compaction shrinks large pore spaces that usually hold air, as well as decreasing total pore space (increasing bulk density.) Depending upon soil texture and structure, tree root growth problems can be initiated with only small increases in bulk density (Figure 9).
For example, roots have difficulty physically penetrating beyond a bulk density of 1.75 g/cc. Oxygen availability constrains tree root growth as air pore space drops below 15% volume of the soil. Table 2 presents soil attributes where tree root growth begins to be significantly limited for each soil texture class.

Compaction prevents root and soil functions essential to life. Compaction is found across all types of sites. Construction sites have been found to average 60% greater bulk density than neighboring native soils. A rule of thumb is an increase in bulk density by 1/3, causes a loss of 1/2 root and shoot growth. Compaction is not easily reversed. Harvest sites (logging decks, major skid trails, and forest road trails) can be effectively mapped after 40 years based only upon soil compaction and tree growth data. Time does not heal all.

There have been many compaction treatments proposed over the years. Surface tillage as deep as possible (at least 8 inches) and sub-soiling (winged bars below 16 inches), can be used when no tree roots are present to decrease bulk density. A soil can be amended with non-compressible, porous materials like washed flyash to provide pore space. Soil can also be amended with large gravel or small blocky stones to provide large airspaces and a bearing surface.

When trees are present, mulching can be used to minimize continued compaction pressure and dissipate raindrop energy and surface erosion. Core aerators made for deep penetrations (12–16 inch long) can be effective but in heavily compacted soil may not be effective beyond 3–5 inches deep and may be difficult to use. Punch aerators create open soil space but compact the side of the surrounding hole. Surface aerators (2–4 inches deep) generate a low bulk density zone over a compacted zone just below, thus presenting a very limited root colonization area. Aerials are undergoing a major conceptual re-engineering period for assisting with restoration of severely compacted soils.

The primary means of reducing compaction problems both concentrate on generating more surface areas/ecological volume for root initiation and colonization. The two methods are vertical mulching and radial trenching. Vertical mulching uses a series of vertical holes augered into the soil to a depth of 14–24 inches on 2–3 feet centers under the drip line of the tree. The treatment can be expanded into soil areas useful for root colonization. The 1–2 inch diameter soil cores should be backfilled with washed, graded, and non-compressible materials open to the atmosphere. A composted organic matter and mineral light mix would be ideal with an organic mulch placed over the surface. Over time, material subsidence will require refilling holes.

Radial trenching uses a trencher or thin back-hole to dig trench lines from 2–14 inches wide. Each trench line begins on the ground surface 4–6 feet away from the tree trunk. As the trencher moves outward from the trunk area, the cutting head is allowed to dig downward to its operating depth. The trenches are backfilled with washed, graded, and non-compressible materials open to the atmosphere.

A composted organic matter and mineral light mix would be ideal with an organic mulch on the surface. Various growth stimulators and soil enrichment materials may be added. Five to six trenches are initiated near the trunk and extend out to one and one-half the drip-line distance. As the distance between trenches increases, intermediate new trenches can be added, depending upon site and soil limitations.

4. WATER

Water is held around the soil particles and within soil pores. Water sticks together and is pulled through a soil to the top of a tree by the process of transpiration. Depending upon soil texture, some water is held too tightly by soil particles to be extracted by trees. The traditional soil-water terms are defined in Table 3.

Tree-available water varies by soil texture. Sandy loams probably have the greatest amount of water available to a tree of any soil texture. Clays contain more total water than other texture types, but most of this water (up to 75%) remains tied tightly to the clay surfaces and micro pores and, so, unavailable to a tree. Sands contain little water but what is present is almost all available for tree up-take and growth. Water movement can be disrupted in urban soils. The many textural/structural interfaces within urban soil profiles allow many water and oxygen availability problems to exist. In highly disturbed urban soils with many interfaces, water around the roots is critical to tree survival. Even the process of installing irrigation (depending upon backfill) can change water flow through the soil. Irrigating to correct turf water shortages will usually over-water trees. Trees should be separately zoned for irrigation in a landscape.

As site water inputs exceed outputs, soil health and tree roots are damaged. In addition, a number of pathogens thrive under poor drainage conditions. Drainage can be estimated by percolation tests. Irrigation should be adjusted to the drainage class of the soil, seasonal precipitation, and evaporation demands. A $20,000.00/100 year old tree is irreplaceable in three generations, while the turf and small
shrubs are immediately replaceable at a modest price. Priority must be given to high-value landscape items like trees (Figure 10).

In the urban landscape the generation and transportation of heat can have an impact on water use in a tree and on a site. For every 18°F increase in temperature above 40°F, site and tree water evaporation and respiration almost double. The more heat a site must dissipate, the more water must be evaporated. Lack of evaporative surfaces and few heat blocking or dissipating shade structures allow heat accumulation on a site. Heat accumulation “cooks” trees and soils present, while heat moving onto the site from surrounding hardscapes demands site water use for evaporation. Irrigation must be tuned for handling additional heat loads.

5. AERATION

Aeration is oxygen moving in large soil pores from atmosphere to tree root surfaces. Soils have combinations of aerobic and anaerobic sites and the balance between them is constantly changing through the seasons, days, or years. Oxygen movement can only be assured by the presence of large pores, fracture lines, decayed root lines, or aeration columns. Compaction and flooding can produce many water-filled pores. Oxygen moves 1,000 times slower across a water barrier (water-filled pore) than across a gas filled pore. Therefore, wet or compacted soils do not allow oxygen to effectively move to roots. Any place where soil atmospheric oxygen drops below 5% concentration, root growth stops.

As oxygen moves in the soil, many organisms use its oxidation power before it reaches tree roots. Under poor drainage and low oxygen conditions, oxygen can be used up quickly. Once the oxygen is consumed, soil organisms (not tree roots) begin to use other elements for respiration. The respiration sequence is oxygen, nitrogen, manganese, iron, sulphur, and carbon. An entire year’s fertilization load of nitrogen can be respired away into inert nitrogen gas within weeks under near anaerobic conditions. Once the soil organisms start to respire sulphur and carbon, many materials are formed that will require purging or rinsing out of the soil for best recovery. The warmer the temperature, the quicker oxygen is consumed and the faster alternative respiration will occur (i.e., doubling rate sequence for respiration with increasing temperature).

Solutions for aeration problems are good drainage and open soil surface for gas exchange. To meet these goals, drain and sump systems can be installed. These systems are made of perforated pipes sunk to various depths. A drain system may include a number of interconnected horizontal and vertical pipes that were either pre-positioned before planting or trenched-in afterwards. The goal of a drainage system is to allow gravitational water to move away from the soil and away from root colonization areas. Sump systems use large diameter perforated pipes vertically sunk into the ground well beyond rooting depth to allow for accumulation of gravitational water in the pipes. These water containing pipes can then be pumped out periodically. These pipes can also be used to quickly saturate a soil area by filling with water during droughts.

The other major form of aeration modification is accomplished by terra-forming or sculpturing the landscape. Designing berms, terraces, raised mounds, and topography changes from grading practices can all be used to gain root colonizable space. These structures must be built to minimize erosion and should be able to withstand a 100-year rainstorm event.

6. ELEMENT HOLDING CAPACITY

Trees take-up essential elements in ionic forms from soils. A small portion of the essential elements are readily available, dissolved in tree-available water. Most essential element ions are held near the surfaces of clay and organic particles. Clays and portions of organic materials (humus) have negatively charged areas that attract and keep the positively charged ions (cations) in close proximity. These binding sites help keep essential elements from being washed from the site. Cations include calcium, manganese, zinc, magnesium, potassium, and ammonium.

Cation exchange capacity (CEC) is a measurement of the positive charged ion holding or storage capacity of a soil. A calculation for rough estimation of CEC is:
CEC = ((% organic matter in the soil) X 2.0) + ((% clay in soil) X 0.5)

The formula suggests how effective additions of clay and composted organic matter might be to a soil. Organic matter is four times more effective for improving CEC as clay. For soil type and texture, relative CEC varies: sand = 1; loam = 5; silt loam = 8; clay = 15. Cation exchange capacity generally increases with soil pH.

Organic materials also have surface areas with positive charges that attract negatively charged ions (anions) like nitrate, phosphate, sulfate, chloride, borate, and molybdate. Anion exchange capacity (AEC) is a small part of soil chemical activity. Anions either move freely with water, like nitrates, or are bound in insoluble forms like phosphates (Figure 11).

7. ESSENTIAL ELEMENTS

There are a number of elements essential to the life and health of living things. Air (CO₂) and soil water (H₂O) provide three essential elements (O, H, and C). Soil provides the remaining 15 essential elements. An ecological system will progress until any one essential element or process becomes limiting. It matters little how much nitrogen is added to a site if zinc is the most limiting element to tree growth. Below is Table 4 which provides a general and relative ratio of essential elements in trees.

On most terrestrial sites, nitrogen is usually limiting for a number of reasons. Phosphorus can be limited on wet and poorly drained soils. Fertilization prescriptions should be nitrogen-centered but assure easy phosphorus availability. Elements most often limiting in order of importance are N, P, Mg, and K. Excessive nitrogen fertilization has caused a number of overdose events and over-medication programs to damage ecosystems and trees, especially the very old and the very young. Ecologically, both large doses and no doses can be less productive and less healthy than mid-ranges.

8. ORGANIC MATTER

Organic matter is once-living materials decomposing and eroding back into the soil (Figure 12). As noted in the above discussions, organic matter can improve soil structure, bulk density, water and element holding capacities, and aeration. Organic materials provide fuel, food, and habitat for the detritus engine of the soil. Urban forest soils often have no or limited organic matter, as well as the associated flora and fauna that break-up and decompose organic materials. Therefore, the natural processes of element cycling usually occur only in small amounts on urban sites. Leaving fallen plant materials on site and/or incorporating organic amendments can greatly improve soil health and in-turn the health of the urban forest.

9. CONTAMINATION

Soil is both easily polluted and difficult to clean or restore. Contamination effects can out-right kill and damage ecological and biological systems. In addition, contamination acts to disrupt and poison restoration processes (Figure 13). General classes of contamination in soils are lead and other heavy metals (a legacy that does not decay); pesticides; salt; petroleum products; biological excretions (urine, feces, etc.); litter/construction materials; soil crusting (hydrophobic surfaces from petroleum, allelopathic materials, and organic coatings); and buried trash from past construction and land-uses (cement wash-outs, general land fills, garbage dump (current or historic), poor coverage with top soil, methane, and soil subsidence associated problems).
Three examples of contamination that might disrupt ecological restoration activities include:

1. Lead in soils from the days of leaded gasoline (in Minneapolis, MN, it was estimated that 2,000 tons per year of lead dust from autos fell onto soil surfaces),

2. Animal and human wastes concentrate toxins and salt content in fresh feces and urine. There is also a risk of viral and bacterial disease with contact of in-place soil or air-bourne soil, and

3. Floods wash down the contents of storage bins, sheds, and tanks from up-watershed to those below, generating deposition and clean-up problems.

Solutions to soil contamination problems begins with identifying concerns and soil testing. Associated with testing for contamination should be development of a water and soil contamination map of the site. Once this map is complete, a prioritization system can be developed for other treatments or activities. Contamination treatments could include the complete removal or tie-up of materials in the soil using pH, plasma jets, organisms, chemicals, and /or barriers. Removal of contaminated soil might fall under toxic waste regulatory agencies to supervise. Mulching and careful nitrogen fertilization across well-drained sites can accelerate bacteria and soil processes that can minimize or destroy some contaminants. Cultivation or addition of a wetting agent might assist with health restoration by breaking-up soil and organic material crusts. Keep human contact away from contaminated areas including collecting or consumption of plant tissues, fruits, nuts, and mushrooms.

**10. TROPHIC ENRICHMENT**

Enrichment is the addition, infection, contamination, or repatriation of the site with various living things. A simple teaching model uses the term “WAFBOM,” which represents worms, arthropods, fungi, bacteria, and organic material added to a site. This multi-level trophic enrichment attempts to restart the detritus ecological engine needed for soil and tree health (Figure 14). There remains a concern about infecting sites with exotic organisms, especially worms and fungi. Gene set trade-off must sometimes be made in site restoration. Fully conceived and operating processes, once established, may eventually eliminate poor species or organisms.

Many urban sites for restoration are far removed (islands) from sources of reintroductions and infections of living things. If you build the perfect restored system, species may find the site or not (if you build it, they may not come). Active intervention and infection at multiple trophic levels can accelerate the site colonization process. Urban sites are tough on beneficial organisms like arthropods, worms, fungi, and bacteria, especially where increased heat loads quickly “burn-out” organic matter in the soil. Many sites could benefit from organism infection in the nursery, or organism inoculum applied at planting time.

Organic matter remains a universal resource for restoration of urban forest sites. The organic matter is the feed stock and habitat for beneficial soil organisms and for tree roots. Composted organic matter can be top-dressed over the site with a thin protective layer of non-compressible, organic mulch covering. Restoration managers are then placed in a position of animal husbandry (microbe-jockeys). Managers
should beware of the wolves (pathogens and exotic higher plants) among the sheep. Native gene sets should always be conserved, but exotics might help recover a site faster, serving as a nurse crop or successional predecessor. Ecological and genetic trade-off must always be made.

Conclusions

A key component in assessing sites for ecological restoration is developing, both for your own reference and others, a site picture, also called determining the site context. Each site should be assessed for its ecological context and societal context. An ecological management unit (EMU), the smallest treatable unit—smallest restorable unit—must be the focus for restoration management activities. In addition to the ecological considerations for a project, it is also important to the success of any restoration project to include the stake-holders, decision-makers and surrounding social systems in all phases of the project. Site assessment is a part of the planning and management process, not a disjunct and separate piece. Remember every site and situation will be different. An initial site assessment should include inventory of resources, space, size, diversity, temporal changes, disturbances, stress, natural cycles, organic matter, management, and a final action-list.

A restoration process includes an assessment of present conditions, how they are changing, and concentration of efforts on site factors that can be repaired or improved—soil health components. Good soil management is essential for (and a part of) healthy and sustainable ecological systems. Since a number of soil features becomes degraded or destroyed over time in highly stressed environments, soil evaluation and improvement becomes imperative. An average urban soil has few essential elements, poor drainage, a compacted, heavy texture, with little organic matter, low diversity and small number of beneficial organisms. Restoration activities need to be prescribed carefully in trophic level order to assure success—start at the bottom and restore upward. The soil is the foundation upon which we restore ecosystem functions and structures. The soil attributes affecting and controlling soil resources to be restored successfully include texture, structure, bulk density, water, aeration, element holding capacity, essential elements, organic matter, contamination, and trophic enrichment.

Suggested Readings


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Table 1. An ideal soil profile

<table>
<thead>
<tr>
<th>Horizons</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A horizon</td>
<td>surface soil with maximum organic matter accumulation, good porosity, many living organisms, most active tree roots, and represents a zone leached by precipitation and soil weathering factors</td>
</tr>
<tr>
<td>B horizon</td>
<td>&quot;subsoil&quot; where clays accumulate</td>
</tr>
<tr>
<td>C horizon</td>
<td>oxidized parent material</td>
</tr>
<tr>
<td>D horizon</td>
<td>unoxidized parent material</td>
</tr>
</tbody>
</table>

Table 2. Soil attributes where root growth begins to be significantly limited for each soil texture class.

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Root-limiting bulk density g/cc</th>
<th>Root-limiting % pores filled with air</th>
<th>% total pore space in soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>1.8</td>
<td>24</td>
<td>32</td>
</tr>
<tr>
<td>fine sand</td>
<td>1.75</td>
<td>21</td>
<td>34</td>
</tr>
<tr>
<td>sandy loam</td>
<td>1.7</td>
<td>19</td>
<td>36</td>
</tr>
<tr>
<td>fine sandy loam</td>
<td>1.65</td>
<td>15</td>
<td>38</td>
</tr>
<tr>
<td>loam</td>
<td>1.55</td>
<td>14</td>
<td>41</td>
</tr>
<tr>
<td>silt loam</td>
<td>1.45</td>
<td>17</td>
<td>45</td>
</tr>
<tr>
<td>clay loam</td>
<td>1.5</td>
<td>11</td>
<td>43</td>
</tr>
<tr>
<td>clay</td>
<td>1.4</td>
<td>13</td>
<td>47</td>
</tr>
</tbody>
</table>

Table 3. Definition of soil-water terms.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field capacity</td>
<td>the amount of water held against the force of gravity</td>
</tr>
<tr>
<td>Permanent wilting point</td>
<td>water content level where the soil holds water so tightly that trees cannot extract it (water contents at or below this level are unavailable to the tree)</td>
</tr>
<tr>
<td>Tree-available water</td>
<td>water present in soil between field capacity and permanent wilting point that trees can extract from the soil</td>
</tr>
</tbody>
</table>

Table 4. Ratio of essential elements in trees. (* = from CO$_2$ and H$_2$O)

<table>
<thead>
<tr>
<th>MACROS:</th>
<th>MICROS:</th>
<th>Transformers:</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrogen 60,000,000*</td>
<td>chlorine 3,000</td>
<td></td>
</tr>
<tr>
<td>carbon 35,000,000*</td>
<td>iron 2,000</td>
<td></td>
</tr>
<tr>
<td>oxygen 30,000,000*</td>
<td>boron 2,000</td>
<td></td>
</tr>
<tr>
<td>manganese 1,000</td>
<td>zinc 300</td>
<td></td>
</tr>
<tr>
<td>nitrogen 1,000,000</td>
<td>copper 100</td>
<td></td>
</tr>
<tr>
<td>potassium 250,000</td>
<td>molybdenum 1</td>
<td></td>
</tr>
<tr>
<td>calcium 125,000</td>
<td>cobalt</td>
<td></td>
</tr>
<tr>
<td>magnesium 80,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>phosphorus 60,000</td>
<td>Transformers:</td>
<td></td>
</tr>
<tr>
<td>sulfur 30,000</td>
<td>cobalt</td>
<td>nickel</td>
</tr>
</tbody>
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