Water Retention and Drainage in Bonsai Soil

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Figures 1 & 2: Above, Examples of how a shallow bonsai pot can support the needs of its tree only if it has an unconventional soil mix.

"Soil mix!" These two simple words can excite the passions of many a bonsai enthusiast, because issues surrounding them are anything but simple. Of course, other aspects of bonsai care matter at least as much as soil composition and can sometimes compensate for soil deficiencies: timely watering and fertilization, ambient light, humidity, and temperature. Nevertheless, spirited debates about the efficacy and optimal proportions of specific soil amendments can be readily stimulated among bonsai practitioners. Many, when challenged, will understandably stick with mixes that have worked for them, but without knowing precisely why.

There is no argument, in principle, about the importance of a good balance between drainage and water retention. Despite this consensus, quantitative evaluations of these properties for common soil components and mixes are not easy to find. As a beginner, I thought it would be fun and interesting to measure some of these characteristics and to share them with the bonsai community at large.

It's all about compaction. (Figures 1 & 2) First, some context for soil issues is in order. Because bonsai live in shallow pots, the growing medium must be very different from that of trees in their natural environments: it must encourage and support a fine, highly ramified network of roots in a very small volume. Centuries of experience have found that a soil mix will at least minimally satisfy the needs of most species used for bonsai if it provides:

- a good balance between drainage and moisture retention,
- a sturdy anchor for the roots,
- a nutrient store that can be easily replenished, and
- a hospitable environment for microbes.

A thin layer of conventional soil would tend to compact (have the air spaces pushed out of it) over time. Resistance to compaction assists both absorption and drainage, because it assures that the requisite amount of air is available to the root system, preventing waterlogging. It also assures that water and added nutrients can be delivered to the entire root system instead of running off the soil surface. This immediately rules out conventional organic components like topsoil as dominant in a successful mix because they compact too easily and break down (become more powdery) over time. Non-compactible organic material can have an important role as a channel to introduce and retain both nutrients and microbes, but in bonsai soil it is generally limited to a third of the mix. So what else can be used to fill out the pot?

Breathing in the ball pit. (Figure 3) If a soil component were composed of nearly rigid, approximately spherical granules of similar sizes, it would resist compaction. Why? Because identical spheres can't be randomly stacked so as to leave less than about 40% of the volume between them as unfilled, allowing free flow of water and air. After all, when a child plays in the ball pit at your local Fun House, you are rightly not concerned about her "drowning" under a pile of balls: there is plenty of air. However, the amount of air available would change if much smaller "balls" (e.g., sand) were introduced into the gaps between the larger ones. To avoid the analogous problem, bonsai soil components are generally screened to allow variation in granule size of only a factor of two or three, in which case the open space would only be modestly reduced compared to identically sized granules. The very small, powdery particles that inevitably arise from gradual breakdown of almost any "soil", sometimes referred to as "the fines", can accumulate excessively in the pot over time: flow of air, water, and nutrients is hindered when this occurs, which is one reason for periodic repotting. A minimum granule size of about 1 mm has been found to prevent the soil from clogging up excessively. Inert materials such as granite, gravel, or coarse sand, screened for uniform size, are commonly added to a mix to improve drainage. In general, larger granule size corresponds to better drainage and smaller size to better water retention. This occurs because, although the fraction of open space is independent of granule size (in the case of spherical granules, anyway), the longer distances between grain surfaces in a larger granule mix are such that gravity overcomes the cohesive forces holding water between adjacent grains. So smaller grain size is one way for a mix to retain water better; larger grain size a way to improve drainage.

Figure 3: Left, A fun-house ball pit exemplifies how a bonsai soil of rigid granules can prevent soil compaction and maintain air and water flow to the root system. Attribution: freedigitalphotos.net, Sura Nualpradid. (http://www.freedigitalphotos.net/images/asian-boy-and-colorful-small-ball-photo-p228298)

Figure 4: Below, Lava rock is both rigid and porous, making it an ideal bonsai soil component. As a bonus, it also can supply important minerals to the roots.

Catch and release. (Figure 4) Ideally, some of the rigid soil granules would also have some ability to absorb water and nutrients and then release them to

Figure 5: Right, Soil that is heavy can better anchor a tree, hindering erosion and protecting it from blowing over in heavy wind.

the roots; imagine each plastic ball in the Fun House pit having small holes in it (like a Wiffle ball) and containing a sponge inside. As it turns out, lava, pumice, and some forms of fired clay (haydite, calcine clay, akadama) are simultaneously rigid and porous to varying extents.

Gone with the wind! (Figure 5) It is also helpful if at least one component is dense because total soil weight is important in supplying ballast, helping avoid container blowover in strong wind and to resist erosion from heavy rains or energetic top-down watering. The pot generally provides the primary source of ballast, and wire secures roots to the pot, but soil can play a supporting role here.

On to the measurements! The ideas and techniques described here are well-known in soil science. In the context of bonsai, noted horticulturalist and bonsai artist Jack Wikle has described[1] these concepts. Lively exchanges of information, measurements, and relevancy of these matters can also be found in numerous online blogs and discussion forums. The measurements presented here are not meant as definitive or absolute, but as reminders of some of the important roles of soil in growing successful bonsai, and to demystify the sometimes-confusing jargon.

Good drainage signals the presence of air pockets distributed throughout the soil, even shortly after a "good watering" (i.e. immersion or gentle pot flooding). Good moisture retention means that some water is held by the soil after drainage. Soil scientists quantify these properties as saturation porosity and field capacity. Saturation porosity is the fractional air content, by volume, of soil just after saturation and drainage; farming soils typically range from 2% to 7% in saturation porosity near the soil surface. Field capacity is fractional water content, by volume, again, just after saturation and drainage; farming soils can operate near 50% in field capacity. Complicating matters more is that not all of the moisture present in the soil is actually available to the roots because the adhesive and cohesive forces holding water to the soil can be stronger than the roots' ability to absorb it. The moisture fraction below which the plant can no longer draw enough water to survive is known as the wilting point, which varies from tree to tree, soil to soil, and from one set of growing conditions to another, but can amount to 20% or more. The important concept here is that water becomes available to a plant only between the wilting point and field capacity: a substantial fraction of soil-held water is unavailable to the roots. The sum of the saturation porosity and field capacity is known as effective porosity, which is the fraction of volume that is both void and available to water. The total porosity is a similar fraction that includes both the effective porosity as well as porous spaces that are too small to admit water. The total porosity is not probed in what appears below.

Figures 6 & 7: Below, A plastic bonsai pot is used for the experiments. Drainage holes are covered with mesh as usual from the inside, held here with duct tape instead of wire. The holes are sealed on the bottom with a temporary strip of duct tape, which is removed to allow the pot to drain. Photo credits: Brian Heltsley.

Methodology

The basic experimental concept is to have a container that can hold soil and water without leakage, but later be drained without losing any soil. (Figures 6 & 7) Mass measurements at each stage most easily provide the necessary data; a digital food scale gives more accurate results than eyeballing volume on a measuring cup. (Figure 8 series) First, the empty container is weighed with result M1. Then it is filled with water; the container now has mass M2. The difference V = M2 – M1 gives the container volume V, in ml (or cc) if the masses are expressed in grams, because water has density 1 g/ml. The procedure for each material is as follows, with mass after each step indicated by M#:

1. Fill the container to the brim with dry material: M3.
2. Add water to the brim, waiting for up to two minutes for the water level to stabilize and for bubbles no longer to be observed. Before weighing, be sure to bring the water level all the way to the brim: M4.

Figure 8: Top series, After the pot is weighed first, empty, and then with water (which together determine volume), the dry sample is weighted. Water is added up to the brim and allowed to become absorbed. After the water level is stable and then topped off, the tape on the bottom of the pot is removed and the pot allowed to drain. Photo credits: Brian Heltsley.

Figure 9: Bottom series, Unscreened samples of perlite (left), calcine clay (center), and red lava-2 (right). Photo credits: Brian Heltsley.

3. Drain container without loss of solids, waiting up to five minutes for drainage to slow to nothing: M5.

With these measurements, material density is D = (M3 – M1) / V, saturation porosity is SP = (M5 – M4) / V, and field capacity is FC = (M5 – M3) / V. The effective porosity, which is the void fraction available to water, is EP = SP + FC.

Ingredients

Bonsai soils tend to have three classes of components, present in roughly comparable proportions: dense and inert, absorptive, and organic[2] . Specific choices for the ingredients and their proportions depend upon regional availability and cost, the species to be grown in the mix, temperature, humidity, wind, and light conditions where it will reside, watering regimen, and finally upon the aesthetic and horticultural preferences of the bonsai artist.

Individual and mixes of soil amendments were tested for water-holding capacities. In what follows below, an asterisk (*) indicates that the given material has been screened to have grain size between 2 mm and 6 mm. (Figure 9 series) (The screening yield, or fraction of the bulk mix that survives, is given in a chart below.) Two commercial mixes were tested as delivered, without screening. (Figures 10 & 11) Four mixes were assembled from screened, individual components, as indicated (exception: silica sand was not screened). Some of the information below originates with bonsai artist Colin Lewis at his blog[3] . The source of the ingredients, (store) or (online), is indicated, and may be more or less convenient for you, depending on your location. All proportions are taken by volume.

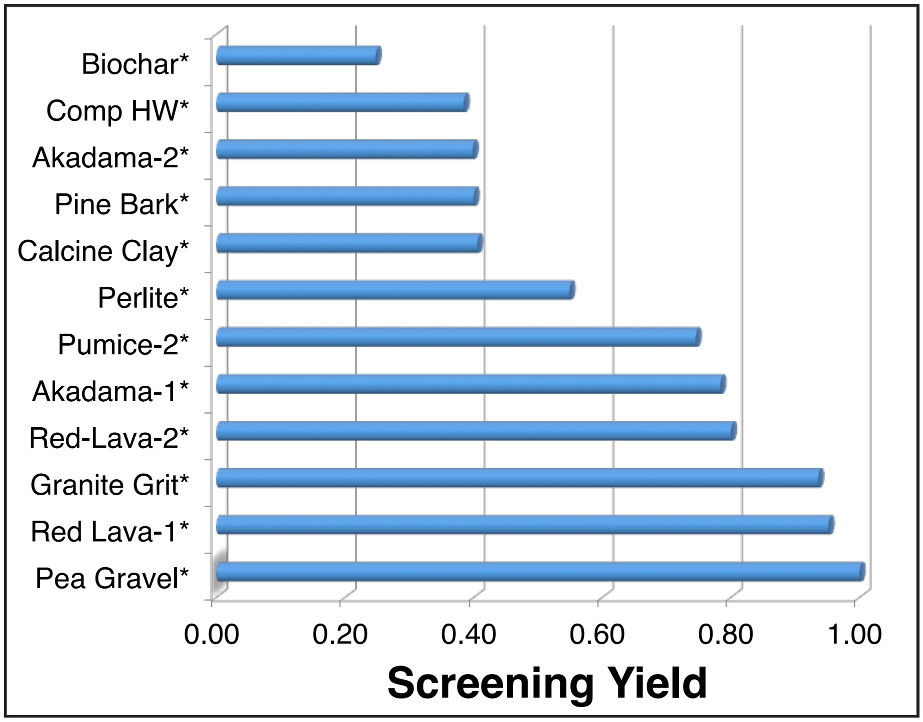
- Akadama: a clay-like mineral mined only in Japan that has excellent water retention and drainage properties. It is unique in that roots grow through the material, not just around them, and supplies important minerals. Two granule sizes were tested here, large (akadama-1), which is 3-6 mm, and medium (akadama-2), which is 1-3 mm. (online)

Figure 10: Left, The commercial soil mix nicknamed Promix-1. Photo credit: Brian Heltsley.

Figure 11: Left, The commercial soil mix nicknamed Promix-2. Photo credit: Brian Heltsley.

- Calcine clay: A mined clay that has been later fired at a temperature just high enough to solidify it and instill a strong ability to absorb water. It is used for conditioning soil on athletic fields and in container gardening. A readily available version sold in the US is Turface MVP®. (local store)
- Pumice: Naturally occurring porous volcanic rock that is off-white to gray in color. It is extracted from mines, typically in Colorado, and provides some minerals. Two slightly different types are examined here, pumice-1 and pumice-2. (online)
- Lava: Naturally occurring porous volcanic rock that is red or black in color. It is extracted from mines, and provides some minerals. Red lava-1 is 2-4 mm in granule size, and red lava-2 is 3-6 mm. (online)
- Perlite: A silicon-based volcanic glass that is mined. When heated to sufficiently high temperatures, vaporization of trapped water causes it to expand rapidly to about ten times its original size, much as popcorn does. It has a very low density, floats in water, and has many embedded microscopic bubbles, some of which allow it to hold water. Used extensively in container gardening for its ability to improve drainage, it has generally been eschewed by the bonsai community due to its low density (it floats!) and bright white color. (local store)
- Granite-grit: Small pieces of sharp-edged granite, marketed as "grit" for poultry gizzards. Grains measure 1.5-4 mm in the "Grower" variety. (local store)
- Pea gravel: Smooth gravel with rounded surfaces, deep gray in color, with grain size of 2-6 mm. Sold for construction purposes. (local store)
- Silica sand (coarse): a sand with fairly uniform grain size of about 1 mm. Not subjected to screening due to uniformity of size. (online)
- Pine Bark: from shredded bark, grains of the right size must be sifted away from both the fines as the larger pieces. (local store)
- Composted hardwood: From composted, shredded hardwood mulch, it is an alternate form of organic additive to bark that is denser, less absorbtive, and slower to decay. (local store)
- Biochar: see the recent article[4] on biochar, which can be added in place of some or all other organic components. (online)
- Promix-1: A 14-ingredient high-density commercial mix of calcine clay, lava, sand, and a fine-gritty organic admixture.
- Promix-2: A low-density commercial mix of screened, composted mulch, calcine clay, vermiculite, and frit (chemically complex glass that supplies minerals).
- Economy mix: The name derives from low cost (see chart). It contains calcine clay, granite-grit, and pine bark in equal proportions.
- Deluxe mix: The name derives from its higher cost. It contains two parts akadama-2 and one part each of red lava-1, silica sand, and biochar.
- Volcanic mix: The name derives from the origins of its larger components. It contains 3 parts red lava, 2 parts pumice-2, 1 part perlite, and 2 parts pine bark.

Figure 12: Right, The screening yield is the fraction of the bulk material that survives screening for size larger than 2 mm but less than 6 mm.



- Kitchen Sink (KS) mix: Everything but the "kitchen sink"- 3 parts calcine clay, 2 parts biochar, and 1 part each akadama-2, red lava-1, pumice-2, perlite, granite grit, pea gravel, silica sand, pine bark, and composted hardwood.

Results & Conclusions

The magic of bonsai soil mixes is, in part, their ability to provide conventional functionality in an unconventionally small volume. A big part of that functionality is delivering air and water to the roots, which in turn depends upon a number of factors. The charts show our results for some common soil amendments and mixes thereof.

The data in the yield, porosity, density, and cost charts can be characterized as follows:

- Densities vary by more than a factor of ~15, from perlite to pea gravel.
- Field capacities range from 11-50%, from pea gravel to unscreened calcine clay.
- Saturation porosities range from 9-43%, from unscreened calcine clay to screened red lava.
- Effective porosities range from 39-69%, from pea gravel to screened calcine clay and biochar.
- Screening out grains smaller than 2 mm, where they exist in quantity, has the expected effect of improving drainage (e.g. calcine clay, perlite, pumice-2, both akadamas).
- Screening yields can be well below 50%, meaning that considerable manual effort (and waste) is involved to use some raw materials. *Note: Pelletized biochar, already available, may address its low screening yield and resultant higher cost, as could pre-screening by the producers.*
- Even after screening out sub-2 mm particles, larger grain size means better drainage (pea gravel vs. granite-grit; silica sand vs. granite-grit; akadama-1 vs. akadama-2, red lava-1 vs red lava-2).
- The three organic additives have similar effective porosities, but the composted hardwood retains less water and drains more easily than either biochar or pine bark.
- The two different brands of pumice, of similar grain sizes after screening, hold and drain water differently. It is likely that materials with complex internal structures and that are the results of natural processes will show this kind of variation, depending on where they were mined. There is also likely to be significant variations in lava samples extracted from different locations. It is also likely that some porous materials would admit and hold more water if soaked for hours, not minutes.

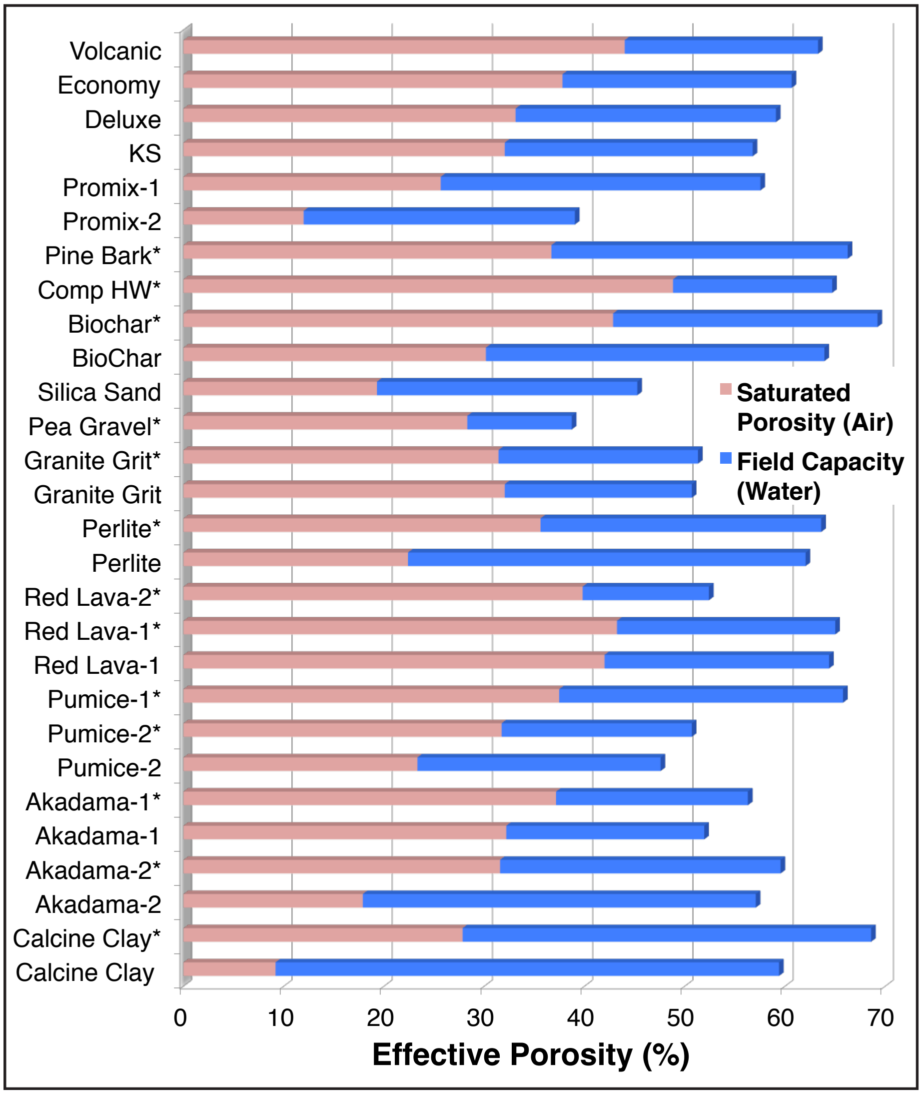


Figure 13: Left, Water retention and drainage characteristics of selected soil amendments and mixtures. An asterisk (*) indicates that the given material has been screened to have grain size between 2 mm and 6 mm. Results may and do vary somewhat with details of measurement technique, dryness of soil, humidity, etc. Soil properties other than those listed do affect growing results. Readers can and should make their own measurements.

- The two commercial bonsai soil mixes are completely different from each other: one is composed of lighter ingredients which achieve a moderately good water absorption and very good drainage, while the other has much smaller grain sizes and denser ingredients, resulting in excellent water retention but worse drainage than the lighter mix. The denser Promix-2 would be more effective in a dry climate where water retention is crucial; Promix-1 could more easily sustain a tree in a wet environment with its superior drainage.
- Prices are such that a good homemade mix can easily cost (possibly much) less than half that of a commercial mix, with the downside of having to purchase large quantities and screen them prior to mixing. The KS mix is such an example.
- Inexpensive but apparently effective components with good drainage and water absorption include calcine clay, perlite, granite grit, pea gravel, and bark. Including other more expensive components with 10-20% fractions would not be terribly costly.
- A mix tends to have the same effective porosity as the volume-weighted average of its components, but apportioned differently between drainage and water retention compared to the ingredient average. For example, the Economy mix has 0.61(EP) = 0.38(SP) + 0.23(FC) compared to the volume-weighted averages of the ingredients 0.62 = 0.32 + 0.30. Conversely, the Deluxe Mix

Figure 14: Below, Density in pounds per quart of material after screening. An asterisk (*) indicates that the given material has been screened to have grain size between 2 mm and 6 mm.

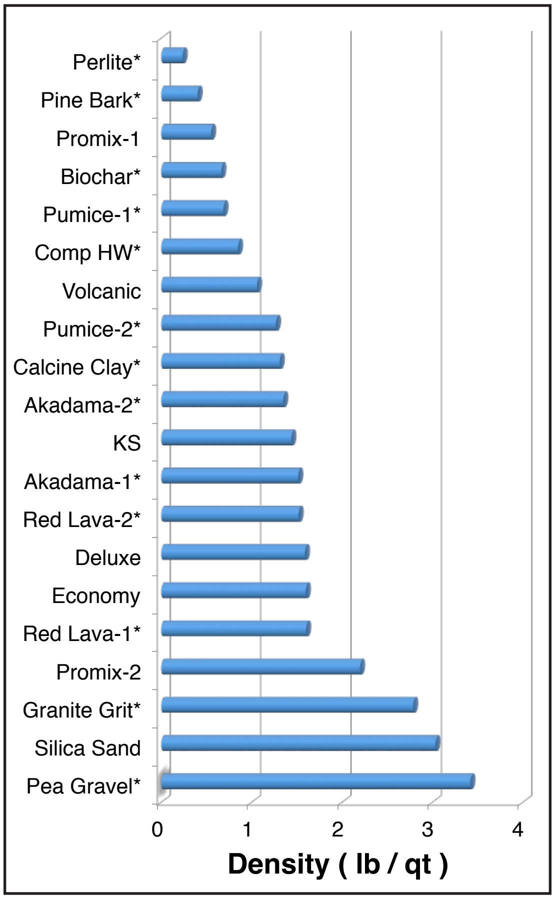
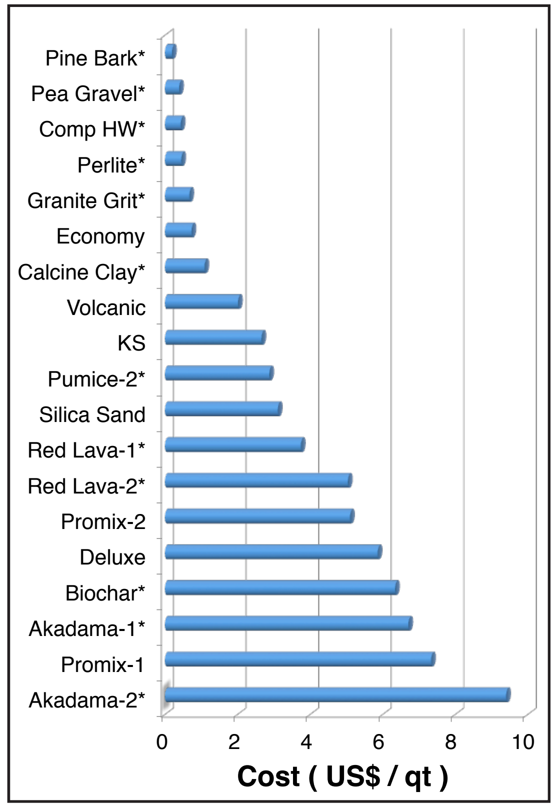


Figure 15: Below, Material cost per quart in US dollars, including the inflation from screening yield. An asterisk (*) indicates that the given material has been screened to have grain size between 2 mm and 6 mm. Based on actual incurred costs, which include taxes and shipping for online orders. You may be able to do better!



has 0.59(EP) = 0.33(SP) + 0.26(FC) compared to the averages of 0.58 = 0.35 + 0.23. So one should be careful about making assumptions in this regard: depending on one's needs, a given mix can be somewhat more or less than the sum of its parts.

- A successful soil mix is likely to have retention and drainage properties that fall within the ranges of FC=18-28% (field capacity), SP=25-45% (saturation porosity), and FC+SP=55-65% (effective porosity).

Final Remarks

After summarizing what seems to be consensus on general matters relating to bonsai soil ingredients and mixes, I have presented quantitative measurements of their densities, porosities, and screening yields, as well as tabulations of my out-of-pocket outlays per quart of useful material. The crucial functional roles of soil density, grain size, and inherent porosity are apparent in the results, as are related economic factors. The information presented allows the choice of soil mix to be based, in part, upon quantitative data, not hearsay. The curious or skeptical reader is encouraged to conduct his or her own measurements to confirm or refute those presented here, because doing so does not require any specialized equipment. It is also a good way to get acquainted, hands-on, with bonsai soils.

The author thanks John Wiessinger for guidance and encouragement, and Prof. Peter Hobbs, Department of Crop and Soil Sciences of Cornell University, for edifying discussions.

1. Jack Wikle, "Upgrading our 'Soil' Mixes", *International Bonsai*, 33, No. 2 (2011): 24-27.
2. This generalization is not a sweeping one: some growers eschew organic ingredients altogether, some grow exclusively in lava or akadama, and some find success with other recipes.
3. http://www.colinlewisbonsai.com/Reading/soils2.html
4. Peter Hobbs, "Horticultural Charcoal (Biochar) Benefits for Bonsai." *International Bonsai*, 35, No. 4 (2013): 22-24.