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Organic growing media are made of a mixture of organic and mineral components. They have been classically used in greenhouse and nursery production, but their use is now rapidly expanding. They also show many similarities to muck soil, being composed of material of similar botanical origin. Classical concepts derived from mineral soil physics need to be adapted to optimize crop growth and water use.

Physical Properties of Organic Soil: Adapting Mineral Soil Concepts to Horticultural Growing Media and Histosol Characterization

J. Caron,* J.S. Price, and L. Rochefort

Growing media are used in a broad range of applications, for which special consideration must be given to their physical and hydraulic character. Because they are relatively fragile, dominantly consisting of dried plant remnants, their preparation, processing, and handling before potting affect their properties. This is complicated by their subsidence and decomposition during use, which leads to a reduction of their initial bulk volume. Organic growing media show many similarities to Histosols because of the common botanical origin of some of their components. For both growing media and Histosols, classical concepts and values related to physical properties like air-filled porosity, bulk density, available water, hydraulic conductivity, gas diffusivity, and field capacity need to be adapted to reflect distinct differences in their composition, structure, and stability compared with mineral soils. Their use in containers with a variety of shapes and sizes influences water and air storage and exchange as well. They can subside extensively as they undergo decomposition. They shrink. Hence, the range of values observed for the physical properties of organic media differs from those of mineral soils. The methods to be used for measuring such properties must be adapted to that specific context of use and to account for their fragile and dynamic nature. Finally, specific norms to guide substrate manufacturing and for diagnosis of plant growth problems have been derived specifically and should be used in such a situation.

J. Caron, Soil Science and Agrifood Engineering Dep., Laval Univ., 2425 rue de l'Agriculture, Québec, QC, G1V 0A6 Canada; J.S. Price, Dep. of Geography, Univ. of Waterloo, Waterloo, ON, N2L 3G1 Canada; and L. Rochefort, Plant Science Dep., Laval Univ., 2425 rue de l'Agriculture, Québec, QC, G1V 0A6 Canada. *Corresponding author (jean.caron@fsaa.ulaval.ca).

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Organic substrates are "soilless media" commonly used in greenhouse and nursery production as well as home gardening. With pressure to increase food production, their utilization has rapidly expanded in the last two decades to other applications such as small berry production—strawberry (*Fragaria* ×*ananassa* Duchesne ex Rozier), blackberry (*Rubus* spp.), and raspberry (*Rubus idaeus* L.) being the most common. Additionally, organic substrates have been used for "green roof" manufacturing, urban agriculture on reconstructed soils, and wastewater filtering applications. They are manufactured mainly from organic components of various origins: composts, manure, and to a large extent peat materials. Peat is a Histosol extracted from the upper horizons of wetlands dominated by an accumulation of incompletely decomposed organic materials. Once processed, peat is the organic growing medium favored for commercial use. Histosols have a long history of being extracted for energy purposes and reclaimed for agricultural production. As a result, peat-based organic growing media and Histosols share many similarities in behavior because they are composed of material of common botanical origin (typically *Sphagnum* mosses, decomposed wood fragments, sedges, etc.). Several monographs have provided details on the origin of Histosols, their properties, and their use (Lucas, 1982; Ilnicki, 2003). Similarly, many textbooks have also covered growing media manufacturing and commercial use (Bunt, 1988; Morel et al., 2000; Raviv et al., 2002; Lemaire et al., 2003). While organic growing media and Histosols present certain characteristics similar to mineral soils, some of the classical concepts used to guide their physical characterization, like field capacity, available water, and aeration guidelines among others, and used in agriculture must be adapted to the specific nature of organic material and for the particular field of applications either as an organic medium or as a cultivated or harvested Histosol. Otherwise, important bias or estimation errors may occur. Here we describe these fields of application and identify the relevant concepts used with mineral soils associated with these fields of application. We also indicate how these concepts should be adapted to growing medium and Histosol characterization.

Fields of Application

Agricultural Use of Peatlands

Histosols found across the world represent 1.9%, on a mass basis, of the total arable soils (Eswaran et al., 1995) and are found in environments where the climate, topography, and dominance of water-logging conditions have favored C accumulation. In such environments, remnant plant materials undergo anaerobic decomposition, which occurs at a much lower rate than in the presence of O_2, and therefore accumulate organic layers during an extended period of time (Clymo et al., 1998). These systems are referred to as *peatlands*. Classically, the peat forming these systems is related to four dominant vegetation types: reed, sedge, moss (*Sphagnum* or *Hypnum*), and/or trees. The peat deposits favored for horticultural substrates are dominated by *Sphagnum* peat mosses (Keys, 1992) and are found mainly in cold, temperate environments (especially the boreal zone of the northern hemisphere). This resource is also important for fuel and cultivation (Korhonen et al., 2008). Sedge-dominated peats can occur in a similar geographic range and are typically associated with hydrogeomorphic settings that contribute surface or groundwater that is enriched in dissolved minerals (Brinson, 1993). They have less desirable properties for making growing media (Morel et al., 2000), having a water-holding capacity inferior to that of *Sphagnum* mosses, and are more readily decomposed (Abad et al., 1988).

Peatlands have been historically used as marginal lands in northern and eastern Europe, first used for energy purposes and then gradually put into cultivation once they were drained adequately and limed to increase their pH to 5.0 to 5.8. Similar development occurred in the United States and Canada, with cultivation taking place in the late 1800s to early 1900s. As a total, about 800,000 km^2 are used in northern Europe (75–85% under meadows and pasture) and 3000 km^2 in North America (Ilnicki, 2003) for agricultural production. Classically, they can be productive land (Lucas, 1982) if managed adequately and if located in relatively warm areas. However, many of these agricultural surfaces in Europe have been converted back to grasslands, silviculture, or conservation areas because of high drainage costs, high NO_3 releases creating environmental pollution problems, cereal lodging (due to high N release), and weather conditions (Ilnicki, 2003). The maximum range of nutrient availability in Histosols for most crops is in the pH range of 5.0 to 5.8, due mainly to the absence of Al and sometimes Fe relative to mineral soils, which maximizes P availability within this range (Lucas, 1982). Due to their high organic matter content, Histosols also tend to chelate micronutrients, hence additional micronutrients are needed to meet plant requirements (Lucas, 1982). The same pH range and need for micronutrients applies to growing media (Bunt, 1988).

In North America, sedge and woody peatlands are used for pasture but also for horticulture (growing, e.g., carrot [*Daucus carota* L.], onion [*Allium cepa* L.], lettuce [*Lactuca sativa* L.], or leek [*Allium porrum* L.]); in the Everglades, a large area (200,000 ha) is used for sugarcane (*Saccharum officinarum* L.) production, and a smaller area (~15,000 ha) is used for sweet corn (*Zea mays* L.) and vegetables (Lucas, 1982; Ilnicki, 2003). The peat from *Sphagnum*-dominated peatlands is typically extracted for substrate manufacturing and horticultural peat moss production for professional growers and home gardening purposes (representing an area of about 0.04% of the *Sphagnum* bogs in Canada). The peat deposits are typically extracted to a depth where *Sphagnum*-dominated peat gives way to the underlying sedge peat. Effective restoration of cutover *Sphagnum*-dominated peatlands requires that drainage ditches be blocked, surface topography associated with its former use be leveled (Price et al., 2003), and plant material including *Sphagnum*, taken from a donor site, applied (Rochefort et al., 2003). However, the natural *Sphagnum* growth rate on these restored peatlands is relatively low (in the range of 105–179 $g\,m^{-2}\,yr^{-1}$), and increasing research efforts are underway to enhance *Sphagnum* growth and develop a *Sphagnum* farming approach (Pouliot et al., 2015).

Sphagnum fiber is a valuable resource that has many uses. Indeed, it can be used in the development of new growing media containing a lower percentage of peat while offering similar aeration, structure, and water retention qualities (Jobin et al., 2014). It also appears as a plant material supply for boreal ecosystem restoration efforts, such as after the cessation of peat extraction activities (González and Rochefort, 2014), mine closures in peatland-dominated areas (Corson and Campbell, 2013), and exploration or petroleum extraction pads within the boreal forest (Sobze et al., 2012).

Northern wetlands have also been used for the cultivation of berries from the *Vaccinium* genus. For cranberry (*Vaccinium macrocarpon* Aiton) production, the topography is leveled and then covered with a sand layer as commonly seen in the American Northeast and in Wisconsin. For highbush blueberry (*Vaccinium corymbosum* L.) production, the soil is mounded into more elevated rows as observed in British Columbia. The low natural topography on which they are formed and the engineered setting makes the water table easy to control for the purpose of production and harvesting. Moreover, their natural pH (4–5.4) falls in the desirable range for both crops.

Horticultural Use of *Sphagnum* and Sedge Mosses

Peat uses have evolved into greenhouse applications because *Sphagnum* mosses in particular are relatively free of weeds and pathogens, decompose slowly, and provide a good balance between aeration and water retention (Schmilewski, 2008). The use of peat in greenhouses was introduced in the 1930s and expanded considerably in the 1960s and 1970s following the pioneering work of Boodley and Sheldrake (1963) in the United States, Puutsjärvi (1969, 1973, 1976, 1982) in Finland, De Boodt and Verdonck (1972) in Belgium, Bunt (1988) in England, and Lemaire et al. (2003) in France, among others. Originally, their work focused on growing media used for crops grown on benches (e.g., cut flowers and lettuce) in greenhouses. It later expanded to potted plants grown in large containers, multicell and plug production for an increasingly large number of species in tree nurseries, greenhouse vegetables, and forest tree seedling production. Also, as was the case for bench-grown crops (cut flowers and tomato [*Solanum lycopersicum* L.]), strawberry and raspberry production is increasingly being done with soilless media in an effort to reduce their sensitivity to soil-borne pathogens (Ajwa et al., 2003; Caron and Rochefort, 2013). As a result, an increasing demand has developed for a high volume of a stable and lightweight material because growing media may have to be exported over a long distance. *Sphagnum* peat has proved a nearly unique worldwide candidate, meeting that demand at a low price and wide availability. Despite important efforts to reduce peat use (Blok and Verhagen, 2009), suitable alternatives remain limited (Raviv, 2005; Carlile and Coules, 2013), with the most promising being bark, wood fibers, coir, and composts (Schmilewski, 2008; Carlile and Coules, 2013). Biochar (a charcoal-based soil amendment) has recently been investigated, too. For example, greenhouse and field trials have investigated the pros and cons of using biochar vs. peat for land reclamation (Saskatchewan Research Council, 2014). Peat proved to be more effective than biochar due to its higher gravimetric water holding (523% for peat vs. 68% for biochar) and sorption capacities. Furthermore, peat typically has a finer structure than the relatively chunky biochar, resulting in a material/peat mixture that is more homogenous than biochar mixtures. Peat is also better able to retain water and nutrients than biochar; thus when targeted plants have been reintroduced in a reclamation project, they have more easily outcompeted undesirable species (Saskatchewan Research Council, 2014). Thus, while biochar additions can ameliorate the properties of borrow pit material and improve the conditions for plant establishment and growth in land-reclamation efforts, peat-based materials appear so far to be more appropriate for greater success of revegetation or higher value food production purposes (Saskatchewan Research Council, 2014), but conclusions are still preliminary and may vary with the properties of the biochar.

In addition to its use as a soil amendment, peat is increasingly being used for filtering applications (Kennedy and Van Geel, 2000, 2001) because of its light weight and low cost, its effective filtering properties, and its capacity to fix heavy metals. Growing media containing 10 to 30% peat per volume has been used in "green roofs" (Getter and Rowe, 2006), where it helps to reduce stormwater runoff to the municipal storm sewer network by absorbing and delaying roof drainage. In South Korea, a group of researchers is attempting to develop a green technology inn which *Sphagnum* peat mosses would be grown on a rooftop to capture C (Kim et al., 2014). Finally, the growing interest in urban agriculture being conducted in a number of container geometries and growing environment configurations will result in an increased demand for growing media.

Despite the high value of peat as a growing substrate, there is concern with the fact that peat comes from peatland ecosystems, which cover only small areas on the planet but provide a wide array of goods and ecological services. Indeed, peatlands are important ecosystems for a wide range of wildlife habitats, supporting important biological diversity and species at risk, freshwater quality and hydrological integrity, C storage and sequestration, and geochemical and paleo archives (Joosten and Clarke, 2002). Consequently a "wise use" approach to peat usage is needed to balance the conflicting demands on the global peatland heritage vs. meeting the needs of humankind. One solution to peat extraction is appropriate rehabilitation and after-use in which, for example, formerly drained cutover peatlands are rewetted and mosses reintroduced so that peat formation processes are restored and biodiversity specific to peatlands is returned (González and Rochefort, 2014).

In addition to peat, biowaste, bark, coir, and wood fibers will be increasingly used (Schmilewski, 2008). The overall increasing use of growing media will result in the world demand for peat continuing to grow, despite substantial efforts to find alternatives (Schmilewski, 2008; Caron and Rochefort, 2013), and hence, this wise use approach is very appropriate and needed.

Relevant Concepts Related to Determination of Physical Properties

Compared with mineral soils, organic mixtures have distinct physical properties among which are a high organic C content, high fiber content, low mineral fraction, low weight and bulk density, a very loose but fragile nature, low plasticity, high water retention, high aeration, and low mechanical impedance. This makes them highly suitable for use as a growing medium and as an appropriate physical support for plant rooting. They are prepared by mixing different components and hence the composition can vary, although this can be adjusted during preparation to achieve targeted properties. Nevertheless, the properties of the final product are also determined by the method of harvesting, stockpiling, bagging, loosening, and mixing steps (Fig. 1). Moreover, because of their highly sensitive structure and their high organic C content,

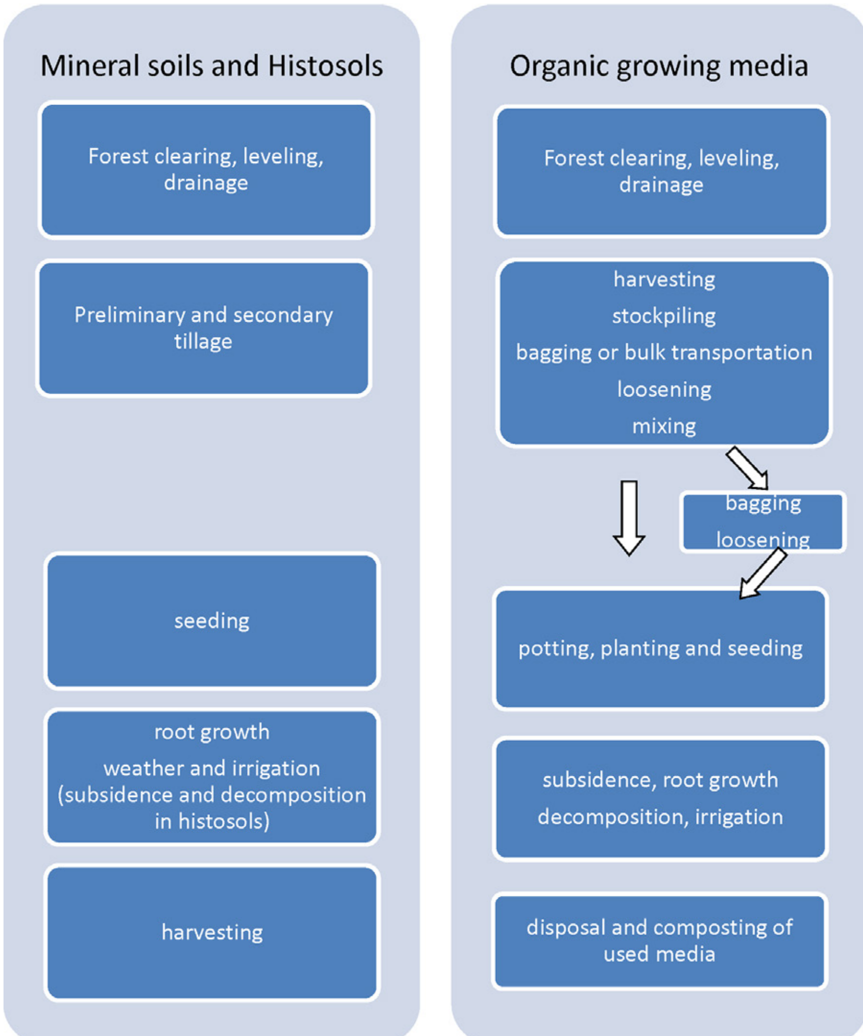

Fig. 1. Comparison of soil and organic growing media preparation and cultivation steps.

they undergo active decomposition and reorganization, which impacts these properties, and they behave very differently from mineral soils in terms of water and nutrient transport as well as air and water storage. Characterizing the nature and optimizing the properties of organic growing media for specific uses requires adaptation of the methods and theory conventionally applied to mineral soils' physical characterization.

Preparation and Composition of Growing Media

Organic growing media composition varies with its end use: nursery, greenhouse vegetables, potted flower mixes, and forest tree seedling production use very different growing medium compositions. Different components, dominantly organic materials, comprise most growing media, with major differences in air and water retention at −10 kPa, as well as other contrasting characteristics related to cost, biostability, availability, etc. (Fig. 2). Bark and peat are the most common components for horticultural application because they provide a lightweight material. Peat has excellent water holding properties of about 0.60 cm^3 cm^{-3} (Fig. 2). Some peat types also provide good aeration, such as white peat at about 0.35 cm^3 cm^{-3} (Fig. 2), and the value is in the same range for coarse bark (Naasz et al., 2008) but lower for composted bark (Naasz et al., 2005). Peat and pine bark decompose slowly, are relatively abundant in North America and Europe, and are relatively close to markets. Peat represents annually 8 million m^3 harvested annually in Europe (Schmilewski, 2009) and a similar amount in North America (Hood, 1997) for the manufacturing of professional growing media. Coconut fiber (coir) is becoming increasingly popular (Schmilewski, 2008), with some physical properties similar to those outlined above for *Sphagnum* mosses (Schmilewski, 2008; Carlile and Coules, 2013), although with world global resources estimated to be considerably less than that of *Sphagnum* peat (Caron and Rochefort, 2013). Its represents about 5% of the peat used in Europe and a similar proportion to bark (Schmilewski, 2009). Additionally, the amount of coconut fiber that can be incorporated into a soil mix is often limited by elevated salinity in some fibers, and depending on their origin and handling, the presence of possible contaminants (Evans et al., 1996; Raviv et al., 2002; Raviv, 2005). Compost properties can vary widely depending on the raw material from which they are derived and the exact nature of the process (Raviv et al., 2002). To be used, composts must be stable, with relatively low salinity, a low concentration of phytotoxic cations and organic molecules, and free of pathogens. They may be added to *Sphagnum* peat or coconut fiber, constituting often 30% of the substrate, sometimes more (Raviv, 2013), and are becoming more readily available. While the stability of compost materials is less of an issue than it was 20 yr ago, given better modern composting techniques, its quality in high volumes remains highly variable because of the numerous sources and processes, with the most suitable being those derived from food and processing industries, alone or mixed with composted manure (Raviv, 2013).

Components other than *Sphagnum* and coconut fiber vary widely (Morel et al., 2000; Raviv, 2013; Raviv et al., 2002). Most of these additional components are organic. However, in some limited applications, they can be 100% mineral (zeolite and perlite), such as for research on space missions, some greenhouse production, and in some green roof applications. One of the mineral components often added to growing media is sand. Sand is typically added to large nursery containers (5 L and larger) to give weight to the container and prevent pots from tipping under windy conditions. Pumice and tuff are also components used pure or mixed with organic components to add weight and provide aeration to the growing medium. Two popular components added to organic substrates often used in tree seedling production and for cut flower production are vermiculite and perlite. They are derived from the unexpanded form of vermiculite and perlite rocks, heated at 300 and 870°C, respectively, to pop up and expand. These components are lightweight and increase the substrate porosity, although they are expensive. Alternatively, non-mineral foam beads can be used in a growing medium to increase its air-filled porosity (Fig. 2). In general, mixes of peat and perlite, vermiculite, or foam beads are unsuitable for environmental rehabilitation projects because the mineral materials may float away, causing a cascade of problems for downstream aquatic organisms.

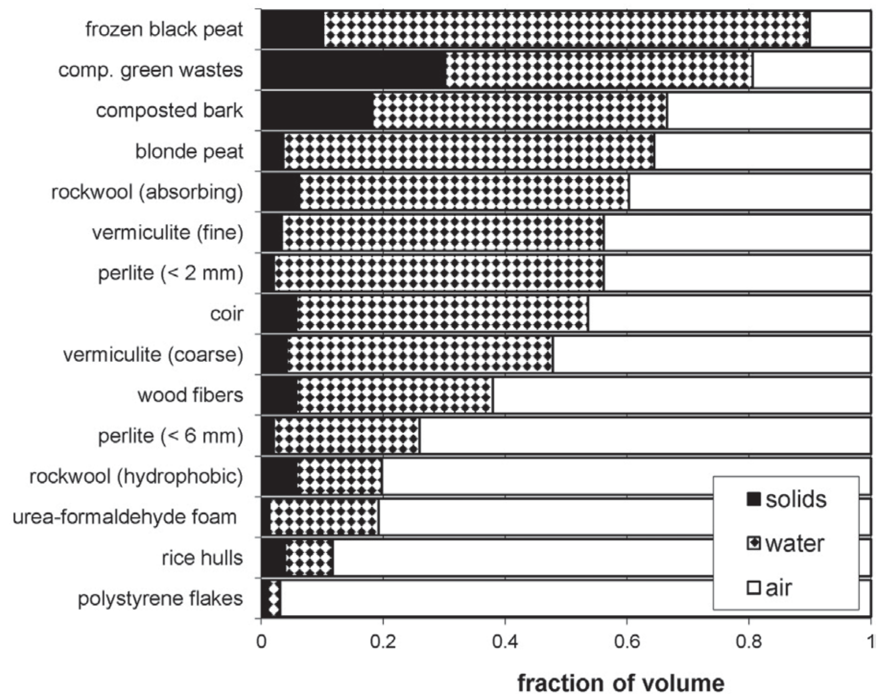

Fig. 2. Proportion of air and water stored in different components of growing media (modified from Schmilewski, 1992).

As with mineral soils, there have been attempts to associate growing media quality and their physical properties with their particle size distribution (Carlson, 1983; Bernier et al., 1995; Puutsjärvi, 1982). Such criteria are still used by some buyers to classify organic growing media. However, organic components are susceptible to damage during sieving (Dinel and Levesque, 1976). Sieving, loosening of compacted raw material, mixing operations, and automated potting procedures may result in improved or degraded properties, in part related to the breaking of fibers (Heiskanen et al., 1996). The properties of commercially prepared growing media are also sensitive to the behavior of different mixtures of materials, which may have a proportional or an interactive behavior (Rivière, 1988). A proportional behavior occurs when the measured properties (air-filled porosity, bulk density, volumetric water content at −1 and −10 kPa) can be predicted from the linear combination of the individual properties of the different components. Interactive effects arise because some of the components can migrate into larger pore spaces and fill some of the voids, resulting nonlinearly in reduced air-filled porosity, increased volumetric water content at specified pressures, and increased bulk density. Growing media commonly display weakly interactive effects related to the mixing of particles; the interactive behavior is linked mainly to three basic factors (Rivière, 1988):

- Water content at the time of mixing. Mixing dry components often results in the migration of fine particles and grains between larger fragments, resulting in an increase in bulk density and lower porosity. Higher water content increases the adhesion of fine particles to larger fragments, reducing the interactive effect.
- Particle size distribution. Large differences in particle size will often result in the migration of fine particles into spaces between larger fragments.
- Fibrous components. Mixing fibrous components results in a weak interaction. Mixing granular and fibrous material often results in interaction, with grains migrating into pores formed between larger fragments.

When interactive effects occur, the resulting properties of the mix are difficult to predict from particle size analysis (Boudreault et al., 2014).

From Mixing to Potting

Bulk Storage Volume

Once prepared, growing media are either compressed in bags or delivered bulk to the end user (Fig. 1). The physical properties of substrates stockpiled and delivered in bulk are affected by the duration of the storage and their temperature and moisture content (Puutsjärvi, 1982). Growing media stored compressed as well as those stored in piles require loosening of the material before potting (Morel et al., 1999). Loosening can be performed by hand or mechanically with screws. Once loosened, the movement of the substrate on a conveyor can result in material segregation (Heiskanen et al., 1996).

Once handled bulk, the later loosened substrate is used in containers of various geometries (pots, plug trays, slabs, etc.). Transplanting machines with conveyors are increasingly being used for such purposes. However, because of their highly sensitive nature, growing media with nearly identical properties before potting may end up with different physical properties depending on the procedure used for potting (Heiskanen et al., 1996). Obviously, the pressure exerted on these media and their initial moisture contents will have a dominant impact on their

Table 1. Air-filled porosity of peat types as a function of the applied pressure (from Verdonck and Gabriëls, 1991).

Applied pressure	Air-filled porosity	Available water
Pa	———— $cm^3\ cm^{-3}$ ————	
Black peat, highly decomposed		
0	0.17	0.25
12.5	0.06	0.29
25.0	0.02	0.32
Blonde *Sphagnum* peat, slightly decomposed		
0	0.13	0.40
12.5	0.11	0.41
25.0	0.09	0.34

properties (Verdonck and Gabriëls, 1991; Table 1), more so than for mineral soils. Organic soils are 15 to 20 times more compressible than mineral soils.

Following potting, irrigation may cause further compaction, particularly if full saturation of the substrate is achieved. The collapse of the initial substrate volume in the containers can represent a bulk volume loss of 10 to 20% (Paquet et al., 1993). As for the drainage of Histosols (see below), the compaction process results essentially from the transfer of most of the overburden pressure to the matrix when water menisci surround the fibers in the early stage of drainage. Indeed, from saturated conditions, the water pressure goes from positive to negative as it drains, so the overburden pressure results in an effective stress on the matrix that causes it to deform. Potted substrates are difficult to fully saturate. By increasing the level of saturation when applying water in the first irrigations, a substantial application of water will result in a much larger number of menisci pulling particles together during the following drainage step. Hence, the magnitude of the first subsidence will be linked to the importance and uniformity of menisci following the first irrigations. Most of the early-stage volume changes take place in the first two or three irrigations, after which a residual volume is obtained (Paquet et al., 1993), hence excessive irrigation may be detrimental to the final volume obtained. Before extensive plant development, the extent of drying will be limited because the substrates are maintained wet following potting. As the extent of plant water uptake increases with plant growth, further drying of the substrate between irrigations result in a water matric potential in the range of −10 to −30 kPa, causing additional volume reduction and shrinkage.

With irrigation, particle reorganization occurs when fine particles migrate (Nash and Laiche, 1981). Decomposition also results in structural collapse (Puutsjärvi, 1982). Given that full plant growth may take weeks to years, the resistance to biodegradation may be of concern. While *Sphagnum* mosses and coir have a high biostability (Morel et al., 2000; Lemaire et al., 2003), compost is more prone to collapse (Raviv, 2013; Morel et al., 2000). The choice of potting material may therefore be adjusted according to the expected duration of its use in order to limit its collapse. Typically, about a third of the initial volume is lost during the first 3 mo of cultivation even in substrates with a large proportion of *Sphagnum* peat (Allaire-Leung et al., 1999). During this period of cultivation, the rooting system will also develop, invading pores (Cannavo et al., 2011; Cannavo and Michel, 2013). This can cause a rapid evolution of soil properties (Jobin et al., 2014; Cannavo and Michel, 2013), with a loss (Cannavo et al., 2011), no change (Allaire-Leung et al., 1999), or an increase in the hydraulic conductivity (Jobin et al., 2014; Cannavo and Michel, 2013) and sometimes an associated increase in total porosity (Jobin et al., 2014).

The fragile nature of Histosols used for agricultural purposes or peat extraction renders them susceptible to subsidence following drainage (Edil et al., 1986). When they are initially drained before cultivation or peat extraction, the reduction in water pressure results in an increase of the effective stress at a given depth in the profile. This is caused by the weight of the overlying material being transferred to the matrix and results in compression, as previously described for substrates in a container. The structure is fragile enough to collapse to a large extent following this gradual transfer (Ilnicki, 2003). As a result, once drained, Histosols will rapidly subside (typically within the first 10 yr) due to the overburden pressure and in a second stage (10 yr and later) due to the accelerated decomposition process caused by an increase in O_2 associated with drainage (Schothorst, 1977). The initial collapse in Histosols of 1 m and deeper can be as high as 10 to 12 cm yr^{-1}, declining to ≤1 cm yr^{-1}, depending on the intensity of drainage. Residual shrinkage dominated by decomposition beyond 10 yr is more stable at about 0.5 to 2 cm yr^{-1} (Ilnicki, 2003, Fig. 10.2).

Properties Related to Water Storage and Transfer

Following irrigation and drainage in a growing medium, some free water will appear at the bottom layer of the container, representing a temporary perched water table. The presence of this perched water table at the base of the container affects the pressure distribution throughout the profile, thus its degree of compaction (i.e., bulk density). Furthermore, because the average potential applied at the top surface of the potted substrate will be in direct connection with the position of the water table, different sizes and heights of container will affect the in situ material properties, thus air and water storage (Bilderback and Fonteno, 1987; Raviv et al., 2002). The higher the container, the lower the water potential at the top (Fig. 3). In Fig. 3, at hydrostatic equilibrium, a matric potential equivalent to −20 cm of matric head occurs at the top of a 20-cm-high container. For typical pots 20 cm high, this means that at mid-height, the average matric head will be −10 cm (about −1 kPa). Hence, the volume of air at the bottom of the container corresponds to that with a suction close to 0 and that measured at the top will correspond to a suction of −20 cm. The proportion of available water will also be affected by the same parameters because the proportion of water at container capacity for a 10-cm-high pot will be greater than for a 20-cm-high container. The concept of field capacity, used in open-field agriculture, therefore becomes more a container capacity concept (White, 1965; Rivière, 1990), itself a function of container form and geometry (Bilderback and Fonteno, 1987).

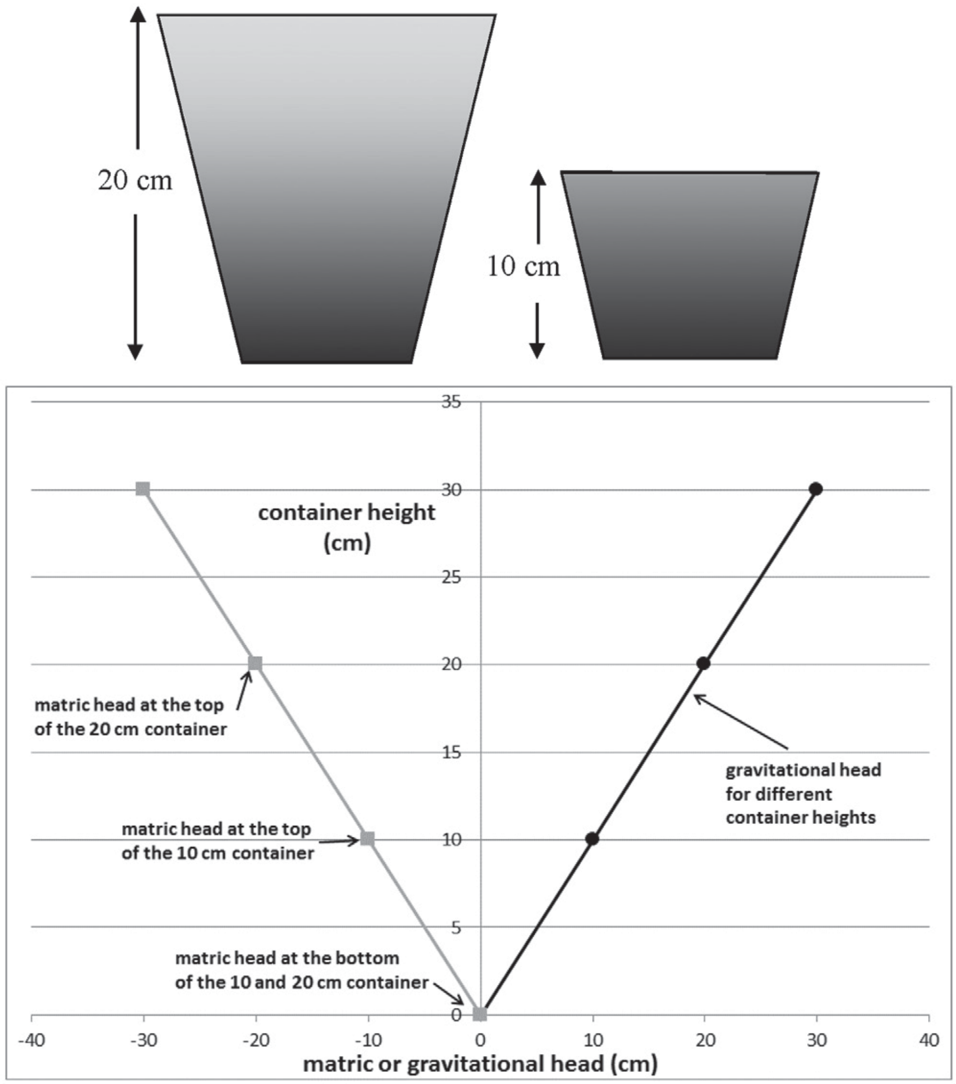

Fig. 3. Distribution of matric and gravitational head in 10- and 20-cm-high pots at container capacity, with a visual representation of the volumetric water content distribution as a function of height in both containers. The higher proportion of dark spots in the shorter container indicates that, for the same water retention curve, proportionally more water will be retained in the shorter container than in the taller one.

Calculations and investigations for growing media require knowledge of the water retention curve. The shape of the water retention curves of organic soils is strikingly different from that of mineral soils (Fig. 4). The total amount of water is very important, reaching as much as 0.96 $cm^3\ cm^{-3}$ in some blonde *Sphagnum* peat mosses and coconut fiber. At saturation, a high proportion of that water is stored between the fibers, including in macropores, and in a higher proportion in menisci between large particle fragments as the soil desaturates (Lemaire et al., 2003). In the case of *Sphagnum* peat, a significant proportion of the water is stored within hydrocysts (or hyaline cells), which are specialized water-holding structures with relatively small pore openings of 18 to 36 μm (Puutsjärvi, 1976). Most of this water is released between water potentials of about −10 to −20 kPa (Puutsjärvi, 1976; Lewis, 1988). Finally, a high proportion of the water still remains within the decaying cell remnants and in structures of other dead plant material fragments such as xylem and phloem cells and vessels. Because of microbial colonies feeding on plant remnants, some of the water also occurs within living, dead, and dormant microbial structures. Recent results suggest that exuded polysaccharides may also store water within the internal coiled structure of these high-molecular-weight compounds (Létourneau, 2009) or in chemically dilated pores (Ours et al., 1997). Relative to mineral soils, a lot of the water is bound within those complex structures, a phenomenon detected by their dielectric properties. Topp et al. (1980) reported a low apparent dielectric constant of about 10 in peat soils despite a volumetric water content of 0.30 $cm^3\ cm^{-3}$, in clear contrast with mineral soils that have an apparent dielectric constant of about 20 for the same volumetric water content (Topp et al., 1980; Paquet et al.,1993). Finally, water is less available at a relatively high potential of −2 to −5 kPa (Jobin et al., 2004; Lemay et al., 2012) in organic media. This is high compared with the limited water availability values in the range of −10 to −60 kPa typically found in mineral soils (Shock and Wang, 2011). This limit of water availability had already been identified by De Boodt and Verdonck (1972) and Puutsjärvi (1976) and later confirmed by multiple researchers (Örlander and Due, 1986; Caron et al., 1998; Jobin et al., 2004). The same limitations of water availability have appeared in Histosols (Lucas, 1982; Périard et al., 2012). Some researchers have identified possible mechanisms for this low availability linked to a loss of contact between roots and growing media (Örlander and Due, 1986), lower transfer rates within the medium in Histosols (Périard et al., 2012; Rekika et al., 2014) or organic growing media (Jobin et al., 2004), and the high proportion of dead-end pores (Caron and Nkongolo, 2004). Indeed, examination of the peat matrix has shown that many of the pores are dead-end (Loxham, 1980; Loxham and Burghardt, 1986), which leads to poor pore interconnections relative to granular mineral soils

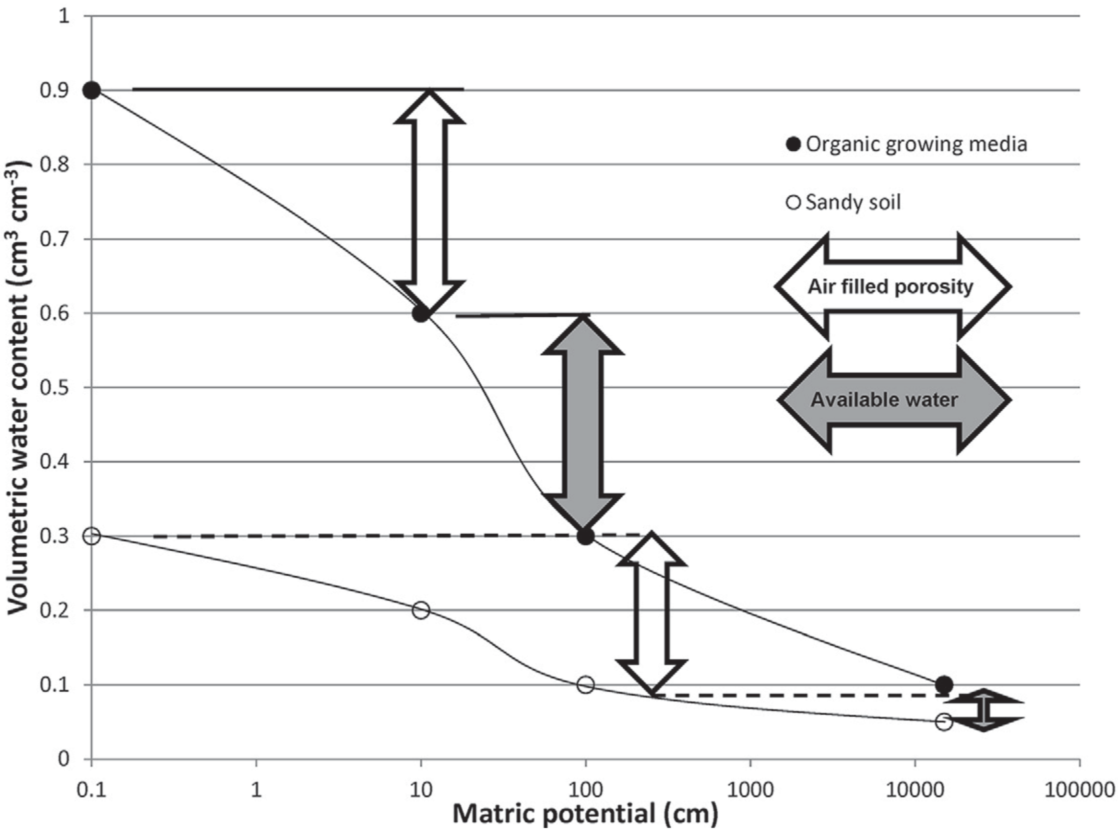

Fig. 4. Comparison of the water retention curves of a peat/bark (66:33 v/v) mix and sand on drainage, with the corresponding interval for available water and air-filled porosity. The position of the arrows corresponds to the limiting lower limit major potential at field or container capacity and the lower limit for characterizing available water (−100 cm for organic growing media and about −15,000 cm for mineral soils).

(Caron and Nkongolo, 2004), with an important impact on gas diffusion (Caron et al., 2005b) and hydraulic conductivity (Örlander and Due, 1986). However, we note that Rezanezhad et al. (2010) described a continuous pore network within a *Sphagnum* soil, albeit of complex geometry and connectivity, that profoundly affected water transfer.

Another striking difference in the water retention curves of organic vs. mineral soils is the hysteresis phenomenon. Hysteresis refers to the fact that the relationship between hydraulic conductivity and water content on the one hand and matric potential on the other hand depends on the direction of wetting. Water content and hydraulic conductivity are typically higher on drainage than on rewetting for the same matric potential. Such an effect has been reported in organic growing media for both the water retention curve and the unsaturated hydraulic conductivity (Otten, 1994; Wever, 1995; Caron et al., 2005a; Naasz et al., 2005; Lemay et al., 2012) and may control to a large extent the performance of growing media under capillary irrigation (subirrigation). Indeed, substrates with high hysteresis on the water retention curve typically have low unsaturated hydraulic conductivity on rewetting, which in some cases presents serious limitations for capillary rise, particularly in materials dominated by coarse fractions (Caron et al., 2005a). This will be of even more interest in the future because subirrigation systems are increasing in use due to their high water efficiency (Caron et al., 2002) and are typically under operation in closed and semi-closed irrigation systems in nursery and greenhouse operations to reduce fertilizer and pesticide losses to the environment (Otten, 1994; Caron et al., 2005a).

A third main striking difference in the characteristics of retention curves in organic vs. mineral soils is linked to the hydrophobicity of some organic components, like *Sphagnum* peat. This is a phenomenon particularly important even under wet conditions, the hydrophobicity being related to the degree of decomposition of the material as well as the initial wetting (Table 2). Typically, wetting agents are added to peat to counter the hydrophobicity phenomenon. However, recent work has shown that despite a proper rewetting, changed wetting angles can be observed close to saturation and

Table 2. Influence of water potential and peat type on wetting angle (from Michel, 1998).

Water potential	Blonde *Sphagnum* peat	Brown *Sphagnum* peat	Brown herbaceous peat
−32 kPa	66.2	69.0	70
−100 kPa	84.5	86.2	81.7
−3 MPa	93.6	96.8	87.1
−100 MPa	104.5	106.4	88.4

therefore strongly influence the shape of the water retention curve on rewetting (Naasz et al., 2008). Still, despite taking changes in the wetting angle into account, strong hysteretic behavior is observed, a possible result of pores having irregular openings (Naasz et al., 2008). Incorporating changes in the wetting angle in the van Genuchten–Durner model results in significant improvement in modeling water retention curves (Naasz et al., 2008).

A fourth striking difference is linked to the high probability of finger flow or preferential flow phenomena in growing media as well as in Histosols. This is partly linked to hydrophobicity, commonly present in dried growing media when they reach pressures of −30 kPa and lower (Michel et al., 1997; Michel, 1998), but this may also be observed because of the layered nature and the segregation phenomenon in Histosols (Lafond et al., 2014). Indeed, when put into cultivation, humic material will migrate from the top surface and will accumulate at interfaces with more fibric horizons. This will then lead to water accumulation at the interface, with water not penetrating the deeper horizon unless a critical water potential threshold is reached (Lafond et al., 2014). Water flux density in peat is not always linearly related to the hydraulic gradient and therefore does not obey Darcy's law, particularly at high hydraulic gradient. This non-Darcian flow type has been reported and observed (Ingram et al., 1974) in peat and attributed to gas entrapment (Rycroft et al., 1975; Ingram et al., 1974) or to bound water. Non-Darcian flow has also been observed for some growing media (Raviv et al., 2002) but not for others (Allaire et al., 1994).

Properties Linked to Aeration

Physical properties linked to aeration processes also differ significantly from those in mineral soils. Indeed, being mainly composed of organic matter, growing media support important microbial activity and are actively decomposing once limed and fertilized. The respiring microbes may compete with roots for O_2 (Naasz et al., 2009), and because of high mineralization rates (Histosols can generate easily between 300 and 700 kg ha^{-1} a year of NO_3–N; Lucas, 1982; Caron et al., 2014b), the overall demand for O_2 might be high, hence requiring higher air-filled porosity to meet respiration needs relative to mineral soils (Naasz et al., 2009).

In peat and organic growing media, the dead-end pores are even found in the macropore fraction (Caron and Nkongolo, 2004). This creates insulated pockets within the substrate and restricts air exchange because of the fibrous and platy nature of some of the organic components (Caron and Nkongolo, 1999). This results in very low connectivity of the pore network, restricting gas and water exchange in a similar way (Loxham and Burghardt, 1986; Caron and Nkongolo, 2004). As a consequence, even at high air-filled porosity, gas diffusion is significantly lower or equivalent to what it would be for a mineral soil with similar air-filled porosity (Table 3). In support of this, studies have consistently reported that crop performance can be linked to gas exchange parameters, like gas diffusion in growing media (Allaire et al., 1996; Boudreault et al., 2014; Nkongolo and Caron, 2006; Caron et al., 2010), O_2 concentration (Blok and Wever, 2008), or O_2 diffusion rate (Bunt, 1991; Raviv et al., 2002; Gislerod, 1982) in spite of substrates having an initial high air-filled porosity (Allaire et al., 1996; Nkongolo and Caron, 2006; Caron et al., 2010). Assessment of aeration using different parameter such as gas diffusivity and tortuosity is therefore critical for investigation of plant responses in growing media (Caron et al., 2014a).

Adapting Mineral Soil Methods to Growing Media and Histosol Characterization

It is clear that at least some concepts used in mineral soils should be adapted to use in growing media and Histosol characterization and data interpretation. The use of particle size distribution, the disturbance of a sample, the rapid evolution of physical properties, and the availability of water and O_2 have the most impact on subsequent characterization and interpretation of physical parameters.

Table 3. Comparative values for some physical properties of minerals soil, Histosols and organic growing media.

Parameter	Mineral soil	Organic growing media or Histosols
Bulk density, g cm^{-3}	1.0–1.8	0.07–0.10 growing media 0.10–0.35 Histosols
Total porosity, cm^3 cm^{-3}	0.30–0.50	0.80–0.95
Saturated hydraulic conductivity, cm s^{-1}	sand: 5 × 10^{-3}† loam: 5 × 10^{-4} clay: 5 × 10^{-5}	0.05–0.350
Potential of lower water availability (irrigation threshold), kPa	−10 to −60†‡	−2 to −10 organic growing media§ −10 to −30 Histosols¶
Relative gas diffusivity (soil to free air) at −0.8 kPa (corresponding air-filled porosity)	sandy loam: 0.0240 (at 0.04 cm^3 cm^{-3} of air-filled porosity)#	growing media (fragments 1–2 mm): 0.0265 (at 0.17 cm^3 cm^{-3}); growing media with large fragments (8–16 mm): 0.007 (at 0.12 cm^3 cm^{-3})

† Brady and Weil (2002).
‡ Shock and Wang (2011).
§ Lemay et al. (2012), Jobin et al. (2004).
¶ Périard et al. (2012).
# Caron and Nkongolo (2004).

The Concept of Particle Size Distribution

Particle size distribution has been extensively used to relate texture to physical properties like saturated hydraulic conductivity, available water, and bulk density, among others, and has been proposed for assessing substrate quality for tree seedlings (Carlson, 1983). While quite successful with contrasting mineral soils, using particle size as a quality criterion with organic growing media has been essentially limited to detecting severe aeration problems (Verhagen, 1997). Otherwise, it is a poor predictor of other properties and growth performance (Caron et al., 2005b; Boudreault et al., 2014), perhaps because the shape of coarse fragments (>10-mm diameter and larger) can result in aeration limitations compared with intermediate sized fragments (2–10-mm diameter; Nkongolo and Caron, 1999; Caron et al., 2005b) in organic growing media and because of the interactive effects of particle shape in mixes (Rivière, 1988).

Consequently, in addition to the particle size distribution, professional experts and researchers demand other standard methods for comparing the quality of growing media (Blok and Wever, 2008; Caron et al., 2014a). In terms of soil physical properties for trade purposes, these standards are limited to the bulk volume, the air-filled porosity, and the available water (Gabriels, 1995; Morel et al., 1999), but for research and application purposes, it should extend to gas diffusivity (Allaire et al., 1996) and unsaturated hydraulic conductivity (Caron et al., 2005a, 2014a), and norms have been proposed and are summarized in Table 4. For comparison of substrates before use, methodological development has focused on performing measurements of the properties of growing media after all the interactions during mixing of components and prior processing steps have occurred (Blok and Wever, 2008; Caron et al., 2008), as processing and mixing significantly alter the properties of substrates.

The Concept of Disturbance and Substrate Evolution

During and after potting, the substrate structure remains fragile. Methods that compact samples before analysis by the use of a standard weight for compaction (Morel et al., 1999) or that apply a suction before measuring the characteristics of potted substrates have been recommended and implemented (Gabriels, 1995; Gabriels and Verdonck, 1991; Hidding, 1999). The many steps following the processing and mixing of the substrate, which involves loosening, filling, and planting in various containers (Fig. 1), may affect the resulting physical properties. Methods exist that compact samples to a bulk density similar to that found in the container. These include applying a weight once the substrate is in the measuring cylinder or applying suction at the bottom of the filled cylinder (Gabriels, 1995) to achieve similar associated physical properties (Morel et al., 1999; Fonteno et al., 1995). Alternatively, in situ methods of characterization to identify properties at different times during root growth have been used; this approach is preferred because it avoids disturbance effects (Caron et al., 2008, 2010; Cannavo and Michel, 2013). The same applies to cultivated Histosols or to natural peatlands, in which disturbance affects their properties. Methods for taking samples and performing measurements should be specifically adapted for the conditions best representing their use, i.e., in the container or within the bog itself (Price et al., 2008; Caron et al., 2008). Driving cores into the substrate is problematic. Extracting material from a container or from a peatland with shovels, for example, and trying to repack cores is unlikely to achieve a representative sample. Preferable approaches include putting instrumentation such as tensiometers and water content probes directly into the container (Paquet et al., 1993; Allaire et al., 1994; Caron et al., 2002; Caron and Elrick, 2005) or into a soil pit (McCarter and Price, 2013; Price et al., 2003). For Histosols, the same approach can be taken with combined instruments. Obtaining frozen samples that are later cut and trimmed while still frozen (Price et al., 2008) is an efficient way to limit disturbance effects for samples undergoing freezing. Alternatively, taking large samples later trimmed to fit into cylinders (while carefully filling the gaps with wax films or bentonite) is another way to avoid compaction effects. Once in the cylinder, they are maintained saturated to avoid settling during transportation from the sampling site to the laboratory.

Table 4. Norms for physical properties of growing media linked to gas and water storage and exchange.

Aeration processes			Liquid water transfers		
				Unsaturated hydraulic conductivity curve parameter	
Air-filled porosity (−1 kPa)	Gas relative diffusivity	Easily available water	Saturated hydraulic conductivity	α_1	ψ_b
cm^3 cm^{-3}		cm^3 cm^{-3}	cm s^{-1}	kPa^{-1}	kPa
0.15–0.40†‡§	0.010–0.015¶ 0.003–0.005 #	0.20–0.30‡	0.08††	9.6‡‡	−0.5‡‡

† From Wever (1995).
‡ De Boodt and Verdonck (1972).
§ Naasz et al. (2008).
¶ From Allaire et al. (1996) for −0.8 kPa in 5-, 9-, and 14-L nursery containers.
# From Boudreault et al. (2014) for −0.6 kPa in tree seedlings containers
†† From Mustin (1987).
‡‡ From Caron et al. (2005a).

When building field lysimeters, the disturbance issue is handled by surrounding the lysimeter with plastic film, excavating one side at a time to place instruments and the bottom pan (Lafond et al., 2014), covering the exposed surface of the lysimeter with polyethylene film coated with bentonite on its inner side, and refilling one side at a time to avoid the collapse of the exposed profile before excavating the next side.

The fact that the structure rapidly evolves due to decomposition and reorganization and is very sensitive to disturbance requires running multiple measurements with time (Allaire-Leung et al., 1999; Jobin et al., 2014). The disturbance issue is then a key factor because of root activity. In this case, it is strongly recommended to use the in situ measurement technique, which takes into account the root system, which becomes part of the soil structure and needs to be characterized (Allaire-Leung et al., 1999; Caron et al., 2008; Cannavo and Michel, 2013).

The Container Geometry

Hydraulic processes linked to water storage and exchange are partly a function of container capacity (the equivalent "field capacity" for substrate in a container), itself related to the container geometry as previously described. Hence, drainage will depend very much on the container configuration, and in practice, substrate water pressure will typically be in the range of −0.5 to −1.5 kPa after saturation and drainage, clearly different from matric potential values encountered in agricultural fields (−10 to −33 kPa). As a result, characterization of the volumetric water content at container capacity, and of the air-filled porosity, should be performed directly by weighing or measuring the water content with time domain reflectometry or capacitive probes on the pot equilibrated at container capacity, a procedure described elsewhere (Caron et al., 2002, 2008). This also applies for saturated hydraulic conductivity determination (Allaire et al., 1994), for which a Mariotte type permeameter designed to sit at the top of the container is used to measure a steady-state water flux density, and a correction factor is applied to correct for flow restriction imposed by the container geometry relative to a normal cylinder. The same approach is used for measuring gas diffusivity in a container (Allaire et al., 1996; Caron and Nkongolo, 2004) and for unsaturated hydraulic conductivity determination (Caron and Elrick, 2005), taking into account the effect of its complex geometry on the gas diffusivity.

As noted above, in addition to container geometry, two additional factors must be considered when performing measurements in containers: the dominant effect of disturbance and the evolution of the substrate during growth due to decomposition and root effects. Consequently, characterization of soil properties directly in containers is by far more relevant than attempting to mimic container conditions using disturbed samples.

Available and Mobile–Immobile Water

As a result of the effect of container geometry, the proportion and the total volume of air and water at container capacity will vary, even in growing media with identical physical properties (Bilderback and Fonteno, 1987). Transfer properties (gas diffusivity and unsaturated hydraulic conductivity) of growing media in containers will also be affected by the prevailing potential at container capacity. As a result, the range of matric potentials measured at container capacity will differ from that in mineral soils. Therefore, calculations of available water (and air-filled porosity) should be adjusted accordingly. The first modification that should be achieved is using the volumetric water content at container capacity as the lower value for calculating the air-filled porosity from saturation as well as the upper value for calculation of the available water. The second modification that should be used is for the lower limit of water availability (Fig. 4). Typically, water in peat and peat–soil mixes becomes less available to plants (the first signs of stress) at a higher range of water potentials (−5 to −15 kPa), with permanent wilting in the range of −30 kPa, compared with that in mineral soils (−10 to −60 kPa for the first sign of wilting and then to −1500 kPa for permanent wilting). Hence, available water should typically be calculated using −10 kPa as the lower limit (DeBoodt and Verdonck, 1972).

When performing these evaluations and calculations, the water desorption curve is used (Bilderback and Fonteno, 1987), and the shape of this curve should be described with the van Genuchten–Durner approach, incorporating wetting angle changes during the rewetting process to take into account hydrophobicity phenomena in such media. It should also take into account the hysteresis phenomenon, since it can be extraordinarily large in organic media. This can be done by taking the desorption curve for overhead irrigation and the rewetting curve for subirrigation and drip irrigation applications (Lemay et al., 2012). This presence of immobile water in peat-based soils and mixes also significantly influences dielectric-based measurements of water content. Calibration curves to determine water content using time domain and frequency domain reflectometry are notably different for growing media (Caron et al., 2002) and peat (Lapen et al., 2000) compared with those used for mineral soils. The need for specific calibration curves occurs when there is more than 0.20 g organic matter g^{-1} soil (Paquet et al., 1993).

Salinity management is also very important in greenhouse and nursery operations, and proper description of salinity buildup may be critical in management issues. The existence of immobile water including bound water and water stored with cell structures is also expected to play a large role in the mobile–immobile water fractions, limiting access for solutes to exchange with moving water (Rezanezhad et al., 2012; Hoag and Price, 1997; Ours et al., 1997). Because the proportion of immobile water during solute exchange may be high in some organic growing media, studies on solute transport should integrate the presence of immobile water when describing salt movement (Rezanezhad et al., 2012).

Aeration Processes

In addition to the recommendation to measure the air-filled porosity directly in containers, studies on aeration processes have confirmed the clear advantage of measuring gas diffusivity to relate the quality of the substrate to plant growth (Allaire et al., 1996; Caron and Nkongolo, 1999; Nkongolo and Caron, 2006; Boudreault et al., 2014). Furthermore, aeration assessment should extend beyond the simple study of air-filled porosity by including gas diffusivity. The very high respiration needs of some organic growing media should also be included because competition for O_2 may limit crop performance in such media (Naasz et al., 2009). As a result, it is recommended that the optimum air-filled porosity should be about 0.30 to 0.40 $cm^3 cm^{-3}$, 0.10 to 0.15 $cm^3 cm^{-3}$ higher than the typical values of 0.20 to 0.30 $cm^3 cm^{-3}$ often reported in the literature for organic growing media. As a consequence of the specific context affecting water and air storage and transfer, specific norms have been proposed to guide the manufacturing of substrates, which are typically different from those guidelines in mineral soils. These are summarized in Tables 3 and 4.

Conclusions

Methods providing minimal disturbance to growing media and Histosols are essential to the analysis of their physical properties. Studies considering hydraulic processes related to Histosols and growing media should be performed under undisturbed conditions as much as possible, ideally in the field or for potted plant studies in the container itself. Such measurements must be repeated to capture the evolution of such properties during use. The physical and hydraulic properties are distinctly different from those in mineral soils. Bulk density is much lower. Typically, air-filled porosity and available water are much higher in organic soils and should be calculated with the van Genuchten–Durner approach, incorporating wetting angle changes during the rewetting process. Estimations should take into account hydrophobicity and the important hysteresis phenomenon. For aeration studies, gas diffusivity should be used. Finally, dielectric type water content sensors used for performing such studies should be calibrated for the specific type of growing medium.

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