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Component characterization and predictive modeling for green roof substrates optimized to adsorb P and improve runoff quality: A review[☆]

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ABSTRACT

This review is a synthesis of the current knowledge regarding the effects of green roof substrate components and their retentive capacity for nutrients, particularly phosphorus (P). Substrates may behave as either sources or sinks of P depending on the components they are formulated from, and to date, the total P-adsorbing capacity of a substrate has not been quantified as the sum of the contributions of its components. Few direct links have been established among substrate components and their physico-chemical characteristics that would affect P-retention. A survey of recent literature presented herein highlights the trends within individual component selection (clays and clay-like material, organics, conventional soil and sands, lightweight inorganics, and industrial wastes and synthetics) for those most common during substrate formulation internationally. Component selection will vary with respect to ease of sourcing component materials, cost of components, nutrient-retention capacity, and environmental sustainability. However, the number of distinct components considered for inclusion in green roof substrates continues to expand, as the desires of growers, material suppliers, researchers and industry stakeholders are incorporated into decision-making. Furthermore, current attempts to characterize the most often used substrate components are also presented whereby runoff quality is correlated to entire substrate performance. With the use of well-described characterization (constant capacitance model) and modeling techniques (the soil assemblage model), it is proposed that substrates optimized for P adsorption may be developed through careful selection of components with prior knowledge of their chemical properties, that may increase retention of P in plant-available forms, thereby reducing green roof fertilizer requirements and P losses in roof runoff.

1. Introduction

1.1. The role of green roofs in urban landscapes

Green roofs provide a unique solution to address issues that arise from urbanization and increasing urban density. As a result of urban development, increases in the total area of impermeable surface, and the loss of total green space are commonly observed. With green roofs, city planners, developers and architects are able to utilize surfaces of minimal economic and environmental value, to reduce the adverse impacts of urban development. Green roofs can provide numerous physical and environmental benefits, both directly and indirectly. Most notably, green roofs retain stormwater, delaying and reducing peak loading times (Carson et al., 2013; Graceson et al., 2013). Additionally, they may cool buildings through evapotranspiration of water retained by substrate (Jim, 2014a, 2014b; La Roche and Berardi, 2014), reduce air pollution (Yang et al., 2008), diminish effects of urban noise pollution (Veisten et al., 2012) and lessen the urban 'heat island' effect (Ambrosini et al., 2014; Norton et al., 2015). Aesthetic (Loder, 2014) and ecological benefits may also be seen through increasing total green space area, through creation of habitat for native animals and plants, and through improvement of biodiversity (Benvenuti, 2014; Francis and Lorimer, 2011; Williams et al., 2014, 2010). With increases in both public and private sector interest and year-over-

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Abbreviations: BD, bulk density; CCM, constant capacitance model; CEC, cation exchange capacity; OM, organic matter; SAM, soil assemblage model; SSA, specific surface area; WHC, water-hold capacity.

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year installed space, it is more important than ever to address lingering questions about whether green roofs act as a source or sink for polluting nutrients, especially P, that may be present in runoff (Berndtsson et al., 2009, 2006; Buffam et al., 2016; Vijayaraghavan et al., 2012).

A common restriction to green roof installation is limited load-bearing roofs, especially in older or retrofitted buildings. Here an important distinction must be made regarding the depth of substrate used in the green roof. Typically extensive green roofs have substrate depths of 15 cm or less, while intensive roof substrate is deeper (FLL, 2008). The depth of substrate determines the total available nutrient pool, the type of vegetation that can be grown on the green roof, and the quantity, quality and delay in runoff after rain events. Thus, load-bearing limitations from roofs require the growing substrate to be lightweight (approx. ≤ 1 g cm^{-3}) and thinly applied, which significantly alters the performance of the green roof (FLL, 2008). Given these constraints, the substrate must still support plant growth and provide all physical, chemical and biological requirements, including suitable pH, adequate soil moisture and oxygen, and retain a sufficient quantity of nutrients in a plant-available form. Substrate water retention is important, especially during times of drought; however, the substrate must also exhibit good drainage to minimize weight of roofs, and to prevent water-logging and potential for anaerobic conditions.

1.2. Fertilization and nutrient leaching

Application of fertilizer represents a major source of nutrients in green roof runoff. Fertilizer is sometimes applied during installation of green roofs but is typically restricted to growing seasons (Clark and Zheng, 2014a, 2013). Fertilizer types include both soluble, slow-release fertilizer solution and pelletized controlled-release fertilizers (CRFs) (Emilsson et al., 2007). The latter is more widely used and is expected to supply plants with nutrients only when needed, and at a rate that does not exceed uptake (Clark and Zheng, 2013). Soluble fertilizers are typically cheaper, and their nutrients are immediately available to plants, but are also more prone to leaching (Emilsson et al., 2007). Understanding the movement of nutrients through green roofs after fertilizer application, through substrate and biomass, then out as runoff, is important for green roof design, upkeep and maintenance, as well as regulatory compliance and environmental stewardship. Phosphorus runoff is of particular concern as it is a leading cause of eutrophication of surface waters (Brooks et al., 2000; Karczmarczyk et al., 2014) and its runoff concentration often exceeds federally-mandated threshold levels (Clark and Zheng, 2014b; van Seters et al., 2009).

Abatement of high-P runoff can be accomplished in two ways, which vary in terms of cost, ease of implementation, and desired outcome. Firstly, substrate components can be selected prior to substrate formulation that will increase the adsorption of P onto colloid surfaces. These components, including natural clays and aggregates (Karczmarczyk et al., 2014), recycled materials and organic amendments (Jang et al., 2005; Vijayaraghavan and Joshi, 2015) have greater P-binding and sorption capacity. Furthermore, the physical properties of these components will in turn determine the physical characteristics of the bulk substrate, including bulk density (BD), porosity, and water-holding capacity (WHC) and permeability. Therefore, substrate formulation may be accomplished by the careful selection of specific components to achieve desired physical and chemical characteristics if they have been quantified beforehand. Conversely, amending green roof substrate after installation has occurred, or through modification of fertilizer regimes, may address issues of nutrient pollution via roof runoff, but may also be more costly, time-consuming and less feasible.

1.3. Phosphorus in soil and soil solution

In conventional soils and green roof substrates, P exists as sparingly soluble organic and inorganic species. In a P-rich conventional soil, total solution P concentrations approximate 1 mg P L^{-1}. Conversely, a soil considered infertile may have only 0.001 mg P L^{-1} (Brady and Weil, 2008). Furthermore, the plant-available fraction is only 0.01% of the total soil P concentration, due in part to rapid precipitation reactions and strong affinity for soil colloids (Brady and Weil, 2008). As such, precipitation and formation of plant-unavailable species has been addressed in the past several decades through over-application of phosphate rock-based fertilizers, leading to oversaturation of soil colloid binding sites (Brady and Weil, 2008). Soluble P in fertilizer is prone to rapid precipitation with Ca and Mg, and Fe and Al in alkaline and acid soil solution respectively (Sharpley and Smith, 1985). These precipitation reactions occur at a rate faster than plant roots can uptake soluble species (approx. 10–15% of the total applied P is immediately available to plants), causing more fertilizer to be applied (Stewart and Tiessen, 1987). This has created issues of P runoff into surrounding surface waters, promoting algal bloom production, leading to eutrophication and creating 'dead zones' for fish and aquatic life (Sharpley et al., 1996). To address this, recent changes to application practices of P-fertilizers have included targeted application with both temporal (i.e. timing of highest plant requirement) and spatial (i.e. applying fertilizer only where needed) considerations (Sharpley et al., 1996).

Phosphorus chemistry in soil and substrate solution is largely controlled by pH, and to a lesser extent temperature, ionic strength and presence of competing ions (Barrow, 2015). Low mobility in soil results from strong, often irreversible, adsorption with soil colloids and through precipitation with metal cations in both high and low pH conditions. Additionally, mineral-P is slow to dissolve, releasing inorganic P species which may then precipitate to form pH-dependent secondary minerals such as strengite ($FePO_4 \cdot 2H_2O_{(s)}$), octacalcium phosphate ($Ca_8H_2(PO_4)_6 \cdot 5H_2O_{(s)}$) and hydroxyapatite ($Ca_5(PO_4)_3OH_{(s)}$). Therefore, soils at risk of P runoff may be stabilized in two ways: (1) amendments to increase the quantity of binding sites thereby increasing the likelihood of greater P adsorption, or (2) reduced application of fertilizer to allow plants to use excess, available P pools (Schulte et al., 2010). Amendments to reduce risks of P runoff may include: (1) biochars (Guo et al., 2014; Jiang et al., 2015; Masto et al., 2013a; Moharami and Jalali, 2014; Nelson et al., 2011; Su et al., 2007), (2) industrial wastes and synthetics (Chardon et al., 2012; Fenton et al., 2012; Liang et al., 2012; Masto et al., 2013a, 2013b; Moharami and Jalali, 2014; Seshadri et al., 2013a, 2013b), (3) clays, natural minerals and synthetic analogs (Argiri et al., 2013; Binner et al., 2015), and (4) organic acids and plant residues (Jalali and Karamnejad, 2011; López-Piñeiro et al., 2011; Schefe and Tymms, 2013). Taken together, these amendments can increase P adsorption through changes to soil solution pH, thereby increasing soluble and plant-available fractions, or by increasing the availability of P-binding sites on the amendment surface.

1.4. Role of green roof substrate and research objectives

The choice of green roof substrate has a large influence on the ability to manage stormwater by delaying peak stormwater flow and eliminating a portion of runoff through retention. Additionally, the substrate will alter incident rainwater chemistry prior to discharge into urban catchment systems. The ability of the substrate to act as a source or sink for a given nutrient or mineral species is variable with reports of increasing or decreasing ion concentrations in runoff found throughout the literature,