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Green roofs as a means of pollution abatement

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ABSTRACT

Green roofs involve growing vegetation on rooftops and are one tool that can help mitigate the negative effects of pollution. This review encompasses published research to date on how green roofs can help mitigate pollution, how green roof materials influence the magnitude of these benefits, and suggests future research directions. The discussion concentrates on how green roofs influence air pollution, carbon dioxide emissions, carbon sequestration, longevity of roofing membranes that result in fewer roofing materials in landfills, water quality of stormwater runoff, and noise pollution. Suggestions for future directions for research include plant selection, development of improved growing substrates, urban rooftop agriculture, water quality of runoff, supplemental irrigation, the use of grey water, air pollution, carbon sequestration, effects on human health, combining green roofs with complementary related technologies, and economics and policy issues.

1. Introduction

Green roofs entail growing plants on rooftops, which partially replaces the vegetation that was destroyed when the building was constructed. In doing so they provide numerous benefits that can help offset the negative aspects of pollution, especially in the urban environment. They can improve stormwater management by reducing runoff and improving water quality, conserve energy, mitigate the urban heat island, increase longevity of roofing membranes, reduce noise and air pollution, sequester carbon, increase urban biodiversity by providing habitat for wildlife, provide a more aesthetically pleasing environment to work and live, and improve return on investment compared to traditional roofs (Czerniel Berndtsson, 2010; Dunnett and Kingsbury, 2004; Getter and Rowe, 2006; Mentens et al., 2006; Oberndorfer et al., 2007; Rowe and Getter, 2010).

They are generally categorized as either 'intensive' or 'extensive'. Intensive green roofs are frequently designed as public places and may include trees, shrubs, and hardscapes similar to landscaping found at ground level (Fig. 1). They generally require substrate depths greater than 15 cm and generally require 'intense' maintenance (Snodgrass and McIntyre, 2010). Intensive roofs also tend to be more expensive than extensive roofs because of the need for a more structurally sound building to support the weight. In contrast, extensive green roofs often never seen, require minimal maintenance, and are generally built with substrate depths less than 15 cm (Fig. 2). Because of the shallower depth, plant choices are limited to grasses, herbaceous perennials, annuals, and drought tolerant succulents such as *Sedum*. Due to building weight restrictions and costs, shallow extensive green roofs are most common. The type of roof installed can have a significant impact on the ecological, social, and economic services it provides in terms of pollution abatement.

This review will evaluate published research to date on how green roofs can help mitigate pollution, how green roof materials influence the magnitude of these benefits, and suggest future research directions.

2. Criteria for selection of articles

To be included in this review, papers had to be written in English and to maximize scientific credibility of this review they had to be published in peer-reviewed journals. The author acknowledges that much early work on green roofs was written in German, but is not readily available to most of the world and much of it was not published in peer-reviewed journals. With some exceptions, papers from proceedings of conferences were not included unless they were published within the last two years and nothing else exists on that particular topic. It is

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Fig. 1. An intensive green roof on the Coast Plaza Hotel in Vancouver, British Columbia (Photo by Brad Rowe).

expected that work appearing in proceedings would have been published in a peer-reviewed journal within that period of time. If it was not, it was assumed that the authors felt the work was flawed in some way and not worthy of publication or it was submitted and rejected.

3. Air pollution

Polluted air is directly attributed to declines in human health (Mayer, 1999). Nearly one-quarter of the people in the U.S. live where there are unhealthful short-term levels of particle pollution,

Fig. 2. Portion of a 10.4 acre extensive green roof on an assembly plant at Ford Motor Company in Dearborn, Michigan. Plant material consists of 13 species and cultivars of Sedum (Photo by Brad Rowe).

while roughly one in ten people live where there are unhealthful levels year-round (ALA, 2010). Increased mortality rates in 95 urban areas within the US have been linked to elevated levels ozone (Bell et al., 2004). In Canada, the Ontario Medical Association attributes 9500 premature deaths per year (OMA, 2008) and estimates increased costs of health care ($506.64 M) and lost productivity ($374.18) as a result of air pollution (OMA, 2005). The most common health related symptoms of air pollution are increased occurrences of respiratory illnesses such as asthma and a greater incidence of cardiovascular disease (Pope et al., 1995).

There has been much published on the ability of plants to clean the air, but little specific to green roofs. Vegetation removes pollutants in several ways. Plants take up gaseous pollutants through their stomates, intercept particulate matter with their leaves, and are capable of breaking down certain organic compounds such as poly-aromatic hydrocarbons in their plant tissues or in the soil (Baker and Brooks, 1989). In addition, they indirectly reduce air pollutants by lowering surface temperatures through transpirational cooling and by providing shade, which in turn decreases photochemical reactions that form pollutants such as ozone in the atmosphere. For example, Akbari et al. (2001) reported that when maximum daily temperatures in Los Angeles were less than 22 °C, ozone levels were below the California standard of 90 parts per billion; at temperatures above 35 °C, practically all days were smoggy. In addition, by reducing the need for air conditioning, a lower requirement for energy results in lower emissions from power plants (Rosenfeld et al., 1998).

In urban areas, trees have been shown to provide a significant contribution to the reduction of air pollutants (Akbari et al., 2001; Nowak, 2006; Rosenfeld et al., 1998; Scott et al., 1998). In the U.S. alone, Nowak (2006) estimated that trees remove 711,000 metric tons per year. However, in many urban sites there is little space to plant trees or cultivate an urban forest because of the plethora of impervious surfaces such as streets, parking lots, and rooftops. For example, in the mid-Manhattan west section of New York, 94% of the land is covered with impervious surface which leaves little room for planting trees at ground level (Rosenzweig et al., 2006). However, rooftops which often comprise 40–50% of the impermeable area in an urban area provide an opportunity to replace impermeable surfaces with vegetation (Dunnett and Kingsbury, 2004).

It is estimated that 2000 m^2 of uncut grass on a green roof can remove up to 4000 kg of particulate matter (Johnson and Newton, 1996). In practical terms, a gasoline powered automobile produces approximately 0.01 g of particulate matter for every mile driven. If a vehicle is driven 10,000 miles per year, then 0.1 kg of particulate matter is then released annually into the atmosphere. Thus, one square meter of green roof could offset the annual particulate matter emissions of one car (City of Los Angeles, 2006). Regarding specific pollutants, Clark et al. (2005) estimate that if 20% of all industrial and commercial roof surfaces in Detroit, MI, were traditional extensive sedum green roofs, over 800,000 kg (889 tons) per year of NO_2 (or 0.5% of that areas emissions) would be removed. In Singapore, sulphur dioxide and nitrous acid were reduced 37% and 21%, respectively, directly above a green roof (Tan and Sia, 2005).

In Toronto, Currie and Bass (2008) studied the effects of green roofs on air pollution using the Urban Forest Effects (UFORE) dry deposition model developed by the USDA Forest Service. The model quantified levels and hourly reduction rates of NO_2, SO_2, CO_2, PM_{10} (particles of 10 μm or less) and ozone as well as their economic value. UFORE calculations were based on vegetation cover, hourly weather data, and data on concentration of pollutants. Trees and shrubs were more effective in removing contaminants than herbaceous perennials largely due to greater leaf surface area. Although intensive green roofs with trees and shrubs are more favorable in terms of reducing pollution, extensive green roofs can still play a supplementary role in regards to air quality.

Yang et al. (2008) also utilized a dry deposition model to quantify the impact of green roofs on air pollution in Chicago. Results showed that air pollutants were removed at a rate of 85 kg ha^{-1} yr^{-1} with ozone accounting for 52% of the total followed by NO_2 (27%), PM_{10} (14%), and SO_2 (7%). The greatest quantity of pollutants were removed during the month of May which further substantiates the value of plants since during a normal year the greatest amount of growth would be expected to occur during Spring. Similarly, the lowest rate of removal occurred during February when plants were dormant. Based on the Yang et al. model, if all rooftops in Chicago were covered with intensive green roofs the quantity of pollutants removed would increase to 2046.89 metric tons. However, the installation costs to accomplish this were estimated to be $35.2 billion.

Besides direct amelioration of air pollutants by green roofs, they also reduce emissions indirectly. Rosenfeld et al. (1998) calculated that emissions from coal fired power plants could be reduced by 350 tons of NO_x per day in Los Angeles by reducing the need for air conditioning. This value equates to 10% reduction in the precursors to smog which to the city of Los Angeles which has an active NO_x trade program results in a savings of one million dollars per day (Akbari et al., 2001; Rosenfeld et al., 1998).

Furthermore, urban air temperatures can be up to 5.6 °C warmer than the surrounding countryside and for every 0.6 °C increase in air temperature, peak utility load may increase by 2% (US EPA, 2003). On the scale of an individual building, green roofs shade and insulate buildings in combination with evapotranspiration that reduces summer indoor temperatures (Santamouris et al., 2007; Sailor, 2008; Takebayashi and Moriyama, 2007). The role of green roofs in this capacity is primarily through a reduction in heating and cooling requirements for individual buildings and in mitigating the urban heat island on the community level. Because buildings account for 39% and 71% of total energy and electricity consumption, respectively (U.S. Green Building Council, 2008), implementing green roof technology on a wide scale could significantly impact energy consumption and in turn pollution. The effect of green roofs on energy conservation and the urban heat island is beyond the scope of this paper. Castleton et al. (2010) reviews current literature and highlights situations where the greatest energy benefits can be obtained.

Because plant species possess varying abilities to remove air pollutants and reduce emissions they can be selected to maximize improvements in air quality (Benjamin et al., 1996). For example evergreen conifers may provide a greater benefit than deciduous species because they retain their leaves year-round. Reductions in particulate matter, ozone, NO_x, and SO_x occur while plants are actively growing and in-leaf. Individual plant species also exhibit vast differences in their ability to uptake pollutants (Morikawa et al., 1998; Takahasi et al., 2003). Morikawa et al. (1998) tested 217 species including *Kalanchoe blossfeldiana*, a succulent in the Crassulaceae family, for their potential to remove NO_2. Sedum, the most common plant species for traditional extensive green roofs is similar to *Kalachoe* in that they are both members of the same family and both exhibit Crassulacean Acid Metabolism. Clark et al. (2005) extrapolated Morikawa's data to compare the annual uptake per unit area of NO_2 for a succulent (*Kalanchoe blossfeldiana* at 0.03 kg m^{-1} yr^{-1}), an herbaceous species (*Nicotiana tabacum* at 1.03 kg m^{-1} yr^{-1}), and a tree (*Eucalyptus viminalis* at 1.18 kg m^{-1} yr^{-1}). Tobacco had 30 times the uptake capacity of the sedum-like succulent, which suggests that sedum may not be the ideal plant if air pollution mitigation is the primary objective of a green roof. In addition to plant selection, Clark et al. (2009) reported that altering the growing substrate by increasing the percentage of organic matter, increasing density, and increasing depth all increase the retention of nitrogen.

As a strategy to remove air pollutants, intensive green roofs are comparable to urban forests as reported by Nowak (2006). If 20% of all existing "green roof ready" buildings in Washington, DC, installed green roofs, the resulting plantings would remove the same amount of air pollution as 17,000 street trees (Deutsch et al., 2005). However, green roofs are much more expensive. A 19 m^2 extensive green roof can remove the same quantity of pollutants as a medium sized tree, but the planting costs are approximately $3059 and $400, respectively (Yang et al., 2008). Even so, green roofs provide numerous other benefits in the long-term.

Although trees found at ground level or on intensive garden roofs play a much larger role in improving air quality than grasses or succulents that are often found on extensive green roofs, the added loading requirements and cost of intensive roofs make it unlikely that they will be implemented on a large scale (Currie and Bass, 2008). Shallow green roofs can augment the urban forest, but cannot replace it. The benefit is difficult to quantify in dollars since the improvement in air quality and thus human health is a benefit to society and not the individual building owner. Reduction in air pollution quantified economically through emission reduction credits could help offset the cost gap for installing green roofs (Clark et al., 2008a).

4. Carbon dioxide

There is little doubt that the earth is warming (National Research Council, 2001). Part of this may be due to natural cycles, but the increase in temperature has coincided with the industrial revolution and the burning of fossil fuels. Burning fossil fuel releases CO_2 as a by-product of combustion and CO_2 is often implicated as a cause because it is one of the atmospheric gases that keeps terrestrial energy from escaping into space, thus resulting in higher temperatures due to the greenhouse effect. According to the Intergovernmental Panel on Climate Change (IPCC, 2007), human activity related to the combustion of fossil fuels has increased carbon dioxide (CO_2) concentrations in the atmosphere 32% since 1750. In the future, emissions of CO_2 due to fossil fuel combustion will probably continue to increase, for example, the U.S. Department of Energy (2010) has proposed constructing over 100 new coal fired power plants by 2017 to meet expected demands for energy.

Green roofs can play a small part in reducing CO_2 in the atmosphere in two ways. First, carbon is a major component of plant structures and is naturally sequestered in plant tissues through photosynthesis and into the soil substrate via plant litter and root exudates. Second, as stated above, they reduce energy needs by insulating individual buildings and by mitigating the urban heat island. A green roof will eventually reach a carbon equilibrium (plant growth = plant decomposition), but initially this man-made ecosystem will serve as a carbon sink. Getter et al. (2009b) quantified the carbon sequestered by four species of *Sedum* in a 6.0 cm substrate depth extensive green roof in Michigan over a period of two years. At the end of the study above-ground plant material and root biomass stored an average of 168 g C m^{-2} and 107 g C m^{-2}, respectively, with differences among species. Substrate carbon content averaged 913 g C m^{-2}. In total, this entire extensive green roof system held 1188 g C m^{-2} in combined plant material and substrate. However, after subtraction the 810 g C m^{-2} that existed in the original substrate, net carbon sequestration totaled 378 g C m^{-2}.

Although, a green roof can act as a carbon sink, one must also consider the embodied energy (total energy consumed, or carbon released, of a product over its life cycle) that goes into constructing it. The components of a green roof likely have a CO_2 'cost' in terms of the manufacturing process over and above those of a conventional roof (Kosareo and Ries, 2007). Hammond and Jones (2008) analyzed many building materials from the beginning through the entire production process. Assuming a generic industry root barrier, drainage layer, and 6.0 cm of substrate consisting of half sand and heat expanded slate by volume as was the case in the Getter et al. (2009b) study, total embodied energy for the green roof components are 23.6 kg CO_2 per square meter of green roof. This equates to 6448 g C m^{-2} which is considerably greater than the 378 g C m^{-2} that was sequestered. Also, since the roof reaches an equilibrium where carbon assimilation equals carbon decomposition, there will be essentially no additional net carbon sequestration on this roof.

Net sequestration could be improved immensely by altering species selection, substrate depth, substrate composition, and management practices. For example, in the Getter et al. (2009b) study, above-ground sequestration ranged from 64 g C m^{-2} to 239 g C m^{-2} for *S. acre* and *S. album*, respectively. Increasing substrate depth would not only provide a larger volume for carbon storage, it would also enable a wider plant palette that could include larger perennials and even trees. In addition, the composition of the growing substrate could be altered. In the Getter et al. (2009b) study, the heat expanded slate component of the growing substrate accounted for 80% of the embodied energy of the green roof. By using alternate materials, the embodied energy could be reduced substantially. For example, in the Pacific Northwest of North America, volcanic pumice is readily available and is often used as a component in substrates. The pumice has been heat expanded by nature and thus its embodied energy is vastly reduced. Furthermore, management practices such as fertilization and watering would have an impact on embodied energy and carbon sequestration.

However, carbon sequestration by plants and the substrate are only part of the equation. There is also a reduction in CO_2 given off from power plants due to the green roof's ability to insulate individual buildings and reduce the urban heat island. In the U.S., buildings are responsible for 38% of carbon dioxide emissions (U.S. Green Building Council, 2008). When the effects of green roofs on the energy balance of an individual building are plugged into Energy Plus, a building energy model supported by the U.S. Department of Energy, Sailor (2008) found a 2% reduction in electricity consumption and a 9–11% reduction in natural gas. Based on this model, a generic building with a 2000 m^2 green roof would result in annual savings ranging from 27.2 to 30.7 GJ of electricity and 9.5 to 38.6 GJ of natural gas, depending on climate and green roof design. When considering the national averages of CO_2 produced for generating electricity and burning natural gas (US EPA, 2007; US EPA, 2008a), these figures translate to electricity and natural gas savings of 2.3–2.6 kg CO_2 m^{-2} and 0.24–0.97 kg CO_2 m^{-2} of green roof each year.

The above estimates pertain only to energy saved by reducing energy flux through the building envelope. There are also indirect reductions of energy use due to the implementation of heat island reduction (HIR) strategies which achieve ambient cooling. Akbari and Konopacki (2005) simulated many different HIR strategies for a variety of climates and building types in the U.S. While not specifically focusing on green roofs, they found that electricity savings due to indirect HIR consisted on average of 25% of energy consumption savings.

As an example of these potential emission savings using Sailor's (2008) model, the campus of Michigan State University in East Lansing, MI has 1.1 km^2 of flat roof surface. If all of these roofs were greened, they could avoid 3,640,263 kg CO_2 emitted per year in electricity and natural gas consumption combined. This is the equivalent of taking 661 vehicles off the road each year (US EPA, 2005). These figures depend on climate, green roof design, and source of fuel for electricity and gas.

In the future, green roofs could be incorporated as carbon trading credits in a cap and trade system. Market based carbon trading is a low-cost method for many companies to manage and lower emissions. Chicago Climate Exchange (CCX) is such a pilot trading program that is voluntary in the United States and is the only cap and trade system for all six greenhouse gases in North America. This program seeks to demonstrate that greenhouse gas trading can reduce emissions across different business sectors (CCX, 2010) and is similar to the highly successful sulfur dioxide (SO_2) emissions trading program implemented in the 1990s (Chestnut and Mills, 2005). Participation in CCX trading for greenhouse gases could help companies meet their reduction targets by purchasing credits from other companies who have exceeded their reduction target, as well as provide financial incentives for those companies who exceed their reduction goals.

5. Fewer roofing materials in landfills

The mechanical lifespan of a typical conventional roof is approximately 20 years. When these roofs are replaced the old roofing materials must be removed, transported, and will likely be placed in a landfill where they not only take up space, but may also leach pollutants. On the other hand, green roofs are estimated to last 45 years or longer in terms of mechanical lifespan (Kosareo and Ries, 2007). This estimate is based primarily on empirical evidence as modern green roofs are a relatively new practice. Supporting this statement is the roof of the water treatment facility in Zurich, Switzerland, that was installed in 1914 and repaired for the first time in 2005, a period of 91 years.

Green roofs last longer because the bituminous roofing membranes are protected by the growing substrate and plant canopy from ultraviolet radiation and the extreme fluctuations in membrane temperature between night and day. When comparing a green roof to a conventional roof in Toronto, Liu and Baskaran (2003) reported the membrane temperature on a convention roof of 70 °C in the afternoon while the green roof membrane only reached 25 °C. The daily expansion and contraction of the roofing membrane stress the membrane resulting in fatigue and eventual failure.

6. Water quality of stormwater runoff

Much has been written regarding the ability of green roofs to retain stormwater (Czerniel Berndtsson, 2010; Carpenter and Kaluvakolanu, in press; Carter and Jackson, 2007; Carter and Rasmussen, 2006; DeNardo et al., 2005; Getter et al., 2007; Hathaway et al., 2008; Hilten et al., 2008; Mentens et al., 2006; Palla et al., 2009; Simmons et al., 2008; Spolek, 2008; Stovin, 2009; Teemusk and Mander, 2007; VanWoert et al., 2005a; US EPA, 2009; Villarreal and Bengtsson, 2005). The reduction in runoff generally ranges from 50% to 100% depending on the type of green roof system, substrate composition and depth, roof slope, plant species, preexisting substrate moisture, and the intensity and duration of the rainfall. For example, if 20% of buildings in Washington, DC, had green roofs, they could store approximately 958 million liters (253 million gallons) of rainwater in an average year (Deutsch et al., 2005). Water retained in the substrate will eventually evaporate or will be transpired back into the atmosphere. In addition, water that does runoff is delayed because it takes time for the substrate to become saturated and to drain. Because runoff is released over a longer period of time, green roofs can help keep municipal stormwater systems from overflowing and reduce potential erosion downstream.

In the U.S. there are 772 communities that do not have separate sewer and stormwater systems (US EPA, 2008b). Because sewage and stormwater are funneled through the same pipe in these communities, heavy rain events can result in a Combined Sewage Overflow (CSO) when the volume of runoff exceeds the capacity of the stormwater system. Under these circumstances, raw untreated sewage flows out of relief points into rivers. In New York City, about half of all rainfall events result in a CSO event and collectively they dump 40 billion gallons of untreated wastewater into New York's surface waters every year (Cheney, 2005). Even in communities with separate stormwater managements systems, impervious surfaces still contaminate waterways by collecting pollutants such as oil, heavy metals, salts, pesticides, and animal wastes that wash into waterways. By retaining stormwater, green roofs decrease the chance of a CSO event and also reduce the cost associated with stormwater systems because they do not have to be as large.

The quantity of roof runoff influences water quality downstream after it exits the roof. The other side of the equation is how green roofs influence water quality of the effluent as it runs off the roof. Many contaminants present in common roofing materials already leach into the runoff (Clark et al., 2008b; Mason et al., 1999) and these contaminants will still be present in membranes on green roofs. But, do plants and growing substrates influence runoff in a positive or negative way? Do they filter pollutants or provide an additional source of contaminants that exacerbate water quality? Heavy metals and nutrients are contaminants of interest. There is also the possibility that particulate matter cleaned from the air that adhered to leaf surfaces will be washed off by rain and eventually leach into the stormwater system, thus trading air pollution for water pollution. Research results are mixed (Table 2).

At first glance, it appears that green roofs are a source of contaminants. Czerniel Berndtsson et al. (2006) analyzed metals and nutrients (Cd, Cr, Cu, Fe, K, Mn, Pb, Zn, NO_3–N, NH_4–N, Tot-N, PO_4–P, and Tot-P) present in runoff from extensive sedum-moss roofs and non-vegetated roofs and showed that with the exception of N which was retained by the vegetation, green roofs were a source of pollutants. Similarly, total N and P concentrations in runoff from two green roofs in North Carolina were greatest from the green roof relative to the control roof and rainfall itself (Hathaway et al., 2008). Total P load was also greatest from the green roof. In Michigan, Carpenter and Kaluvakolanu (in press) compared runoff from asphalt, gravel ballasted, and extensive green roofs and reported that green roofs had the highest concentration of total solids with no significant differences for nitrate and phosphate concentrations. However, mean mass values for nitrate and phosphate from the green roof were lower than from the asphalt roof. In Pennsylvania, runoff from green roofs contained a higher concentration of most of the nutrients and ions measured relative to a conventional roof, but the concentrations were no different than what would runoff of any planted landscape at ground level (US EPA, 2009). However, even though the concentrations were higher, the total amount was less than the conventional roofs because the conventional roofs retained an average of 50% of all rain that fell on them.

Conflicting data could be due to the fact that the age of the green roof can influence runoff water quality. Although Czerniel Berndtsson et al. (2006) reported higher phosphate levels as discussed above, phosphate was not a problem on older mature roofs. Likewise, on the North Carolina roofs, it was suggested that pollutants would decline over time as the green roof aged. In this case the data was collected on new green roofs and the initial growing substrate contained 15% composted cow manure which likely was a large source of N and P (Hathaway et al., 2008). In one of the pioneer studies on green roofs in Berlin, Germany, retention of PO_4 increased from 26% in year one to 80% in year four (Köhler et al., 2002). These roofs also retained a mean of 95%, 88%, 80%, and 67% of Pb, Cd, NO_3, and PO_4, respectively, over a three year period. In Toronto, Van Seters et al. (2009) analyzed runoff samples from an extensive green roof for pH, total suspended solids, metals, nutrients, bacteria, and PAH (polycyclic aromatic hydrocarbons). Loads of most chemicals were lower from the green roof relative to the conventional roof with the exception of Ca, Mg, and total P (Van Seters et al., 2009). Although P concentrations regularly exceeded the Ontario receiving water objective during the first year, they fell significantly afterwards suggesting they were being leached from the growing substrate. As organic matter in the original substrate decomposes one would expect that the amount and concentrations of nutrients would decrease.

The time of year and magnitude of the rain event are also important factors. Steusloff (1998) modeled retention capability of extensive green roofs for heavy metals and reported 97%, 96%, 92%, and 99% retention for Cu, Zn. Cd, and Pb, respectively, during the summer and 34%, 72%, 62%, and 91% during winter. Similar to air pollutants, active plant growth can influence runoff water quality. Regarding the magnitude of a rain event, Teemusk and Mander (2007) compared runoff from a green roof and modified bituminous roof in Estonia for pH, BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), Tot-P, PO_4, Tot-N, NO_3, NH_4, SO_4, Ca, and Mg. Values for pH of the effluent from the green roof increased from 5.2–5.6 to 7.2–8.3, probably due to the carbonate content of the growing substrate. A similar effect on pH was reported on two studies in Pennsylvania, a location where acid rain is a problem (Bliss et al., 2009; US EPA, 2009). Acid rain can exacerbate the leaching of metals such as Cd, Pb, and Zn as their solubility increases as pH decreases (Alsup et al., 2010). During moderate runoff events in the Estonian study, values of COD, BOD, and concentrations of total N and P were greater on the bituminous roof, whereas, during heavy rain events, components were less concentrated and more nitrates and phosphates were washed off the green roof (Teemusk and Mander, 2007). In winter snowmelt all components were greater on the green roof. Higher BOD components from the green roof were likely due to decomposition of plant material.

A direct correlation exists between the magnitude of the rain event and the amount of solids in the effluent. In many cases during smaller rain events, nutrients and sediment that are washed off the conventional roof are retained on the green roof because there was no runoff. This would lead to misleading higher concentrations from the green roof in future larger rain events. This is somewhat reflected in data for a first flush of runoff. Czerniel Berndtsson et al. (2008) measured the first flush and found that with the exception of K and dissolved organic carbon (DOC), concentrations and total volumes of the tested chemicals were higher in the initial first flush than what was washed off later. In contrast, Bliss et al. (2009) reported that most storm events did not exhibit a first flush phenomenon on a green roof in Pittsburgh.

In addition, plant selection, substrate composition, and substrate depth all influence the quality of effluent. Monterusso et al. (2004) compared effluent from green roofs with herbaceous perennials to those growing sedum and found that nitrate concentrations in the runoff were higher from the sedum roofs and also reported higher concentrations from those roofs with a shallower substrate depth. They found no significant differences for P. Similarly, Dunnett et al. (2008b) found that plant composition influenced water retention which likely influenced water quality when comparing differences in vegetation ranging from monocultures of forbs and grasses to combinations of both. The effect of plants is also evident where effluent from an unplanted green roof containing substrate had higher concentrations and totals of N and P than effluent from planted roofs (US EPA, 2009).

Regarding substrate composition, concentrations of both N and P decreased with decreasing percentages of compost in the growing substrate when tested in laboratory columns (Hathaway et al., 2008). Alsup et al. (2010) also found that vegetation and substrate composition influenced the quality of runoff when they tested several substrates for potential use on green roofs. Their results emphasize the point that growing substrates can have an immense effect on the quality of effluent.

Although, the original substrate is important, management of the green roof is also critical. Applications of fertilizers and pesticides to ensure plant growth can be very detrimental to water quality. Emilsson et al. (2007) measured nutrient runoff, nutrient storage, and plant uptake following fertilization of vegetated sedum mats, shoot-established vegetation, and unvegetated substrate following applications of controlled release fertilizer (CRF) or a combination of CRF and conventional fertilizer. Nutrient runoff concentrations and totals increased when conventional fertilizers were used and although the levels decreased over time they were still higher than the concentrations from those roofs fertilized with CRF's at the end of the experiment. There was also less leaching from roofs with established vegetation compared to those that were recently planted.

Overall, it appears that green roofs can have a positive effect on water quality. Based on the data available, green roofs that were a source of pollutants tended to be new, whereas those that were older with established vegetation were not a problem. The initial nutrient load likely is due to decomposition of organic matter that was incorporated into the original mix. Established vegetation and substrates can improve the water quality of runoff by absorbing and filtering pollutants. Of course, water quality of the effluent is dependent on several factors such as substrate composition, substrate depth, plant selection, age of the roof, fertilization and maintenance practices, the volume of rainfall, local pollution sources, and the physical and chemical properties of those pollutants. Also, the use of soluble conventional fertilizers should be avoided due to the adverse impact on stormwater runoff. If nutrient loading is a problem green roofs could be coupled with other low impact development practices such as rain gardens and bioswales.

7. Noise reduction

Excess noise is not only annoying, it can lead to health problems such as hearing impairment, hypertension and ischemic heart disease, sleep disturbance, and decreased school performance (Öhrström, 1991; Passchier-Vermeer and Passchier, 2000). In urban areas, high noise levels are often a problem in enclosed spaces surrounded by tall buildings, along street canyons, and near industrial areas and airports.

Conventional roofs are generally hard surfaces so the potential to reduce sound pressure from roads and other sources in these areas by implementing green roofs is promising. Vegetation in combination with the growing substrate will absorb sound waves to a greater degree than a hard surface. Van Renterghem and Botteldooren (2008, 2009) studied the effects of intensive and extensive green roofs on sound pressure. They found a linear relationship between the percentage of roof space covered with vegetation and the reduction in sound pressure on the opposite side of the building from the noise source or street canyon. Because green roof growing substrates tend to be coarse, sound waves enter the pore space and are attenuated by the numerous interactions with the substrate particles (Van Renterghem and Botteldooren, 2009). Relative to a non-greened roof the reduction is most pronounced at frequencies in the range from 500 to 1000 Hz with a maximum reduction of 10 dB. Increasing substrate depth improved noise reduction up to a depth of 15–20 cm. Roofs with deeper substrate layers provided no further benefit. Of course, many variables influenced noise attenuation including the width–height ratios of the canyons, façade absorption, diffuse reflection, and building-induced refraction of sound (Van Renterghem and Botteldooren, 2008). On the inside of a building noise levels also depend on façade insulation, the sound pressure level outdoors, and whether windows are open or closed. Thus green roofs can have a positive influence on buildings near airports, industrial areas, and in urban settings.

8. Future directions for research

8.1. Plants selection

All of the pollution abatement benefits of green roofs stem from the plants, because they are the components that make a green roof green. Keeping a green roof healthy and thriving will influence how well the roof performs in terms of pollution abatement. Many factors determine survival of green roof plant species including substrate depth (Dunnett et al., 2008a; Durhman et al., 2007; Getter and Rowe, 2009), solar radiation levels (Getter et al., 2009a), and climate with the limiting factor usually being substrate moisture (ASTM, 2006; Durhman et al., 2006; Emilsson, 2008; Monterusso et al., 2005; Wolf and Lundholm, 2008). Also, fertilization often promotes biomass accumulation which in some cases makes the plants more vulnerable to drought (Rowe et al., 2006). There is evidence that evapotranspiration rates influence stormwater retention and energy conservation (VanWoert et al., 2005b; US EPA, 2009; Voyde et al., 2010) and these need further investigation to maximize transpiration while keeping plant alive. There is also a need for plant research on combinations of plants as there is some evidence that green roofs perform better when designed as ecosystems to promote biodiversity instead of monocultures (Lundholm et al., 2010). Plants need to be evaluated in various locations and climactic regions, as well as for management and maintenance practices. An excellent review of the literature on green roof vegetation in North America was recently published in the journal Landscape and Urban Planning (Dvorak and Volder, 2010).

8.2. Growing substrates

There is a need to develop and use green roof growing substrates that minimize leaching of nutrients and other contaminants while still providing adequate physical and chemical properties for plant growth. Organic matter included in the substrate is very beneficial for plant growth, but when it decomposes it may leach nutrients. Economics dictate that substrate composition will depend on materials that are locally available and can be formulated for the intended plant selection, climatic zone, and anticipated level of maintenance. Economically feasible options should be investigated. Components such as recycled waste materials and by-products from foundries or incinerators have potential, but concentrations of contaminants must be considered. For example, bottom ash collected from the bottom of a furnace following combustion often contains heavy metals (Brunner and Monch, 1986). Even if contaminants are present, it may be possible to leach them before utilizing the material on a green roof. In addition, the addition of activated charcoal may filter pollutants and it is possible that plants may sequester or phytoremediate pollutants before they are released in the effluent (Baker and Brooks, 1989).

8.3. Urban rooftop agriculture

There is currently much interest in sustainable local production of food in urban areas. One obstacle is that in many cities there is very little available land for such practices, but most rooftops are wasted empty spaces that could be utilized for this purpose. However, just as there are challenges in keeping typical drought tolerant plants alive on rooftops in porous shallow substrates, these problems can be amplified when growing vegetables. In preliminary studies at Michigan State University we have experienced difficulty growing vegetables on a green roof that are comparable to the vigor and yield of those grown at ground level without added inputs such as frequent irrigation and fertilizer. The relatively high levels of fertilizer applied that is necessary to obtain similar yields has undoubtedly lead to high levels of nutrient leaching. Which begs the question, are we trading the benefits of local food production for decreased water quality? We must also ask ourselves if growing food on rooftops is an efficient process or are we better off utilizing vacant lots, back yards, or green walls to produce vegetables? Rooftop agriculture is an area of great need in terms of research.

8.4. Water quality, irrigation, and the use of grey water

Additional research is needed to substantiate claims regarding water quality of the runoff from roofs with various substrates and types of vegetation. Also, can grey water be used or will there be a buildup of salts in the substrate that will harm vegetation. Along those lines, will phosphates and other pollutants in grey water be filtered by the green roof or will they end up in the effluent?

Regarding irrigation, proper plant selection relative to substrate depth can eliminate the need in most cases. However, sometimes supplemental water is necessary to keep plants alive during drought episodes so the roof can function at its optimal level. Irrigation may also be positive in terms of energy savings as evapotranspiration from a green roof surface not only helps moderate internal building temperatures, but also may be a cost effective method of temperature control. This is because water that is needed to produce electricity is a significant portion of the cost. Mankiewicz et al. (2009) reported that the cost of cooling air using the local potable water supply is between 41 and 93 times lower than using electric powered air conditioning to obtain the same level of cooling. These figures were determined using cost data for the cities of Chicago, New York, Philadelphia, and Seattle. The cost would be even lower if recycled stormwater or grey water was used instead of drinking water.

8.5. Air pollution and carbon sequestration

There are only a few papers regarding the effects of green roofs on the mitigation of air pollution (Table 1). Air pollution can cost billions of dollars per year from hospital stays, employee absenteeism, and lost productivity. Getter et al. (2009b) quantified the carbon sequestered in a shallow sedum-based extensive green roof, but this is the lower limit of a green roof's potential. With climate change currently a hot topic, additional research should quantify the carbon sequestration potential of more sophisticated roofs with trees and shrubs.

8.6. Effects on human health

Nitrogen oxides (NO_x) resulting from combustion of fossil fuels can form ground level ozone that results in respiratory problems, premature deaths, and reductions in crop yields – all of which have economic impacts (US EPA, 1998). Clark et al. (2008a) reported that green roofs yield an annual benefit of \$0.45–\$1.70 per m^2 (\$0.04–\$0.16 per square foot) in terms of NO_x uptake. In addition, when humans view green plants and nature, it has beneficial health effects as well as improved health and worker productivity. Employees that had a view of nature were less stressed, had lower

Table 1
Peer-reviewed journal articles written in English on the effects of green roofs on air pollution.

Reference	Location	Topic
Clark et al., 2008a	Michigan, USA	Integrated stormwater, energy consumption, and air pollution benefits into an economic model on the scale of an individual building. Estimates that NO_x reduction would provide an annual benefit of \$895–3392 for a 2000 ft^2 green roof and would lead to a mean NPV (net present value) for the green roof that is 24.5–40.2% less than the mean conventional roof NPV.
Currie and Bass, 2008	Toronto, Canada	Effect of various vegetation scenarios (trees, shrubs, green roofs, and green walls) on air pollution estimated using the Urban Forest Effects (UFORE) model. Results indicate that intensive green roofs would have the greatest impact, but extensive roofs could augment the effect of trees and shrubs.
Getter et al., 2009b	Michigan, USA	Measured carbon sequestration of sedum-based extensive green roofs over time, included carbon cost embedded in green roof materials, and calculated the reduction in CO_2 given off from power plants due to energy savings.
Yang et al., 2008	Illinois, USA	Estimated level of air pollution removal in Chicago using a dry deposition model. Annual removal of pollutants per hectare of green roof was 85 kg ha^{-1} yr^{-1} with the highest and lowest removal during May and February, respectively. Would remove 2046.89 metric tons if all rooftops in Chicago were covered with intensive green roofs.

blood pressure, reported fewer illnesses, and experienced greater job satisfaction (Kaplan et al., 1988; Ulrich, 1984). Green roofs improve urban air quality and by extension public health and quality of life, but these benefits need to be quantified to a better degree.

8.7. Complementary related technologies

Green roofs are only one technology that can help mitigate pollution. Green walls show much promise because they can cover four sides of a building instead of just the top. A similar option is a vine covered trellis suspended over a roof known as a green cloak. In Maryland, Schumann and Tilley (2008) reported that a green cloak reduced maximum daily indoor temperatures by as much as 3.1 °C during July. This reduction is comparable to a green roof in terms of energy savings and has the advantage of being without most of the additional weight of a green roof (Schumann and Tilley, 2008).

What is the impact of green roofs on the efficiency of photovoltaic cells in various climates? How can green roofs be combined

Table 2
Peer-reviewed journal articles written in English on water quality of runoff from green roofs.

Reference	Location	Topic
Alsup et al., 2010	Illinois, USA	Measured extraction and leachate of several potential green roof substrates with and without vegetation for metals (Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn). Found differences among substrates and vegetation influenced runoff.
Bliss et al., 2009	Pennsylvania, USA	Measured SO_4, P, COD, Tot-N, PB, ZN, Cd, and turbidity. Levels of P and COD were elevated, but most storm events did not exhibit a first flush phenomenon from the green roof. Both the control and green roofs neutralized slightly acidic rainfall.
Carpenter and Kaluvakolanu, in press	Michigan, USA	Compared runoff from asphalt, gravel ballasted, and extensive green roofs. Green roofs had highest concentration of total solids with no significant differences for nitrate and phosphate. Mean mass values for nitrate and phosphate from green roof were lower than from asphalt roof.
Czerniel Berndtsson, 2010	Sweden	Review paper on stormwater
Czerniel Berndtsson et al., 2006	Sweden	Measured runoff from extensive sedum-moss roofs and non-vegetated roofs for metals and nutrients (Cd, Cr, Cu, Fe, K, Mn, Pb, Zn, NO_3–N, NH_4–N, Tot-N, PO_4–P, and Tot-P) and ascertained whether age of roof is significant. Results showed that with the exception of N which was retained by the vegetation, green roofs are a source of contaminants.
Czerniel Berndtsson et al., 2008	Sweden	Measured first flush runoff during simulated rain events. Except for K and dissolved organic carbon (DOC), concentrations and total volumes of the tested chemicals were higher in the initial first flush runoff than what was washed off later.
Emilsson et al., 2007	Sweden	Measured nutrient runoff, nutrient storage, and plant uptake following fertilization of vegetated sedum mats, shoot-established vegetation, and unvegetated substrate. Compared three rates applied as either a controlled release fertilizer (CRF) or as a combination of CRF and conventional fertilizer. Conventional fertilizers caused high concentrations and total nutrient runoff. Established vegetation reduced leaching.
Hathaway et al., 2008	North Carolina, USA	Runoff from two green roofs, a control roof, and rainfall compared for TKN, NO_3 plus NO_2, NH_3, Tot-N, Tot-P, and OP. Total N and P concentrations in the runoff were greatest from the green roof compared to the control roof and rainfall. Total P load was also greatest from the green roof.
Köhler et al., 2002	Germany	Green roof retained 95%, 88%, 80%, and 67% of Pb, Cd, NO_3, and PO_4, respectively. Retention of PO_4 increased from 26% in year one to 80% in year four following installation.
Monterusso et al., 2004	Michigan, USA	Compared sedum to native herbaceous perennials growing on four commercially available drainage systems for NO_3–N and Tot-P in the runoff. Nitrate concentrations in the runoff were higher from the sedum roofs and from those with a shallower substrate depth. There were no significant differences for P.
Steusloff, 1998	Germany	Modeled retention capability of extensive green roofs for heavy metals. Reported 97%, 96%, 92%, and 99% for Cu, Zn. Cd, and Pb, respectively, during the summer and 34%, 72%, 62%, and 91% during winter.
Teemusk and Mander, 2007	Estonia	Compared runoff from green roof and modified bituminous roof for pH, BOD, COD, Tot-P, PO_4, Tot-N, NO_3, NH_4, SO_4, Ca, and Mg). During moderate runoff events values of COD, BOD, and concentrations of total N and P were greater on the bituminous roof. During heavy rain events, components were less concentrated and more nitrates and phosphates were washed off the green roof. All components were higher for the green roof during snowmelt.
US EPA, 2009	Pennsylvania, USA	Compared runoff from green roofs and conventional roofs for pH, EC, turbidity, color, nitrate, P, K, Ca, Fe, Mg, Mn, Na, Zn, and S. Higher concentrations reported for most of nutrients and ions in the runoff, but the loading was not always higher.
Van Seters et al., 2009	Toronto, Canada	Analyzed runoff samples from an extensive green roof for pH, total suspended solids, metals, nutrients, bacteria, and PAH (polycyclic aromatic hydrocarbons). Loads of chemicals were lower than from a conventional roof except for Ca, Mg, and total P.

with other low impact development practices such as rain gardens? We need to ask if green roofs are the most sustainable and cost effective technology for mitigating urban pollution in each situation. Reflective roofs are probably the most logical choice in desert areas such as Arizona. Even so, one must consider all the benefits that green roofs provide. Reflective roofs may be the best and most cost effective choice for energy conservation of an individual building, but they do not do anything for stormwater management, clean the air, deaden sound, or add anything for aesthetics. Furthermore, growing a lush garden with high fertilizer and water inputs may be aesthetically pleasing and provide greater air pollution and energy savings benefits, but it could also result in a higher risk of water pollution.

8.8. *Economics and policy*

What it really comes down to is economics because of the significant cost barrier between green and conventional roofs. Wong et al. (2003) compared the life cycle costs of roof gardens and conventional roofs and determined economic benefits by incorporating energy costs into life cycle costs. Saiz-Alcazar et al. (2006) conducted a life cycle assessment of a green roof in Madrid based primarily on energy savings. Carter and Keeler (2008) conducted a cost benefit analysis for an extensive roof in an urban watershed and determined the net present value (NPV). Kosareo and Ries (2007) compared the environmental impacts of the fabrication, transportation, installation, operation, maintenance, and disposal of a conventional ballasted roof, an extensive roof, and an intensive roof. Clark et al. (2008a) conducted an NPV analysis comparing a conventional roof to a green roof that integrated stormwater, energy, and air pollution benefits of green roofs into an economic model on the scale of a specific building. Niu et al. (2010) built on the work of Clark et al. (2008a) and scaled the benefits at the city wide scale using Washington, DC. Blackhurst et al. (in press) conducted a life cycle assessment using market prices for building materials, construction, energy conservation, stormwater management, and reductions in greenhouse gas emissions to evaluate private and social costs and benefits. Studies such as these are critical for making the economic case for green roofs.

Regarding policy, Carter and Fowler (2008) evaluated existing international and North American green roof policies at the federal, municipal, and community levels and discussed the advantages and disadvantages of regulation, financial incentives, and funding of demonstration or research projects. They then made recommendations on how to successfully implement green roof policy for Athens, GA. If green roofs are to be adopted on a large scale in places like North America, then changes in public policy must be a driver as they are in Germany.

The cost gap between green and conventional roofs can be reduced through research that illuminates the benefits. For example, potential future cap and trade programs for CO_2 would influence energy costs, and in turn improve the green roofs benefits-cost analysis. Further research is necessary to determine the economic impacts of CO_2, as well as non-CO_2 emissions such as NO_x and methane. In addition, other social and environmental benefits of green roofs such as reduced health costs, improved water quality, and other benefits that don't have much to do with pollution such as providing habitat for wildlife and improved aesthetics need to be quantified.

These challenges are not insurmountable, but like most problems we face today, viable solutions require an interdisciplinary team to work together. A horticulturist may look at individual plant species, an engineer may be interested in heat flux through a building envelope, and an architect wants to make sure the building remains standing and does not leak. However, plant selection will influence heat flux and a building's structural integrity will limit the substrate depth and thus plant selection. All of these aspects are connected and thus the need for interdisciplinary research to help mitigate the problems of our built environment. Since roofs represent 21–26% of urban areas (Wong, 2005), they provide a unique opportunity to utilize these typically unused spaces to address pollution concerns while also protecting of our environment through more sustainable practices.

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