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Where and When Soil Amendment is Most Effective as a Low Impact Development Practice in Residential Areas

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Research Impact Statement: Amending soil on as little as 1.5% of sloped yard near disconnected impervious features can reduce runoff by up to 17% when existing soil infiltration is low; this could be promoted as a LID practice.

ABSTRACT: Improving the infiltration capacity of urban soil is critical for effective stormwater management, but existing guidance on soil amendment in residential areas typically calls for tilling and amending soil throughout the entire yard, an approach that is most feasible during development or redevelopment. To develop guidance on less-extensive soil amendment interventions which a homeowner could implement postconstruction, we designed a modeling study to compare four scenarios targeting soil amendment in a single-family yard (1) at disconnected impervious features, (2) at locations with large upslope drainage areas, (3) at locations with a high topographic wetness index (TWI), and (4) randomly (control). We find that soil amendment may be ineffective at reducing runoff from residential areas with high near-surface infiltration rates (e.g., $K_{\text{sat}} > 1 \times 10^{-2}$ m/hr), but can reduce runoff by 46%–73% (up to 15% of precipitation) on yards with lower near-surface infiltration rates. We find that targeting amendment at interfacial hotspots near disconnected impervious surfaces can reduce runoff by over 10× more than amending a random equivalent area and by at least 2× more than targeting amendment by drainage area or TWI. We suggest including this intervention in the suite of low impact development practices promoted to residential property owners since it effectively and efficiently reduces runoff and may appeal to homeowners who are wary of maintenance needs of other practices.

(KEYWORDS: urban hydrology; soils; green infrastructure; stormwater management; urban planning; topographic wetness index.)

INTRODUCTION

Stormwater management is a persistent challenge in urban areas because conventional urban development limits infiltration and thereby increases both runoff and pollutant loads (Walsh et al. 2005). The most conspicuous way urbanization reduces infiltration and leads to hydrologic concerns is through the addition of paved streets, roofs, and other impervious surfaces which seal the landscape (Shuster et al. 2005). Fewer opportunities for infiltration paired with efficient urban drainage networks lead to "flashy" runoff that transports nutrients and pollutants from an array of urban nonpoint sources directly to streams, lakes, and other receiving bodies of water (Carpenter et al. 1998; Gobel et al. 2007). To address increased runoff from impervious surfaces as well as associated problems such as flooding, pollution, and aquatic degradation (Walsh et al. 2005), some stormwater management practices route runoff from impervious surfaces to nearby pervious areas such as yards or medians, an intervention known as "disconnecting" impervious surfaces from the stormwater

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drainage network (Mueller and Thompson 2009; Roy and Shuster 2009). Impervious disconnection is sometimes accompanied by changes to soil, such as when a rain garden or bioretention swale is constructed using engineered soil, but often it is simply assumed that the existing soil in the yard, median, or other urban pervious space is capable of infiltrating much of the runon from the impervious surface.

Urban soils are highly disturbed and can be another important, if less visible, way in which urbanization alters infiltration. Urban soil becomes disturbed during development activities such as excavation, filling, and grading, all of which rapidly reshape soil and disrupt soil-forming processes and soil structure. As a result of this disturbance, urban soil profiles typically lack resource-rich intermediate soil horizons (Herrmann et al. 2018) and rarely match published soil maps (Pitt et al. 2008; Schifman et al. 2018). In addition, compaction from construction and homeowner activities often reduces infiltration rates by a factor of 2–10 or more in residential areas (Gregory et al. 2006; Pitt et al. 2008; Woltemade 2010). These disturbances are not captured in common soil hydraulic property prediction tools (Schifman and Shuster 2019) and soil physical properties can be as variable within an urban site as among sites (Ziter and Turner 2018), so it is difficult to estimate infiltration rates at any given urban location. However, in aggregate, there is evidence that urban pervious areas are limited by their infiltration capacity and can be an important source of runoff. For example, pervious spaces in low-density urban areas (approximately 30% impervious cover) can generate more total runoff than impervious areas (Burges et al. 1998) and the runoff response of developed open space can be more like that of impervious surfaces than natural spaces (Lim 2016). Furthermore, urban pervious areas that are compromised in their ability to infiltrate rainfall are less likely to be able to accommodate runon from impervious surfaces either. It follows that improving the infiltration capacity of urban soil is critical for effective impervious disconnection and stormwater management.

Interventions that modify urban soils and increase infiltration capacity are often implemented during construction when it is easier to use large equipment to manipulate soil (Olson et al. 2013). During conventional development, earthwork such as excavation, fill, and grading is followed by capping disturbed subsurface soils with a thin (e.g., 5–10 cm) layer of topsoil (Schwartz and Smith 2016). A low impact development approach instead leaves native vegetation and soils undisturbed where feasible and otherwise follows conventional earthwork with tillage, soil amendment, or both (Stenn 2018). Tillage involves either deep ripping to depths of 60 cm (Balousek 2003; Olson et al. 2013; Schwartz and Smith 2016) or shallower techniques such as chisel plowing (Balousek 2003) or rototilling (Chen et al. 2014) to around 20 cm. This is often paired with incorporating a soil amendment such as compost to achieve a ratio of 2:1 compost-to-soil in the top 15–30 cm of topsoil (Balousek 2003; Cogger 2005; Pitt et al. 2005; Schwartz and Smith 2016). Tillage alone yields mixed results (Balousek 2003; Olson et al. 2013), but the addition of a soil amendment consistently improves infiltration rates by a factor of 2–10 (Pitt et al. 2005; Chen et al. 2014; Schwartz and Smith 2016). Throughout the remainder of this paper, we define soil amendment as thoroughly mixing in compost or another material with a high infiltration capacity into the soil by hand or by machine in order to increase infiltration rates. We are not considering the effects of tilling alone, recycling lawn clippings, dethatching, core aerating, or topdressing, which are sometimes also considered to be forms of soil amendment (e.g., Balousek 2003; Olson et al. 2013; Milwaukee Metropolitan Sewerage District 2018).

While soil amendment is clearly an effective means of restoring soil hydrologic function during construction or major renovation projects, it is unrealistic to expect a homeowner to voluntarily secure heavy machinery and attempt the same practices at the scale of a residential lot. However, many homeowners are willing to amend soil by hand for much smaller low impact development practices, such as rain gardens. Rain gardens are designed to store, infiltrate, and evapotranspire runoff from roofs and other impervious surfaces and typically feature native vegetation planted in a slight depression with amended or engineered soil (WSOC and WDNR 2018). Rain gardens are generally very effective (Selbig and Balster 2010) and are embraced by many citizens, but others remain concerned about the possibility of standing water and insects as well as the need for maintenance to prevent weedy or trashy appearances (Gao et al. 2018). Interestingly, there is some evidence that much of the hydrologic function of rain gardens are driven by their engineered soils and enhanced infiltration capacity (Selbig and Balster 2010), so requiring depression storage (which sometimes leads to standing water) and native vegetation (which can require weeding) in low impact practices may not be necessary in order to realize hydrologic benefits.

The effectiveness of rain gardens is tied not only to their engineered soils, but also to where they are usually situated: at the interface between impervious and pervious surfaces. Voter and Loheide (2018) identify hot spots of infiltration at impervious-pervious interfaces that drive the parcel-scale hydrologic changes that result from impervious disconnection; using the definition provided by Krause et al. (2017), these hotspots should be considered a key ecohydrologic interface because of the outsized effects they have on residential ecohydrology. In addition, a previous modeling study of a single-family parcel in a humid climate typical of the Midwest with 25% impervious cover and compacted silt loam soil indicates that when impervious disconnection is paired with soil amendment throughout the entire yard, the practices have a synergistic effect on hydrology, changing hydrologic fluxes by up to 2× more than would be expected from summing the effects of individual practices (Voter and Loheide 2018). This indicates that homeowners who have already disconnected impervious surfaces on their property may be able to further reduce runoff from their yard by simply amending soil at these hotspots. If true, this could provide homeowners a way to further reduce runoff from their yard that requires less effort than amending the entire yard, less earthwork than creating a depression for a rain garden, and less ongoing maintenance associated with weeding around native plants. While rain gardens and entire-yard amendment are likely to remain the gold-standard for reducing runoff, a simpler approach may appeal to homeowners whose concerns about these practices (Gao et al. 2018) are difficult to dispel.

An alternate approach of targeting soil amendment at small areas of the yard could be to focus on areas with a high drainage area or topographic wetness index (TWI). These topographic metrics also have a strong relationship with runoff: the drainage area describes how much land is upslope of a given location and may contribute to runoff at that point, while the TWI accounts for both this upslope drainage area and the slope at a given location ($\ln(a/\tan\beta)$; a is the upslope drainage area, β is the local slope) so that locations with high drainage areas which are also flat have the highest TWI (Beven and Kirkby 1979). Topographic metrics like drainage area or TWI are typically well-correlated with spatial soil moisture patterns, groundwater levels, and other ecohydrologic processes (Sorensen et al. 2006) and are used in hydrologic models such as TOP-MODEL to predict runoff (Beven and Kirkby 1979). Using these topographic indices to identify areas within a yard with high soil moisture may also allow homeowners to target soil amendment at small areas.

To explore where shallow soil amendment (top 20 cm) is most effective as a low impact development practice in residential areas, we designed a modeling study that compared the hydrologic effects of amending soil (1) randomly, (2) by drainage area, (3) by TWI, and (4) near disconnected impervious features in a single-family yard. This allowed us to examine the relative benefits of targeting soil amendment at known drainage pathways vs. targeting amendment at more easily identified impervious-pervious interfaces. To understand what baseline soil conditions are required for soil amendment to be an effective low impact practice, we repeated these model simulations for three types of baseline soil: a loam soil with hydraulic properties as measured in a residential neighborhood in Milwaukee, Wisconsin; a loam soil with literature-based hydraulic properties; and a clay loam soil with literature-based hydraulic properties. In order to focus on the benefit that soil amendment may provide in addition to impervious disconnection, simulations featured a single-family parcel where all impervious surfaces are already disconnected.

METHODS

Single-Family Residential Parcel

We designed all model simulations around a single-family parcel that is representative of residential properties in many Midwestern cities. This parcel is 25% impervious and identical in layout to the lowest impact lot (with all impervious surfaces disconnected) that was modeled in Voter and Loheide (2018). Using this layout allowed us to focus on the added benefit soil amendment may provide to efforts to reduct runoff from single family homes. In the modeled parcel, the yard slopes away from the house in all directions at a 2% grade with added microtopography. Impervious features include the house and attached garage ($151.5\ m^2$), which are disconnected via four downspouts; the driveway (3×9.5 m), which has a 2% transverse slope to the yard in addition to the 2% slope to the street; the front walk (0.5 m wide), which also has a 2% transverse slope to the yard; and the sidewalk (1 m wide), which is separated from the street with a 2 m grass curb strip (Figure 1; Table 1). For additional details about the lot layout, see Voter and Loheide (2018).

Field Data Collection

To design baseline soil scenarios, we used soil texture observations and measurements of saturated and near-saturated hydraulic conductivity and at six residential blocks in Milwaukee, Wisconsin. We measured saturated hydraulic conductivity using a Turf-Tec double ring infiltrometer (Turf-Tec Infiltrometer IN2-W; Turf-Tec International, Tallahassee, Florida) at three properties in each residential block. Sites were presaturated by filling a metal cylinder slightly larger than the Turf-Tec up to three times before

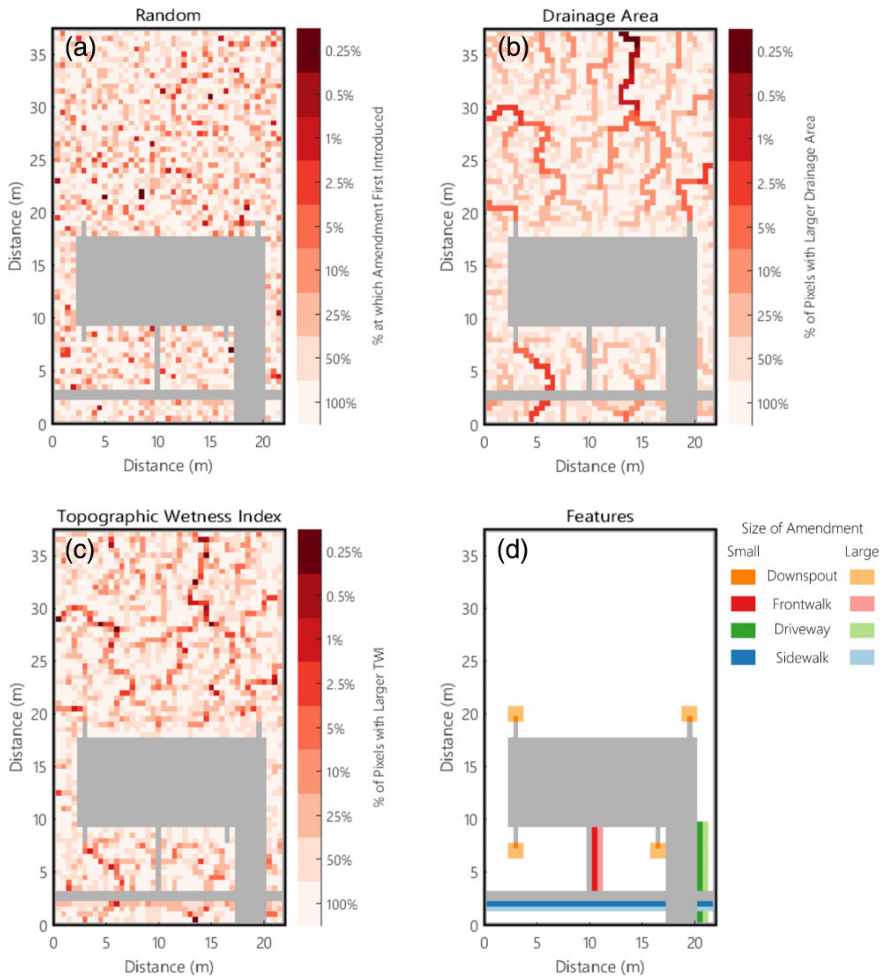

FIGURE 1. Location of amended soil for random amendment (a) drainage area-based amendment (b), topographic wetness index (TWI)-based amendment (c), and impervious feature-based amendment (d) scenarios. Black arrows in (d) indicate the direction of flow across impervious surfaces (same in all scenarios).

TABLE 1. Area of impervious features.

Impervious feature	Drained area (m^2)
Downspouts (each)	36–40.5
Sidewalk	19
Driveway	28.5
Frontwalk	3

beginning tests. We performed a series of 15 min tests until the same infiltration rate was recorded twice. We measured near-saturated hydraulic conductivity using tension infiltrometers (Mini Disk Infiltrometer; METER Group, Inc., Pullman, Washington) at three locations within each of the three properties in each residential block. Suction head was set to −2 cm for all tests, following the protocols of USEPA (2016). We also performed a qualitative textural analysis of soils at each location within each property (Thien 1979). Most sites (45/54) were clayey (clay, clay loam, sandy clay, silty clay, or silty clay loam). However, at the area of interest chosen for this paper, most sites (7/9) were loam.

Hydrologic Model

We ran all models using ParFlow.CLM, a process-based hydrologic model which couples 2D kinematic wave overland flow to 3D variably saturated subsurface flow and accounts for vegetation processes using the Community Land Model (Ashby and Falgout 1996; Jones and Woodward 2001; Maxwell and Miller 2005; Kollet and Maxwell 2006, 2008). We used a 0.5 m horizontal spatial resolution and a variable vertical resolution with the top 15 elements at 0.1 m, followed by two elements at 0.25 m, 12 elements at 0.5 m, six elements at 0.25 m, and the bottom five elements at 0.1 m. The high resolution of our domain and complex coupling of hydrological processes results in very resource intensive models; each of our 108 simulations required 3–5 days to run using resources at the UW-Madison Center for High Throughput Computing. This approach is important for capturing (1) the lateral transfer of water from disconnected impervious surfaces to the yard and (2) the three-dimensional diffusion of wetting fronts in soil with mixed distributions of amended and unamended soil.

Models are forced with hourly atmospheric inputs for April 1–November 1, 2017 for Milwaukee, Wisconsin from the North American Land Data Assimilation System-2 (NASA 2015), which is considered an average year in Milwaukee, Wisconsin (Milwaukee Metropolitan Sewerage District, personal communication, 2019). Initial conditions were developed by forcing a 1D model of turfgrass with silt loam soil with 300 years of hourly meteorological inputs for the area (10 loops of WY1981–WY2010) and using the vertical pressure head profile on April 1 of the last simulated year. All boundary conditions are as in Voter and Loheide (2018), including the constant pressure head boundary condition of zero at the bottom of the domain (i.e., a 10 m deep water table), since regional water table maps suggest a water table 6–24 m deep throughout much of the city including the sites where soil measurements were collected (SWRPC and WGNHS 2002).

Model parameterization is informed by observed conditions in a temperate urban area (Milwaukee, Wisconsin), with weather inputs, boundary conditions, percent impervious cover, and soil characteristics all based on observations. However, simulations are not designed to represent a specific residential parcel and thus are not calibrated to surface runoff or soil moisture data at a specific site. Instead, this study is designed to be a sensitivity analysis of the relative effects of (1) baseline soil condition, (2) extent of soil amendment, and (3) approach to targeting soil amendment. Confidence in results therefore requires confidence that fundamental physics are well-represented in ParFlow. Recent intercomparisons of ParFlow and six other integrated hydrologic models for several benchmark scenarios, including flow across semi-impervious "slabs" with adjacent infiltration (comparable to runon to a yard from disconnected impervious surfaces), indicate that there is remarkable agreement in temporal dynamics, particularly for unsaturated and saturated storage and infiltration-excess runoff, though absolute values can vary across models (Kollet et al. 2017). We honor the limits of this uncalibrated sensitivity study by focusing exclusively on the relative differences in runoff among scenarios in our analysis. All our simulations closed the water balance (input precipitation vs. simulated outflows plus changes in storage) with a cumulative error of <0.1 mm, or 0.02% of precipitation.

Baseline Soil Scenarios

On the basis of field data, we developed three baseline soil scenarios to be representative of the urban soils in the area of interest as well as the broader Milwaukee area (Table 2). The measured soil scenarios use the geometric mean of saturated hydraulic conductivity measurements and the standard deviation of the log of near-saturated hydraulic conductivity measurements for the selected area of interest, with other soil hydraulic parameters based on literature values for loam soils (Carsel and Parrish 1988). As a sensitivity analysis, and to characterize the effect of the large uncertainty associated with estimating the hydraulic conductivity of urban soils, the loam soil scenarios and the clay loam soil scenarios are both based on literature values for the soil texture (Carsel and Parrish 1988) with log-transformed saturated hydraulic conductivity parameters (Quan and Zhang 2003). These three baseline soil scenarios capture a 1.5 order of magnitude range in saturated hydraulic conductivity. Hydraulic conductivity for near-surface impervious surfaces is based on literature values for paved surfaces (Wiles and Sharp

TABLE 2. Modeled soil parameters.

Soil parameter	Units	Measured soil	Loam soil	Clay loam soil	Amended soil	Impervious surfaces
Saturated hydraulic conductivity (K_{sat}), mean	m/hr	4.75×10^{-2}	5.16×10^{-3}	9.05×10^{-4}	1.15	1×10^{-4} (top 20 cm) 3.6×10^{-9} (below 20 cm)
Saturated hydraulic conductivity (K_{sat}), log standard deviation	log m/hr	0.33	1.18	1.45	—	—
Porosity	m^3/m^3	0.43	0.43	0.41	0.42	0.01
Saturated moisture content	—	1.00	1.00	1.00	1.00	1.00
Residual moisture content	—	0.19	0.19	0.23	0.10	0.01
Van Genuchten α	1/m	3.60	3.60	1.90	1.56	2.00
Van Genuchten n	—	1.56	1.56	1.31	1.39	3.00

2008) and is near-zero for basements and foundations.

Amended Soil Scenarios

Amended soil parameters are based on measured saturated hydraulic conductivity, bulk density, and moisture holding capacity for engineered soil with sand, compost, and topsoil for bioretention basins (Thompson et al. 2008) with additional parameters estimated from soil pedotransfer software (Schaap et al. 2001). Where present, amended soil only replaces the top 20 cm of the subsurface; the baseline soil always remains below the top 20 cm.

We explored four approaches to targeting shallow soil amendment (top 20 cm): (1) randomly, (2) at areas with the greatest upslope drainage area, (3) at areas with the greatest TWI, and (4) by proximity to disconnected impervious surfaces (Table 3).

We used the first three approaches to select an increasing fraction of the yard to amend, ultimately amending 0.25%, 0.5%, 1%, 2.5%, 5%, 10%, 25%, 50%, and 100% of the yard. While it is unlikely that a homeowner would choose to amend ≥10% of the yard, we included these scenarios to more completely characterize the relationship between reduction in runoff and incremental area amended. With the drainage area and TWI approaches, we first ranked all parcel soil pixels by each metric such that the top-ranked pixel represented the pixel with the greatest drainage area or the largest TWI, then selected an increasing fraction of soil pixels to amend from this ranking (top 0.25%, 0.5%, 1%, 2.5%, 5%, 10%, 25%, and 50%; Figure 1b, 1c; Table 3).

We used the fourth approach to explore targeting soil amendment at the interfaces between impervious and pervious areas (Figure 1d; Table 3). At each impervious feature, we tested two levels of amendment: small and large. For the downspouts, the small

TABLE 3. Modeled amendment scenarios.

Amendment type	Scenario name	Percent of yard	Description
Entire yard	Yard 0%	0	None of yard amended
	Yard 100%	100	Entire yard amended (top 20 cm)
Random	Random 0.25%	0.2	X% of yard pixels randomly selected for amendment
	Random 0.5%	0.5	
	Random 1%	1	
	Random 2.5%	2.5	
	Random 5%	5	
	Random 10%	10	
	Random 25%	25	
	Random 50%	50	
Drainage area	Drainage area 0.25%	0.25	Top X% of yard pixels by drainage area amended
	Drainage area 0.5%	0.5	
	Drainage area 1%	1	
	Drainage area 2.5%	2.5	
	Drainage area 5%	5	
	Drainage area 10%	10	
	Drainage area 25%	25	
	Drainage area 50%	50	
TWI	TWI 0.25%	0.25	Top X% of yard pixels by TWI amended
	TWI 0.5%	0.5	
	TWI 1%	1	
	TWI 2.5%	2.5	
	TWI 5%	5	
	TWI 10%	10	
	TWI 25%	25	
	TWI 50%	50	
Feature	Downspout — small	0.2	0.5 m × 0.5 m area amended at each downspout outlet
	Downspout — large	1.5	1.5 m × 1.5 m area amended at each downspout outlet
	Frontwalk — small	0.5	0.5 m strip amended downslope of frontwalk
	Frontwalk — large	1.0	1 m strip amended downslope of frontwalk
	Driveway — small	0.7	0.5 m strip amended downslope of driveway
	Driveway — large	1.5	1 m strip amended downslope of driveway
	Sidewalk — small	1.5	0.5 m strip amended downslope of sidewalk
	Sidewalk — large	3.1	1 m strip amended downslope of sidewalk
	All — small	2.9	Small downspout, frontwalk, driveway, and sidewalk
	All — large	4.2	Large downspout, frontwalk, driveway, and sidewalk

amendment was a 0.5 × 0.5 m area at the outlet of each downspout (0.2% of the yard), while the large amendment was a 1.5 × 1.5 m area (1.5% of the yard). For all other features, the small amendment targets a 0.5 m strip of soil adjacent to the feature (0.5% of the yard at the front walk, 0.7% at the driveway, 1.5% at the sidewalk) and the large amendment targets a 1 m strip (1.0% of the yard at the front walk, 1.5% at the driveway, 3.1% at the sidewalk). In addition to simulating each intervention separately, we also simulated the combination of all small and all large feature-based amendments. Feature-based scenarios amend 0.2%–4.2% of the yard (Table 3). We assume that the yard retains its original slope after soil amendment and that depressions are not introduced during this process.

RESULTS

Baseline Water Balance

Prior to soil amendment (Figure 2a), runoff from the lot (street excluded) is not a major component of the growing season water balance (April–November) for the measured soil scenario (2% of growing season precipitation), however, it is for the loam soil (14%) and the clay loam soil (34%). This result confirms that the effectiveness of impervious disconnection strongly depends on the saturated hydraulic conductivity (K_{sat}) of the soil, which in these scenarios ranges from 4.75×10^{-2} m/hr (measured soil) to 5.16×10^{-3} m/hr (loam) to 9.05×10^{-4} m/hr (clay loam). As runoff increases, deep drainage decreases (53% measured soil, 44% loam, 18% clay loam), which is an expected outcome for this temperate location (Voter 2019). Evapotranspiration (ET) equates to about 50% of precipitation for the growing season, with only slightly higher values in the more retentive soils.

Amending the Entire Yard

Replacing the top 20 cm of the entire yard with amended soil reduces growing season runoff by 46%–73% in all soil types (Figure 2b). However, in the loam and clay loam soils, this equates to a reduction of 9% (loam) to 15% (clay loam) as a percent of precipitation, while amending the measured soil only reduces runoff by 1% as a percent of precipitation. The remaining baseline soil (at depths below 20 cm) continues to influence surface runoff, which remains the highest in the clay loam soil (18% as a percent of precipitation), followed by the loam soil (5%), and the measured soil (1%). The reduction in runoff is generally offset by an increase in deep drainage, a typical hydrologic response to low impact practices in temperate areas (Voter 2019). However, ET is slightly higher when the top 20 cm of soil is replaced by the more retentive amended soil.

Amending Randomly, by Drainage Area, or by TWI

In all cases, amending by drainage area or TWI is more effective than random amendment (Figure 3). This pattern emerges more clearly when we present the change in growing season runoff relative to the maximum possible reduction in runoff for each baseline soil scenario (Figure 3d–3f), instead of presenting only the absolute change in runoff as a percent of precipitation (Figure 3a–3c). The effectiveness of targeting drainage pathways is also encompassed in the distance between plotted model results and the one-to-one lines in Figure 3d–3f. A result which plots on the one-to-one line would indicate that every soil pixel in the yard contributes equally to runoff and cannot accept runon, that is, the yard behaves like an impervious surface and there is no added benefit to targeting amendment on the drainage pathways enhanced by runon from impervious surfaces. The clay loam soil scenarios ($K_{sat} = 9.05 \times 10^{-4}$ m/hr) plot

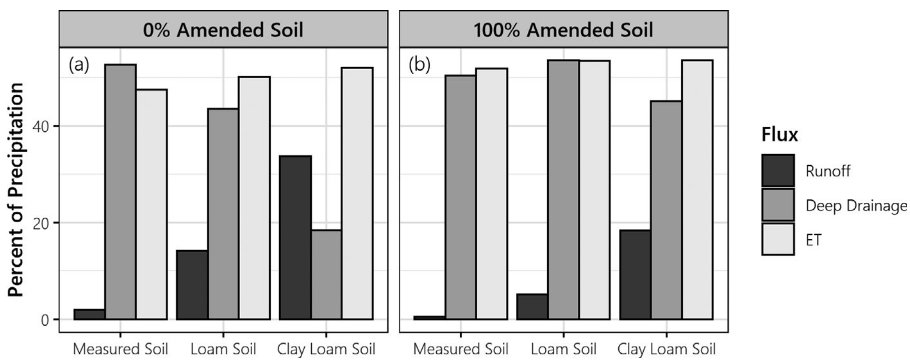

FIGURE 2. Water balances for the 0% amendment (a) and 100% amendment (b) scenarios for all three soil types. Runoff, deep drainage, and evapotranspiration (ET) are presented as a percent of total growing season precipitation.

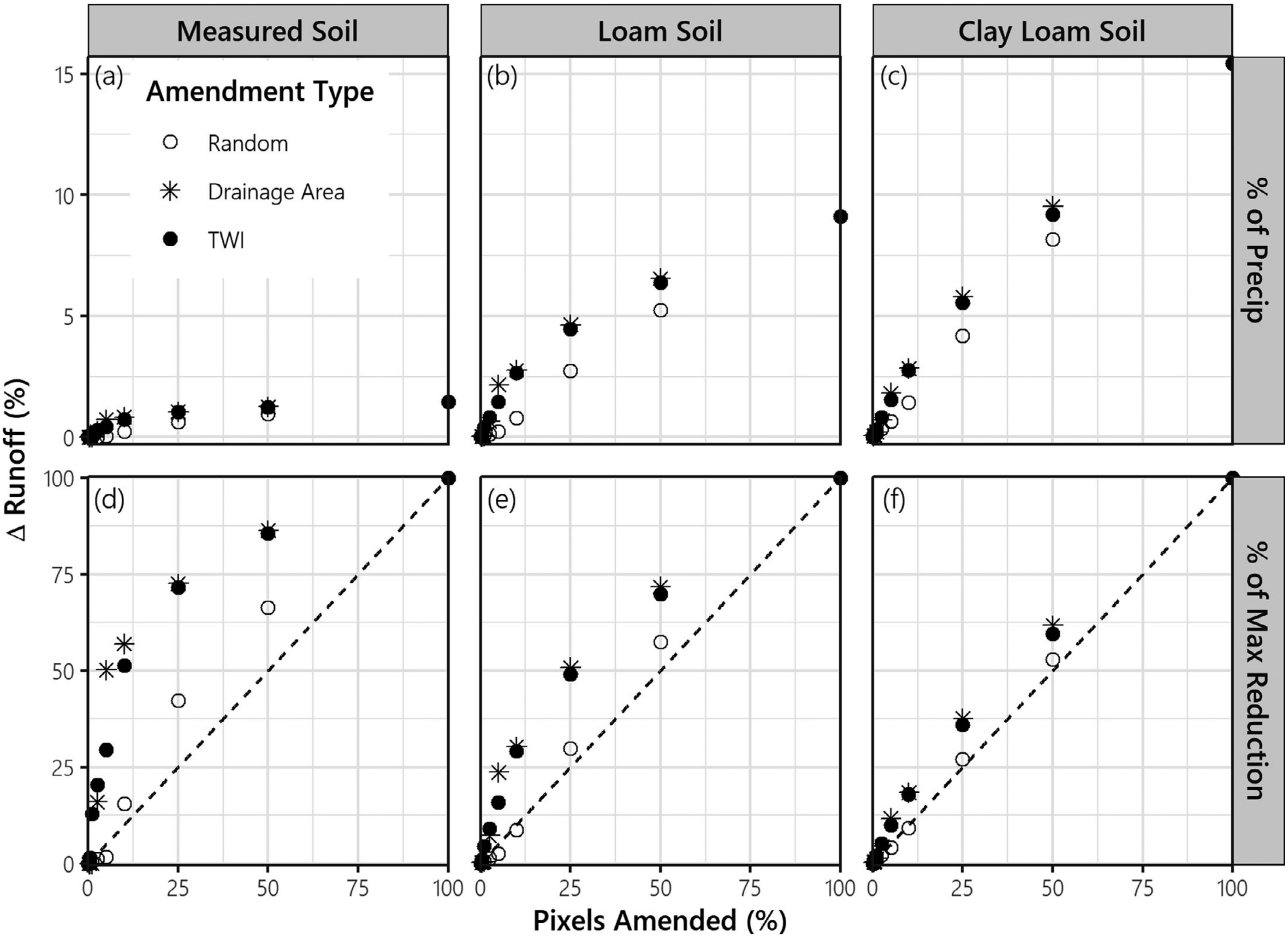

FIGURE 3. Reduction in runoff as a percent of precipitation (a–c) and as a percent of the maximum reduction in runoff (d–f) for the drainage-based amendment scenarios for each soil type. Dashed line indicates one-to-one relationship between the percent of pixels amended and the change in runoff as a percent of the maximum reduction.

most closely to this line, followed by the loam soil scenarios ($K_{sat} = 5.16 \times 10^{-3}$ m/hr) and the measured soil scenarios ($K_{sat} = 4.75 \times 10^{-2}$ m/hr), though all remain above it. Notably, all the random amendment scenarios which amend 25% or more of the yard also plot above the one-to-one line. This indicates that amending a random 10%–25% of the yard captures some drainage pathways, even when their exact location is unknown.

As an increasing portion of the yard is amended based on drainage area or TWI, there are diminishing returns on the corresponding reduction in growing season runoff (Figure 3). Much of the reduction in runoff is achieved by the highest priority pixels in terms of drainage area or TWI. For example, amending the top 25% of soil pixels based on drainage area or TWI leads to approximately 73% of the maximum reduction in runoff with measured soil (Figure 3d), 50% of the maximum reduction with loam soil (Figure 3e), and 37% of the maximum reduction in runoff with clay loam soil (Figure 3f). Because the measured soil has a much lower maximum reduction in runoff, amending 25% of soil pixels on measured soil leads to only a 1% change in runoff as a percent of precipitation (Figure 3a) compared with 5% for loam soil (Figure 3b) or 6% for clay loam soil (Figure 3c). In other words, in soils with higher infiltration capacity, the relative benefit of targeting amendment at drainage paths is higher, but the net runoff reduction is lower. As the extent of amendment increases beyond the highest priority pixels in terms of drainage area or TWI, there is less of a difference between the drainage area or TWI approach and the random approach, since many of the highest priority drainage area or TWI pixels are incidentally amended via the random approach by the time 50% or 75% of the yard is amended.

Amending at Impervious Features

Both the combined and the downspout feature-based scenarios plot substantially above the drainage area- and TWI-based scenarios, which indicate that it can be even more effective to target soil amendment near impervious features than to target locations with the highest drainage area (Figure 4). This may be because amending part of a drainage pathway can be sufficient to manage overland flow; the drainage area and TWI scenarios tend to incrementally add area along the same drainage pathways as an increasing fraction of the yard is amended (Figure 1). Targeting soil amendment at sidewalks is comparable to the drainage area- and TWI-based scenarios, but amending soil near the frontwalk and driveway is only marginally effective; these scenarios plot on or near the one-to-one line (below the drainage area and TWI scenarios) for all soil types. Amendment effectiveness is driven by the area of the targeted impervious feature (Table 1) as well as its position relative to other impervious features. For example, while the sidewalk is smaller than the driveway, amended soil at the sidewalk also intercepts some runoff from the front downspouts and the frontwalk due to the slope of the yard (Figure 1).

Area Amended vs. Reduction in Runoff

To examine the relationship between effort (i.e., size of amended area) and reduction in runoff, we compared the reduction in growing season runoff from amending one entire yard to the reduction in growing season runoff from amending an equivalent area spread out across targeted locations on multiple yards (Figure 5). For example, amending the top 10% of the yard in terms of drainage area or TWI at 10 parcels results in a total amended area equivalent to amending 100% of one yard. The factor of improvement is then the ratio of the total reduction in runoff from amending 10% of ten parcels vs. the reduction in runoff from amending 100% of one parcel. If this factor of improvement is greater than one, it indicates that spreading out effort across multiple homeowners can reduce runoff more than asking one homeowner to amend their entire yard. At the most extreme end, this tradeoff in "effort" is questionable; amending 0.2% of 500 parcels is probably much more difficult than amending 100% of one parcel. However, at intermediate levels there are clear benefits to targeting soil amendment and spreading out effort across multiple parcels. For example, persuading 70 households to amend a 1.5 × 1.5 m area at their downspouts could reduce runoff by 33× (measured soil), 17× (loam soil), or 6× (clay loam soil) more than amending 100% of one parcel (Figure 5).

DISCUSSION

When Soil Amendment is Most Effective

Shallow soil amendment (≤20 cm) may not be effective at reducing runoff in some urban parcels with a

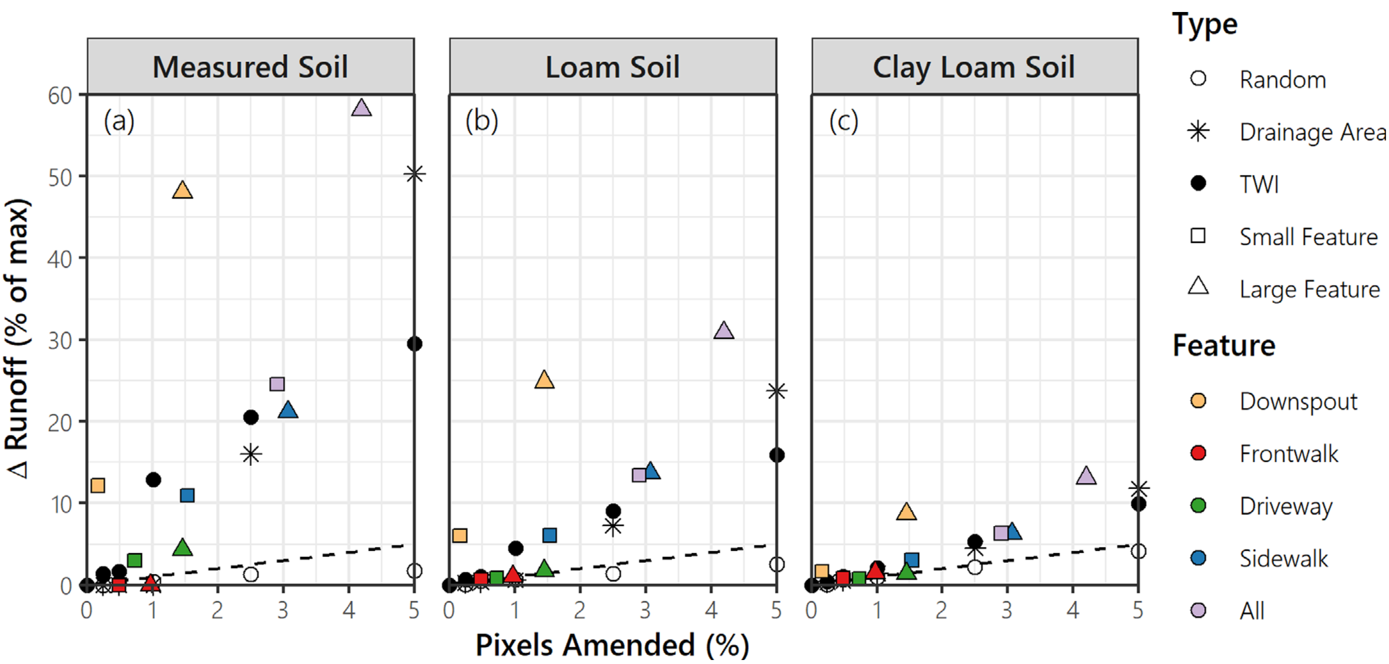

FIGURE 4. Reduction in runoff as a percent of the maximum reduction in runoff (a-c) as in Figure 3d–3f, but with feature-based amendment scenarios added and the x-axis limited to the region of interest.

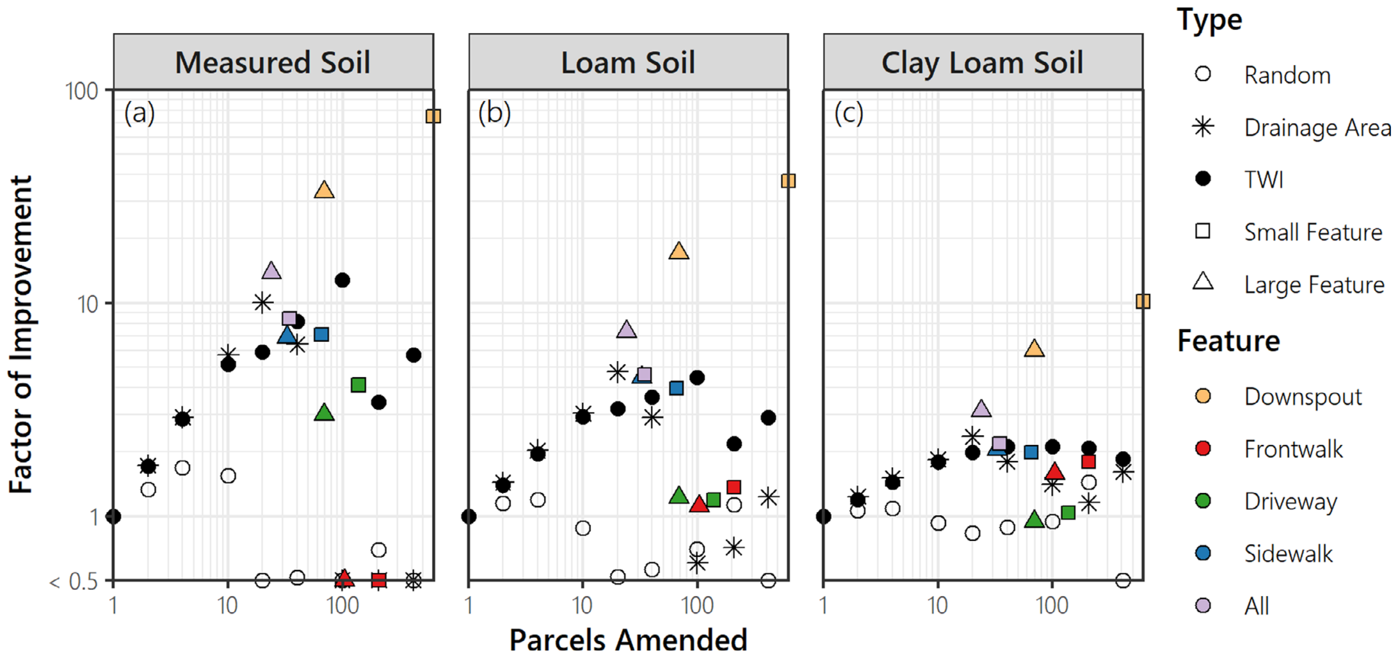

FIGURE 5. Factor of improvement relative to amending 100% of one parcel when amending an equivalent area spread out across multiple parcels with measured (a), loam (b), or clay loam (c) baseline soil.

high infiltration capacity because little runoff is generated from these parcels. In this study, modeled parcels based on measured soil hydraulic properties at Milwaukee residential parcels produced negligible runoff (2% as a percent of precipitation) even without soil amendment (Figure 2a). In our simulations, this heterogeneous loam soil had a mean K_{sat} of 4.75×10^{-2} m/hr, which is within the range of values reported by other studies of urban soil infiltration rates. For example, Woltemade (2010) recorded median infiltration rates of 4.2×10^{-2} m/hr at residential sites with loam and silt loam soils in central Pennsylvania. Similarly, based on the United States Environmental Protection Agency (USEPA)'s assessment of hydraulic conductivity at over 400 parcels in 12 United States (U.S.) cities, Schifman and Shuster (2019) report median near-saturated hydraulic conductivity ($K_{near\text{-}sat}$) above 1.0×10^{-2} m/hr in six cities and median K_{sat} above 1.0×10^{-2} m/hr in three cities. It is possible that runoff might be more substantial on the parcels with high near-surface infiltration rates if a low-K_{sat} layer of soil was present at depth. Low-K_{sat} layers can impede vertical drainage, create a perched water table and limit the effectiveness of infiltration-based low impact development practices (Selbig and Balster 2010) and our own simulations illustrate that the unamended K_{sat} of soil below 20 cm influences runoff even when 100% of the top 20 cm of soil is amended (Figure 2b). However, a homeowner would not penetrate deep low-K_{sat} soil layers with shallow tilling and amendment. Thus, the soil amendment interventions we simulated are not a useful low impact development practice on residential areas with high near-surface infiltration rates (e.g., mean $K_{sat} > 1 \times 10^{-2}$ m/hr); runoff from these yards is already inconsequential.

However, soil amendment can be an effective and important means of reducing runoff when existing soil has a low mean near-surface infiltration rate. The hydraulic conductivity values used for the loam and clay loam soil scenarios (mean $K_{sat} = 5.16 \times 10^{-3}$ m/hr for loam; mean $K_{sat} = 9.05 \times 10^{-4}$ m/h for clay loam) are lower than the measured values from this study, but still well within the range of what has been measured at urban residential properties. For example, the median infiltration rate measured by Woltemade (2010) on newer properties (<10 years old) was 7.0×10^{-3} m/hr. Similarly, Schwartz and Smith (2016) recorded a mean infiltration rate of 5.9×10^{-3} m/hr on a conventionally developed field in Baltimore, Maryland. Importantly, six of the 12 cities included in the USEPA assessment of urban soil hydrologic conductivity have median $K_{near\text{-}sat}$ between 2.0×10^{-3} m/hr and 7.0×10^{-3} m/hr and eight of the cities have median K_{sat} between 1.0×10^{-3} m/hr and 4.0×10^{-3} m/hr (Schifman and Shuster 2019). Our model simulations indicate that shallow soil amendment on properties with low K_{sat} values (within the ranges above) could increase the degree to which impervious disconnection reduces runoff by 9% as a percent of precipitation (64% relative to baseline runoff; loam $K_{sat} = 5.16 \times 10^{-3}$ m/

hr), 15% as a percent of precipitation (46% relative to baseline runoff; clay loam K_{sat} = 9.05 × 10^{-4} m/h), or more for sites with lower infiltration rates. This aligns with results from previous studies which have emphasized that the effectiveness of disconnection-type low impact development practices depends on the hydrologic conductivity of existing soil (Schifman et al. 2018) and may do little to reduce runoff unless paired with soil amendment (Voter and Loheide 2018).

Furthermore, our study demonstrates that the threshold at which soil amendment becomes relevant is around K_{sat} = 1.0 × 10^{-2} m/hr for a temperate city like Milwaukee, Wisconsin. Our results highlight a clear transition between a soil with K_{sat} = 4.75 × 10^{-2} m/hr (measured soil), which produces very little runoff even without amendment, and a soil with K_{sat} = 5.16 × 10^{-3} m/hr (loam), on which shallow soil amendment can reduce runoff by up to 9% as a percent of precipitation. The threshold may vary depending on local climate and typical storm intensity (Voter 2019); for example, a region with higher storm intensities may have a transition at higher K_{sat} values. However, we expect that at all locations there exists a threshold in baseline K_{sat} values above which soil amendment has little effect, but below which soil amendment is a beneficial low impact practice.

Where Soil Amendment is Most Effective

When infiltration rates are sufficiently low that shallow soil amendment is an effective low impact development practice, it is possible to target soil amendment at easily identified locations within a yard to reduce effort, but still realize hydrologic benefits. Based on our model results, targeting drainage pathways is always more efficient than randomly amending equivalent portions of the yard. This can be seen in Figure 2e, 2f, where all drainage area and TWI scenarios plot above the randomly selected scenarios, as well as in Figure 5b, 5c, which shows that targeting portions of the yard with the highest drainage area across multiple parcels can reduce runoff by up to 4.7× (loam soil) or 2.4× (clay loam soil) more than amending the entire yard on one parcel. We recognize that drainage pathways can be difficult to identify for a given parcel without specific knowledge of downspout locations and high-resolution elevation information. Fortunately, our study shows that it can be even more effective to target more easily identified impervious features such as downspouts and sidewalks, with factors of improvement as high as 37.4× (loam soil) and 10.2× (clay loam soil) if a small area is amended at downspout outlets (Figure 5). The best impervious features to target on the parcel modeled in this study are disconnected downspouts and sidewalks, which correspond with the areas on this parcel that intercept the most runon from impervious surfaces. These findings confirm previous evidence that impervious-pervious interfaces are important interfacial hotspots that substantially influence larger-scale urban hydrology (Krause et al. 2017; Voter and Loheide 2018). Our results demonstrate that it is effective to improve infiltration just at these ecohydrologic interfaces in order to appreciably reduce runoff (Figure 4).

Implications for Residential Low Impact Development Practices

Our study indicates that soil amendment, a low impact development practice known to be effective during development or redevelopment (Balousek 2003; Olson et al. 2013; Chen et al. 2014; Schwartz and Smith 2016; Stenn 2018), can also effectively reduce runoff when downscaled and targeted at disconnected impervious surfaces by homeowners. In fact, it can be even more powerful to ask homeowners to amend small areas of the yard (e.g., 1.5% of the yard in 1.5 × 1.5 m areas near disconnected downspouts) than it would be to ask homeowners to amend the entirety of their yard if more homeowners are willing to implement the smaller low impact practice. Based on our modeling results, if 70 homeowners in a neighborhood with baseline soil K_{sat} < 1.0 × 10^{-2} m/hr adopted the smaller low impact practice, it could be 6×–17× more effective at reducing runoff than one homeowner amending the same total area, but only within property lines of a single lot. Our results indicate that it is possible to drastically reduce the total area treated with low impact development practices while still capturing most of the hydrologic benefits, provided those low impact practices target impervious-pervious interfaces (Voter and Loheide 2018).

Homeowner guidance on low impact development practices frequently emphasizes disconnecting impervious surfaces or constructing rain gardens, but rarely mentions soil amendment. For example, the USEPA provides resources for homeowners on eleven green infrastructure techniques, including downspout disconnection and rain gardens, but does not mention soil amendment or yard conditions (USEPA 2015). Similarly, local governments and nonprofit organizations tend to focus on downspout disconnection, rain gardens, and other impervious-centric practices in their homeowner outreach materials (e.g., CNT 2014; Philadelphia Water, 2016; WSOC and WDNR 2018), but to the extent that the yard is considered, the focus is typically on vegetation (e.g., replacing turfgrass with native plants and trees). Some guides do mention soil amendment, but imply that it is a whole-yard practice (Lancaster County Clean Water Consortium 2017) or define soil amendment as recycling lawn clippings, dethatching, core aerating, and topdressing (Milwaukee Metropolitan Sewerage District 2018). We know of none which suggest amending soil near impervious features as a stand-alone practice.

Our results also demonstrate that high infiltration landscapes do not necessarily have to be contained within a closed depression to effectively reduce runoff; sloped surfaces with high infiltration rates can also function as effective low impact development practices. This is an important observation because targeted soil amendment may be an appealing alternative to homeowners who are willing to amend soil for a rain garden, but reluctant to commit to long-term maintenance or risk standing water. We suggest including this intervention in the suite of low impact development practices promoted to residential property owners. In order to effectively implement this practice, a homeowner would first need an estimate of the infiltration capacity of their yard, since soil amendment yields little added benefit when yard infiltration rates are already high (e.g., above 1.0×10^{-2} m/hr). This can be approximated using a single-ring infiltrometer test, which is described in many publicly available homeowner guides for the purposes of rain garden design (e.g., WSOC and WDNR 2018). Next, the homeowner would remove and set aside turfgrass in the small, targeted area and use a shovel or small rototiller to mix the desired amendment (e.g., compost, or sand and topsoil) into the top 20 cm of soil before replacing turfgrass. Our study shows it is critical to site this practice next to a disconnected impervious surface that slopes to the yard, so it would be important for a homeowner to carefully evaluate slopes near their own impervious-pervious interfaces and observe how water flows from their own unique walkways and downspouts during heavy rain events.

Future research into targeted soil amendment should expand upon this study to also evaluate the potential impact of this intervention on water quality. In this modeling study, we based amended soil on an engineered mix of sand, compost, and topsoil (Thompson et al. 2008). While compost has beneficial hydrologic properties, it can also be a source of zinc, lead, and other heavy metals (Smith 2009). In addition, under some conditions, the strong wetting fronts which develop due to infiltration-based stormwater management practices may increase nutrient and pollutant loads to groundwater (Fischer et al. 2003). Fly ash, biochar, and other types of soil amendment have been shown to be effective at removing heavy metals and nutrients in bioretention basins (Zhang et al. 2008; Tian et al. 2019) and may be similarly important for targeted soil amendment on residential parcels.

CONCLUSION

Soil amendment, which consists of mixing in compost or other soil additives into near-surface soil, is effective at reducing runoff when implemented during development, but is rarely considered a reasonable homeowner intervention, partly due to the expense and effort required to amend an entire yard. Our modeling study shows that when impervious surfaces are disconnected and existing soil infiltration is low (mean $K_{\mathrm{sat}} < 1.0 \times 10^{-2}$ m/hr), shallow soil amendment (top 20 cm) is effective at reducing runoff from a single family home by up to 64% (9% as a percent of precipitation; loam soil scenarios) or 46% (15% as a percent of precipitation; clay loam soil scenarios) under climatic conditions typical of the Upper Midwest, U.S. Furthermore, we demonstrate that targeting soil amendment near impervious features can capture much of the hydrologic benefit of soil amendment while drastically reducing the spatial extent of amendment. Amendment areas that intercept the highest amounts of runon, such as near downspout outlets or at the edge of sidewalks, are the most efficient at reducing runoff. Our study shows that spreading out effort across multiple parcels and targeting soil amendment at small areas near impervious-pervious interfaces (e.g., 1.5% of the yard in 1.5×1.5 m areas near downspouts) can be $6\times$–$17\times$ more effective than a single homeowner amending their entire yard. We suggest that soil amendment on a sloped yard near disconnected impervious surface can be promoted as an effective low impact development practice which may appeal to homeowners who remain wary of the maintenance requirements of other interventions.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: In the Excel file, sheet S1 lists the total surface runoff, deep drainage, and evapotranspiration as a depth (mm) and as a percent of precipitation for all modeled scenarios. Sheet S2 lists the change in surface runoff, deep drainage, and evapotranspiration relative to a 0% amendment scenario for all modeled scenarios. Sheet S3 lists the improvement factor for all modeled scenarios. Sheet S4 includes all information in Sheets S1–S3 in a coding-friendly format.

DATA AVAILABILITY

Model inputs data to replicate results are included in tables and references in this paper. Input data, processing scripts, and summary output data are also posted publicly on github (https://github.com/cvoter/residential-soil-amendment).

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AUTHORS' CONTRIBUTIONS

Carolyn B. Voter: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; software; validation; visualization; writing-original draft; writing-review & editing. **Steven P. Loheide:** Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing-original draft; writing-review & editing.

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