Stresses on the Vegetation in Green Stormwater Infrastructure

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1. Introduction

1.1. Background

The growth of urban areas is accompanied with the impervious surfaces and the environmental impacts of stormwater. Recent reports about sewage discharged into rivers and The Great Lakes in Chicago is not atypical.[1,2] In the past three decades, many efforts have been directed at sustainable and distributed stormwater treatment systems to achieve low impact developments. Different from the centralized waste water treatment like the Big Tunnel and Reservoir Project in Chicago,[1,2] distributed green infrastructures treat stormwater onsite and it has become the most popular practices among these efforts. For example, bioretention areas are shallow vegetated depressions for retaining and/or detaining stormwater before it is infiltrated and discharged to downstream or groundwater. It offers the advantages of reduced runoff volume, pollution, erosion, peak discharge rate, runoff temperature, and heat island effect, as well as enhanced habitat creation, site aesthetics and groundwater recharge. Vegetation enhances the stormwater treatment in terms of the removal of pollutants, most of which happened to nutrients for plants.

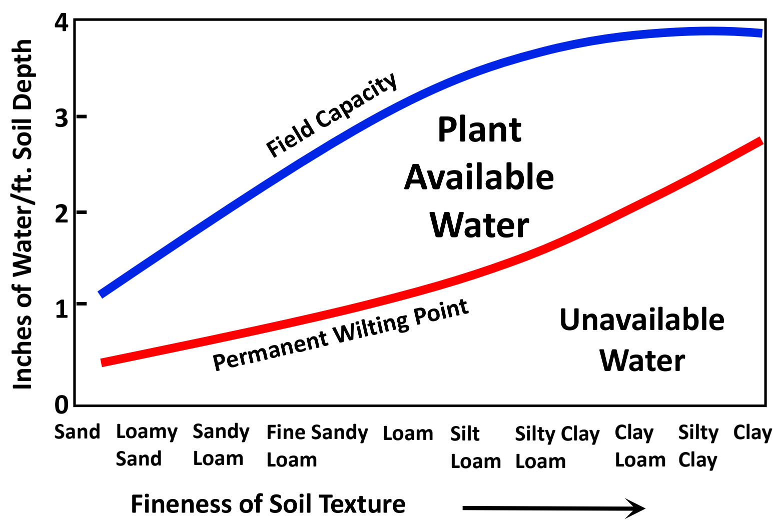

Figure 1. Plant Available Chart, adapted from Ohio Agronomy Guide,14th Ed, Bulletin 472-05[3]

However, plants often fail before established. The main reason is that plants undergo constant stresses like flooding and drought conditions. By design, green infrastructures are flooded during storms. Also by design, the growth media drain and dry out quickly between precipitation events, so to make room for next storm and to prevent overwatering issues. To achieve this, very porous growth media are used in these systems. As a result, soil moisture changes quickly from soaking wet to bone-dry in short period. The extreme variations in soil moisture makes it very hard for any plants to survive. If we look at the fundamental aspect of this program, it is the limited plant available water (PAW), defined as the water between field capacity (FC) and permanent wilting point (PWP), as illustrated in Figure 1 for different types of soils. In sandy soils, which is the same or similar to the media used in GSIs, the plant available water is very low.

So the main water stresses in the GSIs is due to the limited amount of PAW, not due to the lack of water. Both FC and PWP are intrinsic properties of the growth media (soil composition, chemical and physical properties of soil particles, and bulk density). So is the PAW. Water that exceeds the FC is either wasted through runoff, evaporation, competition and/or drainage. When the water is kept in place, it depletes air from roots and will cause root rot issue. So it is either wasted water or wasted plants, sometimes both. Water below PWP cannot be used by plants. The compacted soils and limited soil volume that are very common for urban areas and around GSIs further reduces the amount of PAW.

1.2. "'Solid Water' with Air Pockets"--SWAP: How does it work?

As a way to increase the PAW without changing the soil composition and structure, which is known as soil amendment and can be very expensive we proposed a possible solution as "'Solid Water' with Air Pockets" (SWAP), in a technology trademarked as TreeDiaper® or SteadySpring®. As illustrated in Figures 2 and 3, SWAP is the water above FC. But the presence of air pockets allows vital air supply to roots. So, it significantly increases PAW without causing overwatering issue. As soil dries, it triggers SWAP to re-hydrate the soil via osmosis. And because osmosis is a mutual process driven by osmotic pressure, SWAP can capture and recharge with some of the excess water that is otherwise wasted. As a result, the soil moisture is stabilized in a healthy range for trees and shrubs. Combination of this more efficient use of water, slow releasing and recharging with precipitation / irrigation water, SWAP greatly reduces watering frequencies. In the areas with only short drought periods, it may eliminate watering need, as demonstrated below.

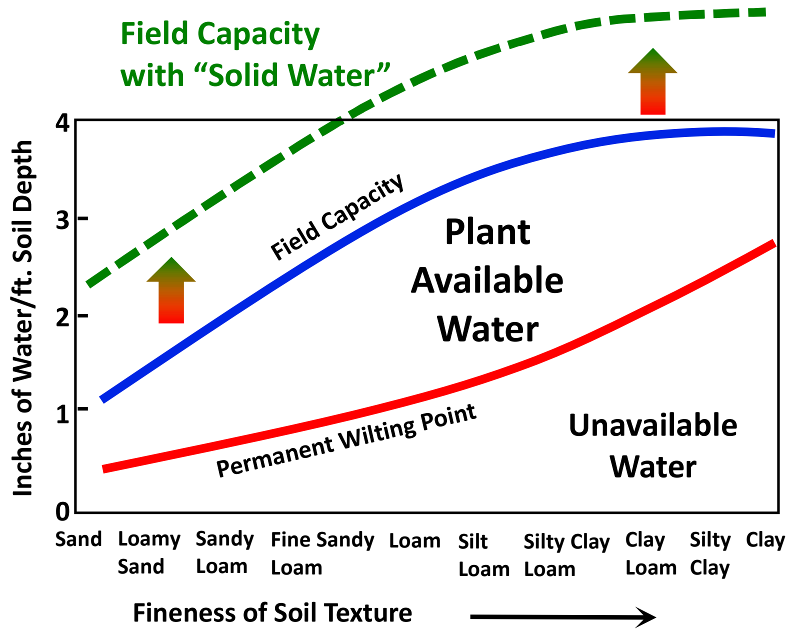

Figure 2. Using "'Solid Water' with Air Pockets" System to boost Field Capacity without causing overwatering issue

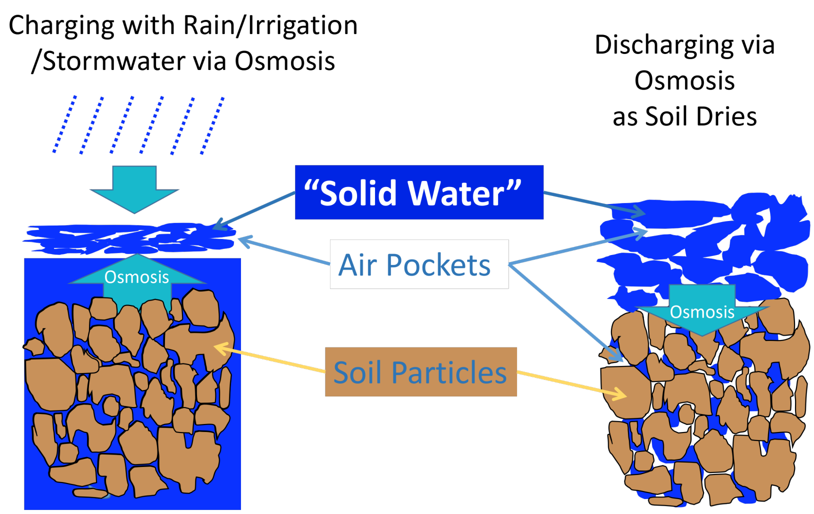

Figure 3. Illustration of how "'Solid Water' with Air Pockets" System

1.3. Preliminary Trials

Two preliminary trials were done in Fairfax County Virginia and Portland Oregon started in 2018-2019. In the trial in the Fairfax county, it was in the parking lots of McLean Metro Station. Shown in Figure 4 is the layout of the parking lot. The first flash of stormwater runoff, typically has more pollutants and sediments flow into the tree wells. The overflow would flow into the overflow well. Because it is supposed to be cleaner, it is allowed by EPA to be discharged into the streams and rivers directly. There are four tree wells: two with multstem shrubs, two with single stem trees. Two

Figure 4. Preliminary trial in Fairfax County Virginia

of them were installed with SWAP system while the other two are used as control.

Four months after the installation, to be exact it was 6 PM on April 27th, 2019, we stopped by to check the soil moisture. It was about 30 hours after a 0.6” rainfall. The soil moisture meter is on a 0-10 scale; the higher the number, the wetter the soil is. Under SWAP systems, soil moisture was found around 7. In the control area, soil moisture was found at 3. In regular plant bed where regular soil are used, the soil moisture was found to be around 9.

Table 1. Soil Moisture measurement on the parking lot of the Fairfax County trial

Figure 5. Preliminary trial in Portland OR. Google Street View image (upper) showing two newly planted trees in a roadside GSI. The left side tree was installed with a watering bag that was refilled twice every 17 days. The right side tree has a SWAP system installed.

Treewell and Plant Beds	Plant Type	SWAP system	Soil Moisture 6PM, 4-27-2019
A (Tree Well)	Evergreen Shrub	Yes	7±1
B (Tree Well)	Evergreen Shrub	No	3±1
C (Tree Well)	Deciduous Tree	Yes	7±1
D (Tree Well)	Deciduous Tree	No	3±1
E (Plant Bed)	Evergreen Shrub and Flowers	No	9±1

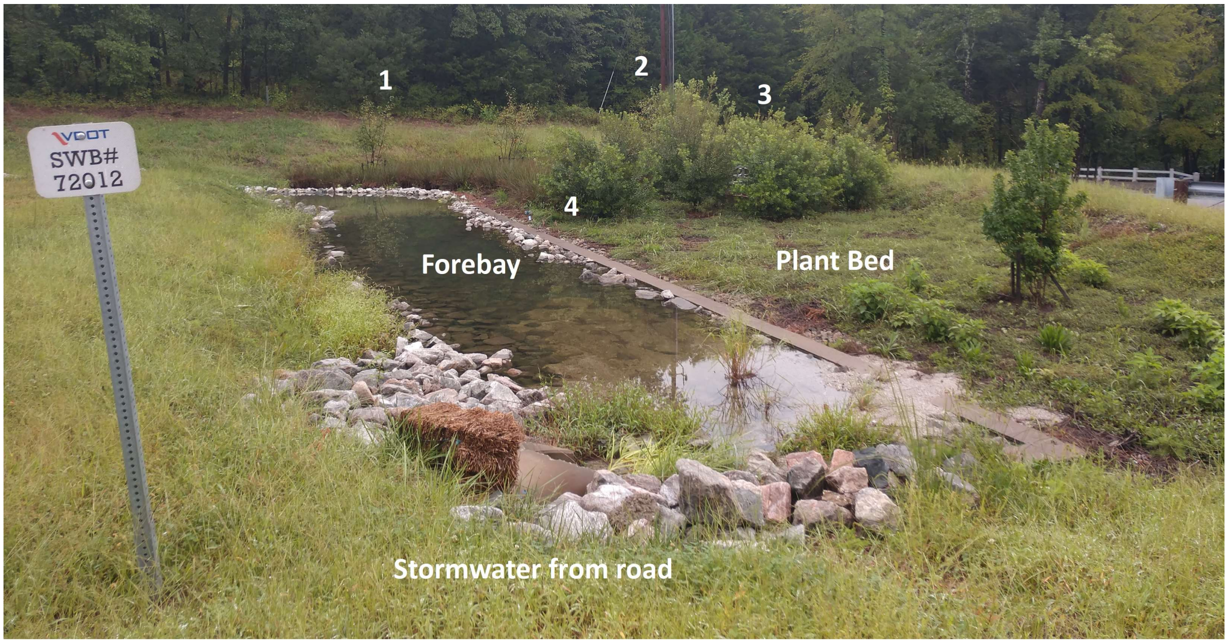

Figure 6. Field Test of SWAP in VDOT Bioswale 72012 off Route VA 711.

In the Portland Oregon trial, SWAP was installed in a GSI system near 909 East Burnside St. Two trees were planted, one with a watering bag and the other with a SWAP system. The watering bag should be refilled twice a week, but they were only refilled twice every 17 days. When we visited the site in Sept 2019, the soil under the watering bag was very dry, while the soil moisture under the SWAP system was moist, as shown in Figure 5. No soil moisture measurement was done at this site and we only did visual observation. From the pictures, it also appears that the tree with the watering bag has more yellow leaves on it.

2. Experimental Setup

The promising results from these preliminary trials suggested a more thorough study on the soil moisture in GSIs. So we made a request to the Virginia Department of Transportation (VDOT) to carry out such a study in a newly constructed bioswale off route VA 711 in Powhatan County, Virginia. The permit was granted in August 2020 and the study was started in September 2020. Figure 6 shows the layout of the bioswale and the selection of four plants for the trial with the rest of the plants used as controls. The stormwater from the road surfaces flows into the fore-bay, where coarse sediments are allowed to settle before entering the plant bed.

Soil moisture measurements were not done on the days when the growth medium is soaking wet to avoid soil compaction from foot traffic. However, a few data points were collected when there is standing water to confirm the soil moisture level. It is also used as a way to calibrate the soil moisture meters.

Soil Moisture Meters: A double metal type of soil moisture meter was used for the measurement. The two different metals form a battery and powers a circuit in the meter. The current through the circuit is used as indicator of the soil moisture. This type of soil moisture meter can easily affected by the concentration of ions e.g. road salt. So we avoided the months when there are salt spray on the roads.

3. Results

It is found that the plant bed of bioswale is flooded when there is more than 3/4" of rainfall. And the soil moisture was found to be at 9-10 when the bed is flooded. It also shows the soil moisture meter worked as designed. In the fall of 2020 when the experiment was first started, there was 15 inches of rain from Sept 1st to

Nov 10th and it was distributed rather evenly. The fore-bay was full or half full for most the time during this period. Although the main objective was to observe the soil moisture during an extended dry periods, we were also very interested in learning how soil moisture changes in the growth media during a wet period. Figure 7 shows the soil moisture from September to November 2020. Surprisingly, the soil moisture under the SWAP system was lower than the control area in between the rain events. Of course, there is no difference in soil moisture (both are at 9-10) during an rain event or when the plant bed is flooded. It means the some of the excess water was absorbed by the SWAP system. The range of the soil moisture variation under SWAP I from 5-7. In contrast, the rang in the control area was 3-10. Interestingly, the overall average was not significantly different, 5.9 versus 7.4.

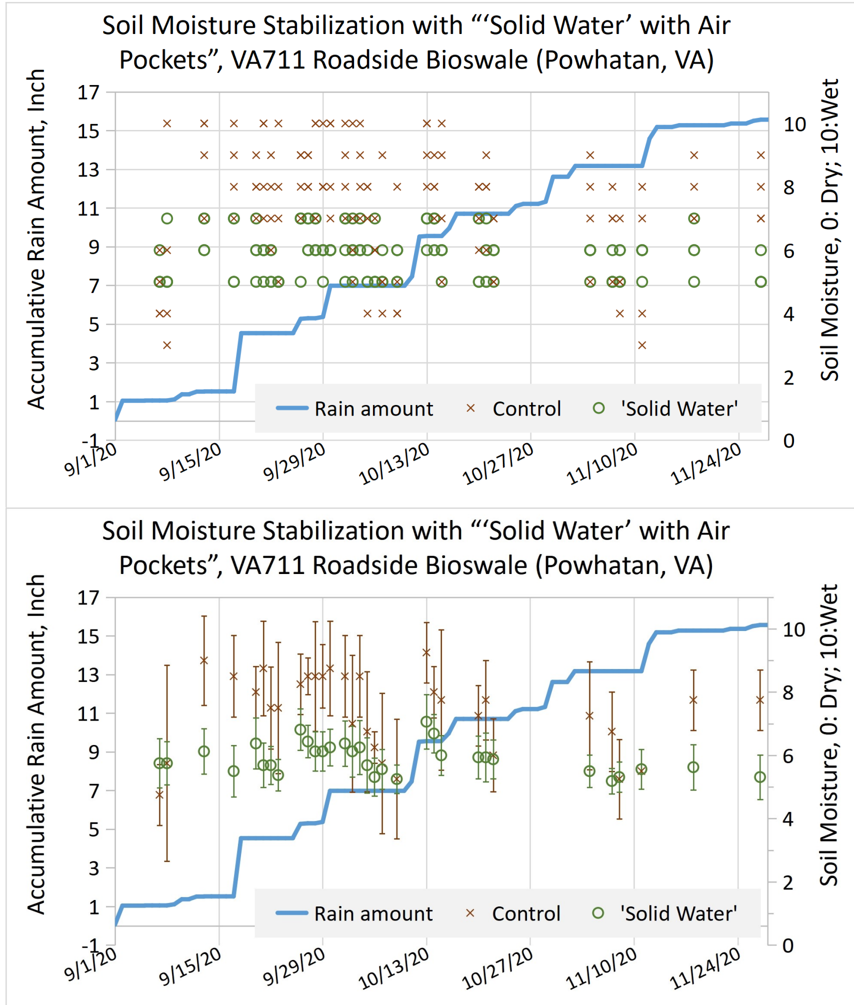

Figure 7. (**a**, upper) Raw soil moisture readings and accumulative rainfall data and (**b**, lower) the average soil moisture in the fall of 2020

In April 2021, the experiment resumed and the soil moisture data is shown in Figure 8 a & b. The rain accumulative rain amount was from the beginning of this experiment in September 2020. During the extended dry period in May 2021 (0.6" rain in 33 day period, April 26-May 28), the soil moisture in the control area dropped from 6.3 (as high as 9 in the raw data) to 1.3 (as low as 0 in the raw data). The soil moisture under SWAP dropped from 5.4 to 3.5. Near the end of the dry period, there were signs of stresses in the trees and shrubs in the control area. And the plants installed with SWAP did not have this issue.

4. Discussion

As a trend projected by the USDA Forest Services,[4] the urban will grow from 3.5% of land mass in the USA in 2010 to more than 8% of land mass in 2050. The new developments and booming construction industry are clear-cutting the forests and wood lands that doesn't let stormwater run off as fast and as much as in the urban area, thanks to the impervious surfaces and reduced tree canopy. GSIs, as a way to mitigate this problem will be more popular as there is no other way around this problem. For example, after spending billions of dollars in their Tunnel and Reservoir project that was started decades ago, it is failing because as little as 2/3" of rain will overflow the system and cause massive discharge of untreated sewage in the waterway.

But in order for the GSIs to work, the soil moisture fluctuation must be solved. A 2019 survey among stormwater professionals regarding their opinions of GSIs revealed that the main concerns is the establishment of the planting materials, shown in Appendix. SWAP system can not only stabilize the soil moisture, but also reduce the amount of stormwater runoff. The water that is stored in there are not contributed to the runoff. Not every place in the USA has 50 inches of rain per year. For areas like Southern California where there is essentially no rain for more than half of the year, an irrigation system is typically the standard specification for GSIs. Still, the SWAP system can help to stabilize the soil moisture for the irrigation system, especially on mitigating the overwatering issues.

There are many other factors contributing to the problems in GSIs, such as compacted soils, limited soil volume, pollutants, deicing salts, sediments, and simply the harsh growing condition in typical urban areas. Compacted soil and limited soil volume issues may significantly reduce the growth potential of the plant materials. Unfortunately, the construction process itself is the main reason the soil is compacted. Sediments removal is part of regular maintenance requirements. When it is not performed as required, the sediments add to soil depth, blocks the growth media and slows down the stormwater infiltration rate. It then causes overwatering problems.

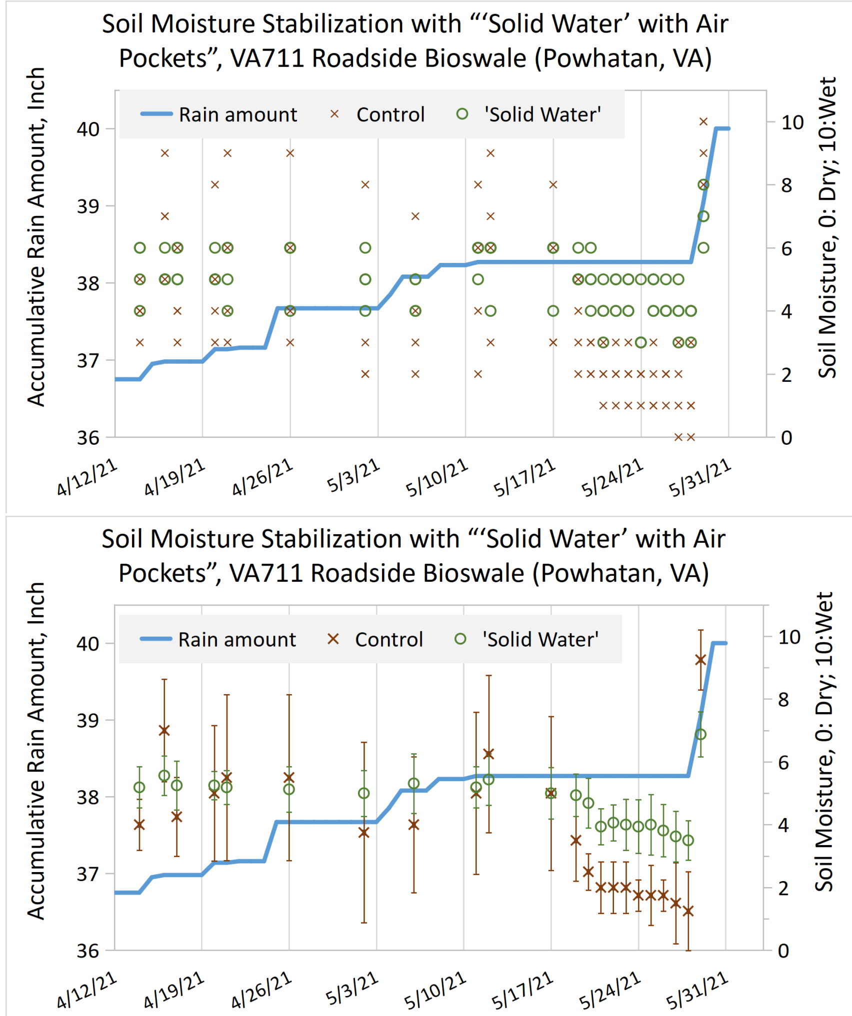

Figure 8. (**a**, upper) Raw soil moisture readings and accumulative rainfall data and (**b**, lower) the average soil moisture in the spring of 2021

Deicing salt may cause severe damages to the plants in the GSI. GSIs are designed to take the first flash of stormwater runoff, in which salt can be very concentrated. The only way to get rid of salt is to leach it out and wash away. Ironically, most irrigation systems are not working when salt is used. The SWAP system, however, is designed to work in all seasons. When salt is washed into the system, it changes the osmotic balance and causes SWAP to release the stored water. This extra water can then wash salt away or at least to mitigate the salt damages by reducing the salt concentration.

5. **Acknowledgments:** We appreciate the assistance, permits, and collaboration from David Alexander of Fairfax County, Va, Amber Fox of City of Portland, Ryan McGrath and Michael Ebersole of Virginia Department of Transportation. Without their help, these experiments would not be possible.

6. References

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Appendix.

A 2019 survey among stormwater professionals regarding their opinions of Green Stormwater Infrastructure was done and the results are shown in below. Out of 200 people we reached out to, we received 36 responses.

Q1:	Do you use Green Infrastructures for Stormwater Management?
A1:	33 Yes; 3 No/Never/Doesn't work
Q2:	What is the No. 1 challenge of Green Infrastructures? (Followup question to people answered "Yes" to Q1)
A2:	21 Maintenance; 10 Construction; 1 Regulation; 1 Misunderstanding
Q3:	What is the No. 1 problem associated with maintenance? (Followup question to people answered "Maintenance" to Q2)
A3:	16 Plant Establishment; 3 Sediments; 2 Training/Vetting of Contractor
Q4:	What is the No. 1 problem with Construction? (Followup question to people answered "Construction" to Q2)
A4:	4 Soil work; 3 Construction process itself; 3 Sizing

The survey was sent to about 200 stormwater professionals, not limited to Green Stormwater Infrastructures, but with almost equal numbers of professionals in the conventional Grey Stormwater Infrastructures. The survey was done by email/LinkedIn message/phone call/face-to-face meeting. The questions were not provided all together. Instead, the first question was asked first. Based on the response, the corresponding followup questions were asked. Because the first question was asking them whether they use GSI or not, we believe the GSI professionals are heavily favored in the number of responses. Among the 36 responses, 33 said they use GSI and 3 said no/never/doesn't work. A followup question was not addressed by the person who said "It doesn't work!", so we grouped it together with the "No" group.

Among all responses, plant establishment is the number one problem GSI professionals are facing in their day-to-day operations.