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Assessing micro-irrigation clogging risk through water quality classification systems

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ABSTRACT

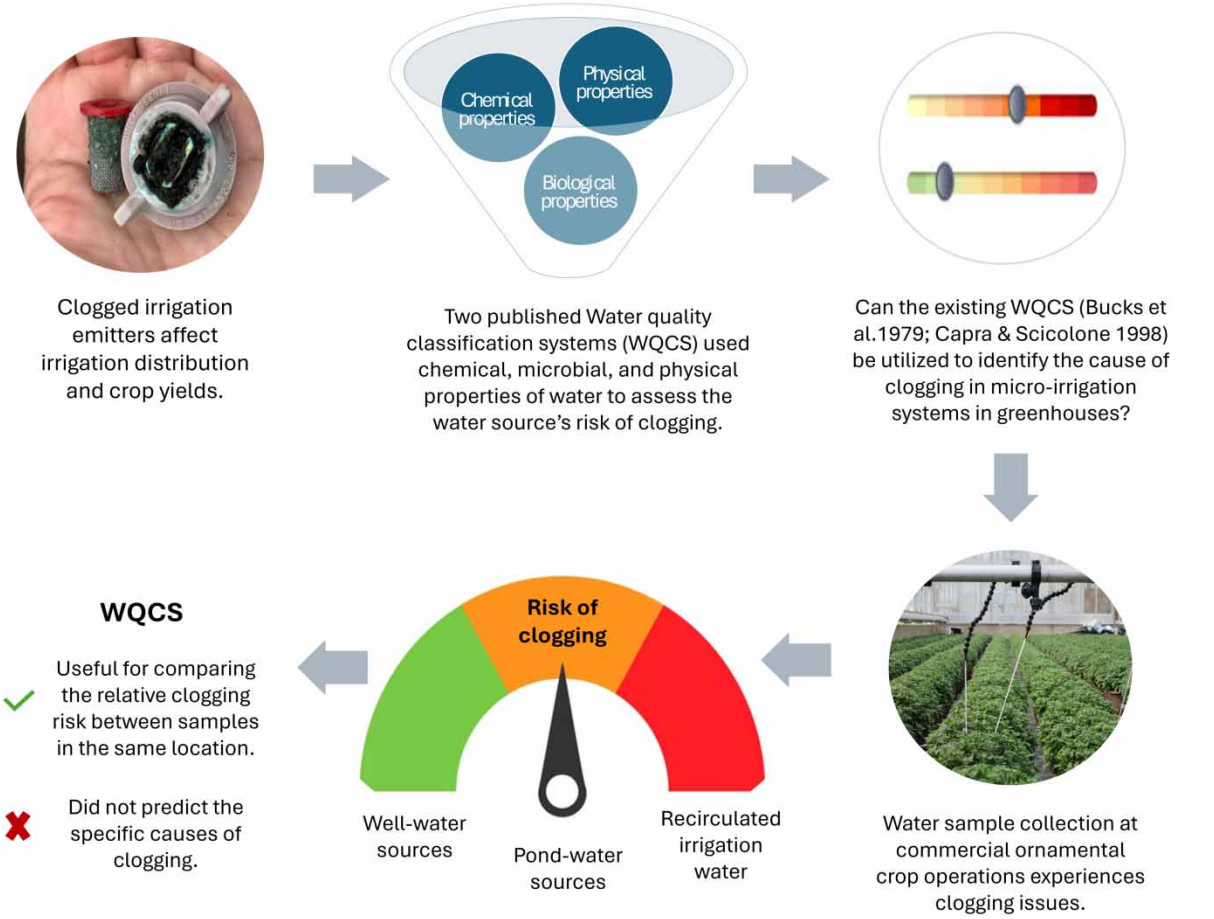
Water quality classification systems aim to assess the overall risk of clogging in micro-irrigation systems. However, their ability to predict potential clogging based on water quality characteristics remains untested, particularly in controlled environment agriculture. This project aimed to evaluate if the existing classification systems could be used to identify the cause of clogging in micro-irrigation systems in greenhouses. Water from eight commercial greenhouses with reported clogging was analyzed for physical, chemical, and biological properties to rate the risk of clogging according to the classification systems. In general, iron and manganese from the fertilizers and high microbial load resulted in high ratings. However, the ratings lacked insight into the specific causes of clogging, disregarding interactions among chemical and microbial factors and qualitative characteristics of specific microbial phenotypes (e.g., production of polysaccharides or iron oxidation) that lead to clogging. Furthermore, the systems overemphasize nutrient levels typically used in greenhouse fertigation as the cause of clogging – which is not commonly observed in practice. Enhancing these systems requires parameters reflecting these interactions and microbial traits influencing clogging. Further research needs to develop these parameters in new systems with robust and precise thresholds in which emitter performance, profitability, and sustainability are affected.

Key words: biofilm, controlled environment agriculture, emitter performance, iron precipitate, microbiome, total suspended solids

HIGHLIGHTS

- The water quality classification systems (WQCS) did not predict the specific causes of clogging or hazard levels of water sources.
- WQCS were useful to compare the relative risk between samples in the same location.
- WQCS do not consider interactions among chemical and microbial factors, the qualitative characteristics of microbial communities, and they overemphasize the value of plant essential elements.

GRAPHICAL ABSTRACT



INTRODUCTION

Clogged irrigation systems affect irrigation uniformity (Capra & Scicolone 1998), the emitter-discharge rate (Ravina *et al.* 1992), crop yields (Sadeh & Ravina 2000), and the useful life of irrigation equipment (Gilbert *et al.* 1981), which leads to crop losses and increased labor and production costs (Raudales *et al.* 2017). Clogging is mainly caused by the accumulation of suspended particles such as chemical precipitates (e.g., calcium, magnesium, iron, and manganese), minerals (e.g., silt), organic matter, or the accumulation of biofilm and algae (Bucks *et al.* 1979; Adin & Sacks 1991; Capra & Scicolone 1998). Therefore, monitoring water quality and implementing an adequate clogging risk assessment is critical to establish management strategies that prevent crop loss and mitigate the economic risks associated with clogged irrigation systems.

Two water quality classification systems assess the overall risk of clogging and classify water sources by risk level in drip irrigation systems. The system reported by Bucks *et al.* (1979) – from now on referred to as the *Bucks system* – works by rating water sources based on the concentration of chemical, physical, and biological parameters and then estimating a combined score (Supplemental Material 1). This system, or some of its components, has been adopted by the Food and Agriculture Organization (FAO) (Ayers & Westcot 1985), the United States Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS 2013), and several university extension publications (Storlie 1995; Hanson *et al.* 1997; Rogers *et al.* 2003; Grabow *et al.* 2005; Shortridge & Benham 2018) to evaluate clogging risks in micro-irrigation systems. Although some publications referenced Hanson *et al.* (1997) and Hassan (1998) as the source for the guidelines, their guidelines can be traced back to the classification system proposed by Bucks *et al.* (1979).

The system reported by Capra & Scicolone (1998) – from now on referred to as *Capra & Scicolone system* – works by assigning a clogging hazard rating of 'Minor, Moderate, or Severe' based on the electrical conductivity (EC) and the concentration of total suspended solids (TSS), iron, manganese, calcium, and magnesium

(Supplemental Material 2). Details on how to use the rating systems are outlined in the Methods section of this article. Both classification systems were developed based on a combination of observational data – samples collected on farms, and the researchers' experience – instead of data from controlled experiments. Moreover, there is limited evidence that classification systems may be applied as a tool to identify and predict the causes of clogging. Identifying the source of clogging may help develop robust water quality thresholds and assist operators and system designers in making decisions to effectively manage water to minimize clogging risks.

Our objective was to evaluate if the existing water quality classification systems could be used to identify the cause of clogging in micro-irrigation systems in greenhouses. In this project, we sampled water at commercial greenhouse operations that reported frequent clogging of irrigation systems. Where applicable, we rated the water parameter values using the Bucks and Capra & Scicolone water classification systems.

METHODS

Locations

Randomized and equal probability sampling was not possible because we were looking for greenhouse operations that had persistent and complete clogging of irrigation emitters in Connecticut, USA. We selected eight commercial operations producing ornamental crops in containers using different water sources and reporting different clogging points in their operations. Sampling occurred once annually, between late spring and summer, 2015 and 2017. Four operations were sampled in April to May 2015, one in June 2016 and eight in July to Aug. 2017. The description of each location is listed in Table 1.

Table 1 | Years and water sources sampled, clogging points and frequency, and water treatments used by each commercial greenhouse in the study

Location	Years sampled	Water source	Clogging points	Clogging frequency[a]	Water treatment between source and emitter
A	2015, 2017	Two wells	Disk filter, water pump	Daily with every irrigation	2015: Disk filter + peracetic acid 2017: Disk filter
B	2015, 2016, 2017	Well and treated recirculated nutrient solution	Screen filters, irrigation boom	Daily after irrigating for approximately. 60 min	Well water: Screen filter Recirculated water: Fabric filters 177 and 149 μm, granulated active carbon filter, peracetic acid, and screen filter
C	2015, 2017	Well	Disk filter	High frequency during the summer. Grower reported no clogging during 2017	2015: Disk filter 2017: Peracetic acid and disk filter
D	2017	Well	Irrigation boom emitters	Multiple times a week	Screen filter
E	2017	Well	Drip emitters and tubing	High frequency in June	Screen filter
F	2017	Public	Screen filter	High frequency during the summer season	Acid injection and screen filter
G	2015, 2017	Pond	Drip emitters and tubing	All year long with high frequency during the spring season	Screen filter 177 μm
H	2017	Pond	Emitters in propagation areas	High frequency during the summer season	Screen filter

[a]Description of clogging by growers.

To understand the nature of clogging and the design of irrigation water distribution systems, we conducted informal interviews and conversations with the growers. We inquired about their water sources, the points and frequency of clogging, and the availability of any water treatment at their farms. Table 1 summarizes the information gathered through these interviews, conversations, and walkarounds.

Sampling

Three 1-L water samples were collected directly from either the source or closest outlet to the source and from the farthest emitter in each location. Location B had two water sources, the well water and the recirculated nutrient solution that were sampled after water treatment, which included multistage filtration (membrane filter, fiber media, and granular-activated carbon filters), peracetic acid injection, and iron-chelates injection. For all samples, water ran for at least 1 min before sample collection. We kept the samples at 4 °C and processed them within 24 h of collection.

Sample processing

We shipped the samples to a commercial analytical laboratory to measure pH, EC, concentration of calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonate (HCO_3^{1-}), calcium carbonate ($CaCO_3$), iron (Fe^{2+}), and manganese (Mn^{2+}), among the standard nutrients measured for plant growth. We estimated the total dissolved solids (TDS) 640 scale by multiplying the EC in $mS{\cdot}cm^{-1}$ by a constant of 640 (Corwin & Yemoto 2020). In 2017, we measured total and soluble iron using the Orion™ AQUAfast™ AC4078 kits and the Orion™ AQUAfast™ AQ4000 colorimeter (Thermo Fisher Scientific Inc., Beverly, MA). The difference between total and soluble iron indicated the concentration of insoluble iron. We measured TSS using the American Public Health Association (APHA) standard method 2540 D (APHA 2012). We used the APHA standard method 9215 C heterotrophic plate counts (HPC) to enumerate the total amount of culturable aerobic bacteria in the water samples.

Clogging risk rating

We rated the risk of emitter clogging of each sample according to the *Bucks* and the *Capra & Scicolone* systems. The Bucks system (Supplemental Material 1) ratings were conducted as follows: (1) physical, chemical, and biological parameters were rated for their clogging risk from 0 (low risk) to 10 (high risk) depending on the concentration in the samples; (2) for the chemical contributors to clogging (dissolved solids, iron, and manganese), the parameter with the highest rating was selected to represent the chemical category rating; (3) if the water pH was above 7.5, then the iron/manganese rating was multiplied by two; (4) a combined score was created by adding the 'Physical–Chemical–Biological' independent scores. A combined score below 10 (e.g., '0–0–0') represented a low risk of emitter clogging. A combined score between 10 and 20 (e.g., '0–10–5') was considered a moderate risk of emitter clogging, and a combined score between 20 and 30 (e.g., '10–10–10') was considered a high risk of emitter clogging.

The Capra & Scicolone system (Supplemental Material 2) rates clogging hazards as *minor*, *moderate*, or *severe* according to specific levels of chemical and physical water quality parameters. We compared the ratings of the samples from the source and emitters to observe how water quality changed as it flowed through the irrigation system in each location.

DNA sequencing and microbial community characterization

In 2017, we extracted DNA from microorganisms in the water from locations A, B, E, F, G, and H. Briefly, up to 1 L of the water passed through a 0.22 μm pore size hydrophilic polyethersulfone membrane filter (Supor® PES, Pall Corporation, Port Washington, NY), then DNA was extracted from microorganisms on the filter using the DNeasy PowerWater kit (QIAGEN GmbH, Germany). The University of Connecticut Microbial Analysis, Resources, and Services (MARS) laboratory conducted library preparation and sequencing. The DNA was quantified using the Quant-iT PicoGreen kit (Thermo Fisher Scientific Inc.). Bacterial *16S rRNA (V4)* and fungal *ITS2* genes were amplified using 30 ng of DNA. The V4 region was amplified using 515F (5′-GTGCCAGCMGCCGCGGTAA-3′) and 806R (5′-GGACTACHVGGGTWTCTAAT-3′) primers with Illumina adapters and dual indices – 8 basepair Golay on 3′ (Caporaso *et al.* 2012) and 8 basepair on the 5′ (Kozich *et al.* 2013). The ITS2 region was amplified with ITS3 (5′-GCATCGATGAAGAACGCAGC-3′) and ITS4 (5′-TCCTCCGCTTATTGATATGC-3′) primers (White *et al.* 1990) using the same dual indexing design as the V4 region. Three subsamples were amplified using Accuprime PFX PCR master mix (Thermo Fisher Scientific

Inc.) with the addition of 10 μg bovine serum albumin (BSA). (New England BioLabs, Ipswich, MA). The polymerase chain reaction (PCR) conditions consisted of 95 °C for 2 min, then 30 cycles of 15 s at 95.0 °C, 1 min at 55 °C, 1 min at 68 °C, and a final extension at 68 °C for 5 min. PCR products were pooled for quantification and visualization using the QIAxcel DNA Fast Analysis (QIAGEN GmbH, Germany). PCR products were normalized based on the concentration of DNA from 250 to 400 bp and then pooled using the QIAgility liquid handling robot. Combined PCR products were cleaned with Mag-Bind RXNPure Plus (Omega bio-tek, Norcross, GA) and then sequenced on the MiSeq using a v2 2 × 250 base pair kit (Illumina, Inc., San Diego, CA).

Sequences were demultiplexed using onboard bcl2fastq and then processed in Mothur v. 1.39.4 following the MiSeq SOP (Kozich *et al.* 2013). Specific commands can be found here https://github.com/krmaas/bioinformatics/blob/master/mothur.batch. Merged sequences that had any ambiguities or did not meet length expectations were removed. Sequences were aligned to the Silva nr_v119 alignment (Quast *et al.* 2013). Taxonomic identification of OTUs was done using the RDP Bayesian classifier (Wang *et al.* 2007) against the Silva nr_v119 taxonomy database. Alpha (inverse Simpson index) and beta diversity (Bray–Curtis dissimilarity) statistics were calculated by taking the average of 1,000 random subsampling to 10,000 reads per sample in Mothur. Nonmetric multidimensional scaling (NMDS) and permutational multivariate analysis (PERMANOVA) were conducted using the vegan package (Oksanen *et al.* 2015) in R 3.3.2. A subsampled species matrix was used for indicator species analysis (de Cáceres & Legendre 2009). Figures were drawn in R 3.3.2 using ggplot2 2.2.1 (Wickham 2011) and RcolorBrewer 1.1-2.

RESULTS AND DISCUSSION

Clogging risk classification

Even though all locations reported a high incidence of clogging, water source samples were classified as a low to moderate risk of clogging based on both classification systems (Table 2). Well water sources were classified as a low risk of clogging, mainly associated with chemical factors, except in location C where manganese levels led to a moderate risk rating. The municipal treatment facility water source was classified as a low risk of clogging. Pond water sources were classified as a moderate risk of clogging, mainly attributed to bacteria in both locations G and H plus TSS in location G. Based on the classification systems, it was not possible to identify the causes of clogging in locations A, B (well water sources), D, and E.

Recirculated irrigation water in location B was rated as low quality with a high risk of clogging mostly attributed to high bacterial counts and high mineral levels from dissolved fertilizers (Table 2). Recirculating water is a strategy to reduce nutrient runoff into the environment, save water, and lower costs (DeVicentis *et al.* 2015; Raudales *et al.* 2017), with the added risk of clogging (Table 2 and Supplemental Material 3). In general, recirculated water has more microbial load, nutrients from fertilizers, and organic matter. It remains to be determined whether the increases in microbial load are beneficial or detrimental for plant health or irrigation efficiency.

The grower in location B reported that screen filters and emitters were clogged with recirculated nutrient solutions despite using a multiple-stage water treatment system. Capra & Scicolone (2007) indicated that clogging prevention depends on the type of filter, water quality, and emitter. They observed that vertical gravel media filters (1.5 mm crushed granite with a 20 $m^3 \cdot h^{-1}$ flow rate) resulted in high emitter performance and lower clogging incidence and severity, while screen filters were clogged and did not prevent emitter clogging. Liu & Huang (2009), Oliver *et al.* (2014), and Zhou *et al.* (2017) found that emitters with discharges above 2 $L \cdot h^{-1}$ and pathways wider than 1.5 mm were less sensitive to clogging when using urban wastewater. The evidence from the literature suggests that the risk of clogging depends on the design of the irrigation system, not water quality alone. Therefore, understanding the risks of clogging must involve modeling water quality compatibility with the design of the distribution and treatment systems. In other words, prevention of micro-irrigation emitters requires designing water treatment and distribution systems that match the characteristics of the water source.

The risk of clogging ratings increased from the source to the emitters in locations A, B, C, E, and F because of a high number of bacteria and mineral content from dissolved fertilizers (Table 2 and Supplemental Material 3). The risk of clogging ratings for the treated recirculated solution did not change from the source to the emitters (Table 2). Our observations are similar to those of Meador *et al.* (2012) who reported a higher number of bacteria at the farthest outlet compared with the source, thus increasing the risk of biological clogging based on the ratings. The organic matter, nutrients, biofilms inside pipes, and irrigation scheduling may influence planktonic bacteria in water. Ravina *et al.* (1992) and Zhou *et al.* (2013) observed that emitter clogging is a gradual process

Table 2 | Clogging risk ratings of each commercial greenhouse sampled according to Bucks *et al.* (1979) and Capra & Scicolone (1998) water quality classification systems

		Bucks rating system[b]					Capra & Scicolone system[c]					
Location[a]	Sampling point	Physical	Chemical	Biological	Total	Clogging risk	TSS[a]	EC[a]	Iron	Manganese	Calcium	Magnesium
A	Well	0[c]	3	0	3	Low	Low	Low	Low	Low	Low	Low
	Emitter	0	3	5	8	Low	Low	Low	Low	Low	Low	Low
B	Well	0	0	4	4	Low	Low	Low	Low	Low	Low	Low
	Emitter	0	3	4	7	Low	Low	Low	Low	Low	Low	Low
	Treated recirculated	0	8	10	18	Moderate	Low	Moderate	Moderate	Low	Low	Severe
	Emitter recirculated	0	8	10	18	Moderate	Low	Moderate	Moderate	Low	Low	Severe
C	Well	0	9	1	10	Low	Low	Low	Low	Moderate	Low	Low
	Emitter	0	10	1	11	Moderate	Low	Low	Low	Moderate	Low	Low
D	Well	0	4	1	5	Low	Low	Low	Low	Low	Low	Low
	Tank	0	4	1	5	Low	Low	Low	Low	Low	Low	Low
	Emitter	0	4	1	5	Low	Low	Low	Low	Low	Low	Low
E	Well	0	2	0	2	Low	Low	Low	Low	Low	Low	Low
	Emitter	0	2	4	6	Low	Low	Low	Low	Low	Low	Low
F	Municipal	0	3	0	3	Low	Low	Low	Low	Low	Low	Low
	Emitter	0	10	7	17	Moderate	Low	Moderate	Low	Low	Low	Moderate
G	Pond	4	2	10	16	Moderate	Low	Low	Low	Low	Low	Low
	Emitter	0	4	9	13	Moderate	Low	Moderate	Low	Low	Low	Moderate
H	Pond	0	2	10	12	Moderate	Low	Low	Low	Low	Low	Low
	Tank	0	1	10	11	Moderate	Low	Low	Low	Low	Low	Low
	Emitter	0	1	7	8	Low	Low	Low	Low	Low	Low	Low

[a]Commercial greenhouses are described with letters from A to H (Table 1). TSS: total suspended solids and EC: electrical conductivity.
[b]According to Bucks *et al.* (1979): Each physical, chemical, and biological parameter is assigned a rating from 0 to 10 based on the water testing results (Supplemental Material 1) and assigned in a combined three-digit rating of 0-0-0. For the chemical rating, the one with the highest rating between dissolved solids, iron, or manganese was selected. If the pH was above 7.5, the chemical rating was multiplied by two. Overall, the risk of clogging is expected to be low, moderate, and severe if the added values of the combined rating fall between 0–10, 11–20, and 21–30, respectively.
[c]According to Capra & Scicolone 1998 (Supplemental Material 2).
[d]See Supplemental Material 3 for numeric values from the water sample testing.

for which the biofilm and microbial growth inside the pipes is the leading cause, with emitters in the middle or end part of an irrigation line being more prone to clogging than those at the head of the irrigation line. These observations suggest that the environment inside the irrigation system is favorable for microbial growth and water treatments with residual effects are required to prevent an increase in biological clogging risk as water reaches the farthest emitters.

Bucks *et al.* (1979), Capra & Scicolone (1998), and Shinde *et al.* (2012) argue that the risk of chemical clogging increases when fertilizers are added to the nutrient solution. Bozkurt & Bulent (2006) reported that drip emitters are susceptible to clogging when using fertilizers that supply calcium and sulfates. However, fertigation is a standard practice in greenhouses, and not all systems experience clogged emitters, suggesting the existing classification systems may overestimate the risk of chemical clogging when using fertigation. In addition to water quality parameters, meta-analysis studies have shown that emitter design features (such as flow path length, width, and depth) and operating time can influence the risk of clogging (Liu *et al.* 2022; Lv *et al.* 2024). Although the meta-analyses did not account for biological water quality indexes, Liu *et al.* (2022) highlighted the potential interactions of microorganisms with the studied water quality parameters. Their results indicate that Fe and Mn promote extracellular polymers (EPS) and biofilm formation in clinical settings, and highlighted that TSS particles can serve as sites for microbial aggregation, growth, and EPS production, which further increase TSS concentrations. Lv *et al.* (2024) stated that further research should evaluate the impact of interactions between microorganisms and water quality on clogging. Therefore, it is suggested that classification systems should include indicators that consider specific interactions between water quality parameters that lead to chemical precipitation and biological clogging rather than looking at the concentration of individual elements.

The risk of clogging ratings for pond water sources decreased from the source to the emitters because TSS and bacteria were lower at the emitters than at the source (Table 2). This reduction could be caused by filtration (0.15 mm screen filters in location G) and settling of particles in the storage tank (location H). Bacteria may attach to suspended particles (Jeng *et al.* 2005), which emphasizes the importance of removing suspended particles as part of an integrated treatment approach to reduce risks associated with microbial loads such as biofilm, algae, and pathogens. The interaction between TSS and the EPS secreted by microorganisms has been linked as a possible cause of drip emitter clogging (Zhou *et al.* 2013; Oliver *et al.* 2014) and should be explored to improve the reliability of the classification systems.

Microbial community characterization

Microbial diversity and community composition differed by location and type of water source. Bacterial and fungal diversity was higher in pond water compared with well water (Figure 1). While the microbial load

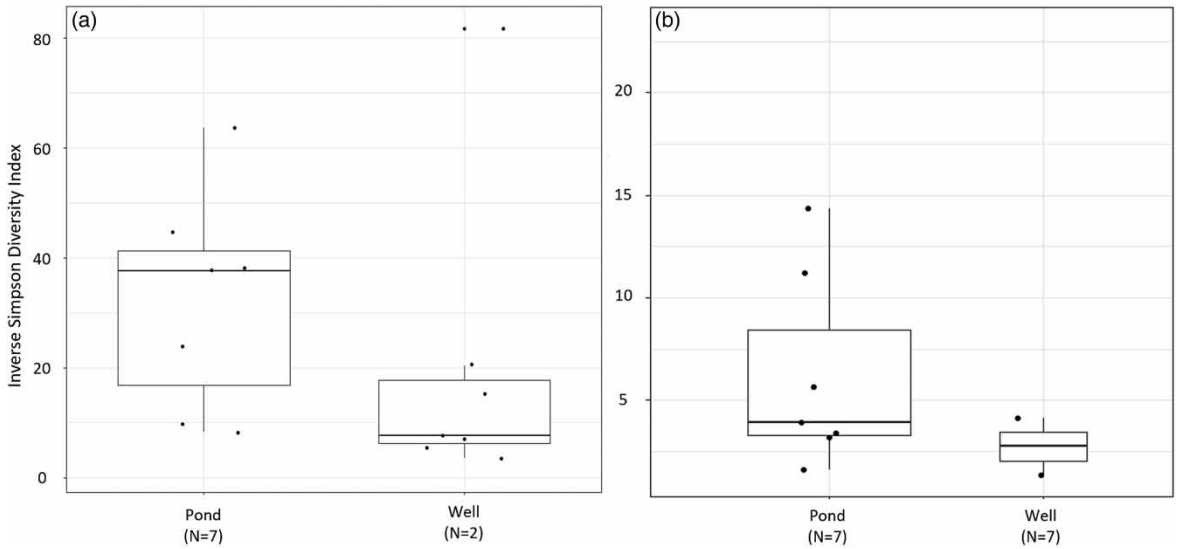


Figure 1 | Microbial richness (alpha-diversity) by water source. Inverse Simpson diversity index of (a) bacterial and (b) fungal communities in irrigation water from different sources. Municipal and recycled water sources were not included because only one data point could be sequenced.

increased in recirculated nutrient solutions relative to the well water (Table 2), the microbial community composition did not differ significantly (Figure 2). PERMANOVA tests on the Bray–Curtis dissimilarity metric (Figures 2 and 3) showed the microbial communities differed by locations (bacteria: $P = 0.01$, $R^2 = 0.56$, fungi: $P = 0.01$, $R^2 = 0.67$) and by water source (bacteria: $P = 0.01$, $R^2 = 0.22$, fungi: $P = 0.02$, $R^2 = 0.39$). The microbial communities were similar (bacteria: $P = 0.99$, $R^2 = 0.19$, fungi: $P = 0.80$, $R^2 = 0.51$) in the water source and at the emitters (Figures 2 and 3), despite the overall increase in the number of bacteria as the water flowed from the source to the emitters (Supplemental Material 3). Bacterial communities were similar within pond samples, and they differed from well and municipal water sources (Figure 2). Well water sources had similar fungal communities, and they differed from pond and municipal water sources (Figure 3). Lindström (2000) and Yannarell *et al.* (2003) propose that the microbial diversity of lakes and ponds depends on the level of eutrophication and seasonality. The microbial diversity of groundwater sources depends on spatial heterogeneity, temporal variability, well depth, and pollution with chemical anthropogenic contaminants (Pedersen *et al.* 2008; Griebler & Lueders 2009). Our data provide no evidence that may directly explain the variability of microbial communities in samples. Presumably, the bacterial communities were similar within pond water sources because they were collected during the same summer season. With well water sources, the variability of microbial diversity may be explained by differences in geographic location and other unaccounted factors (e.g., well depth, mineral composition around the wells).

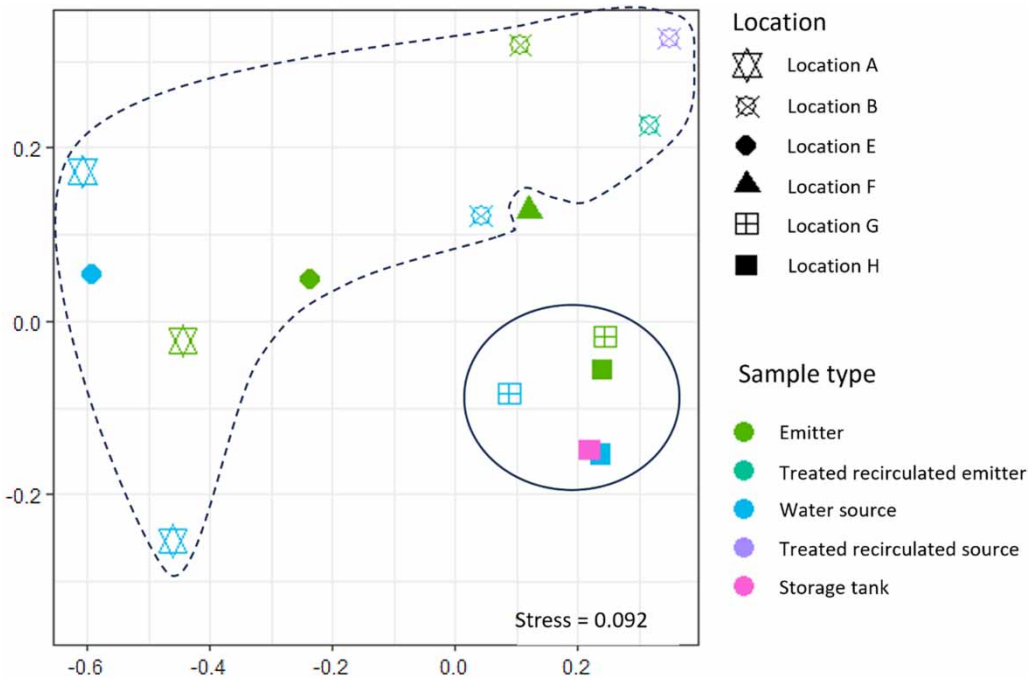


Figure 2 | Bacterial community dissimilarity (beta diversity metric) between location and sample type. NMDS analysis of operational taxonomic unit (OTU)-based clustering of irrigation water bacterial communities. Distances were calculated using the Bray–Curtis similarity metric. Difference between centroids was tested using PERMANOVA of variance. Locations that used well water sources are surrounded by the dotted line; locations that used pond water are surrounded by a solid line; and the location that used a public water source is not surrounded by any lines. Commercial greenhouse locations are described with letters from A to H (Table 1).

The bacterial community of our water samples had bacteria genera with the potential of clogging because of their ability to attach to surfaces, oxidize iron, form biofilms, and form flocs – loosely aggregated particles (Figure 4 and Supplemental Material 4). Supplemental Material 4 summarizes the bacteria taxa from our samples and their phenotypic adaptations that may contribute to clogging. The bacteria genera *Asticcacaulis*, *Caulobacter*, *Prosthecobacter*, and *Sporichthya* use holdfasts or prosthecae to attach to surfaces. Surface attachment is the first step for biofilm formation when microorganisms switch from a planktonic state to a sessile state. The bacteria genera *Acidiferrobacter*, *Ferriphaselus*, *Gallionella*, *Sideroxydans*, and TRA3-20 (unclassified) exhibit filamentous growth and oxidize ferrous iron, which may result in clogging due to precipitation of ferric iron and filamentous growth. Some strains within the bacteria genera *Hymenobacter*, *Pseudomonas*, *Rhizomicrobium*,

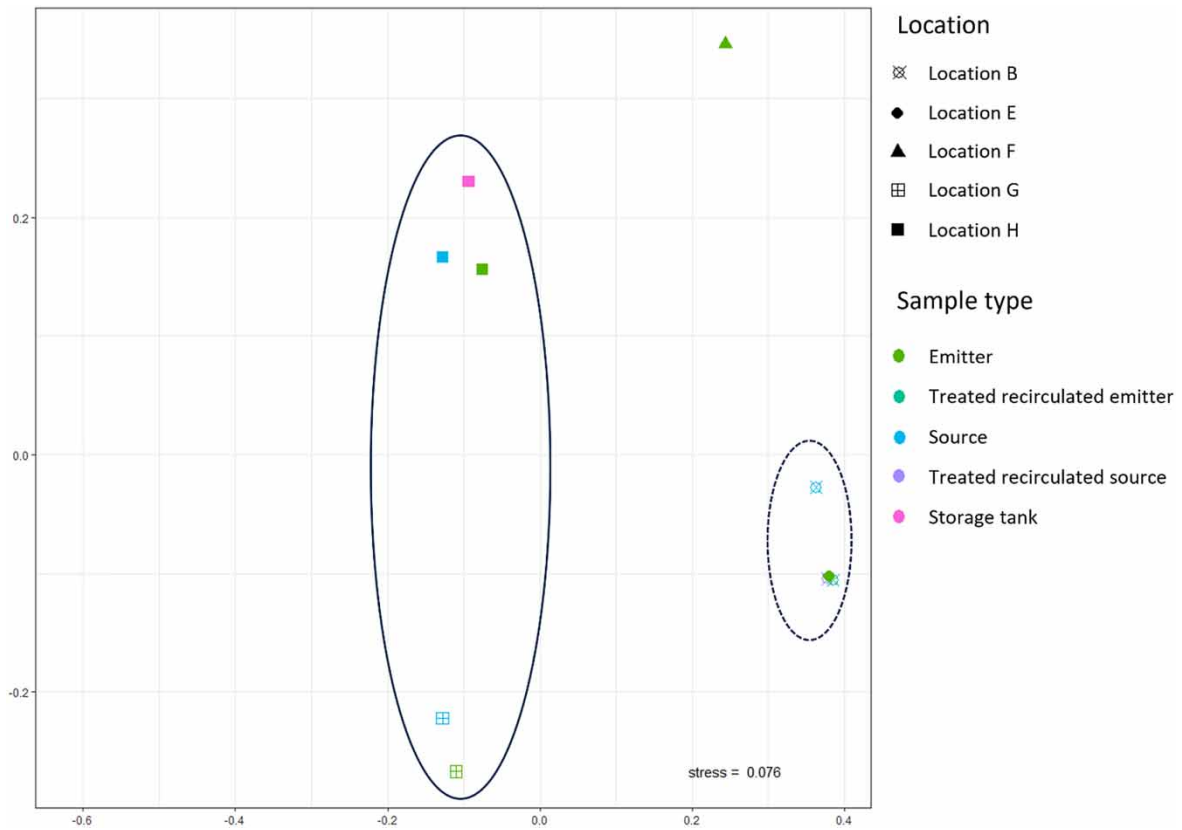


Figure 3 | NMDS analysis of OTU-based clustering of irrigation water fungal communities. Distances were calculated using the Bray–Curtis similarity metric. Difference between centroids was tested using PERMANOVA of variance. Locations that used well water sources are surrounded by the dotted line; locations that used pond water are surrounded by a solid line; and the location that used a public water source is not surrounded by any lines. Commercial greenhouse locations are described with letters from A to H (Table 1).

and *Rhodobacter* produce extracellular polysaccharides to grow as biofilms in the rhizosphere. However, their ability to form biofilms inside irrigation systems remains unproven. In addition, the bacteria genera *Gordonia*, *Crenothrix*, *Alkanindiges*, *Singulisphaera*, *Phenylobacterium*, *Blastocatella*, and *Zoogloea* form aggregates (flocs), which increase TSS, and those floating aggregates may lead to the clogging of irrigation emitters. The fungal community of our water samples had no known phenotypes that could result in clogged irrigation systems. The bacteria genera present in the tested water samples have phenotypic adaptations (e.g., adhesion to surfaces, exopolysaccharide production, and chemotrophic metabolism) that can be targeted to develop molecular methods that quantify the biological clogging potential in a water sample.

Use of the classification systems to identify the sources of clogging

The classification systems failed to identify the sources of clogging. The following case studies are provided to discuss why the systems failed and to propose ways to improve the systems to accurately identify the sources of clogging.

Biological clogging

Locations B and E were classified as having a low risk of clogging (Table 2) despite the visible filamentous growth blocking screen filters, drip emitters, and tubing. Well water in location B contained cyanobacteria (Obscuribacteriales and *Elstera*), iron-oxidizing bacteria (*Gallionella*), biofilm-forming bacteria (*Hymenobacter* and *Phenylobacterium*), and floc-forming bacteria (*Zooglea*) that may have contributed to biological clogging (Figure 4). The water in location E had low numbers of aerobic bacteria (Table 2 and Supplemental Material 3), but the samples had bacteria taxa with phenotypic adaptations that may have contributed to clogging. These adaptations include photosynthetic cyanobacteria (Chromatiales and Obscuribacteriales), iron oxidation (TRA3-20 unclassified and *Acidiferrobacter*), biofilm formation (*Rhizomicrobium*), and floc formation

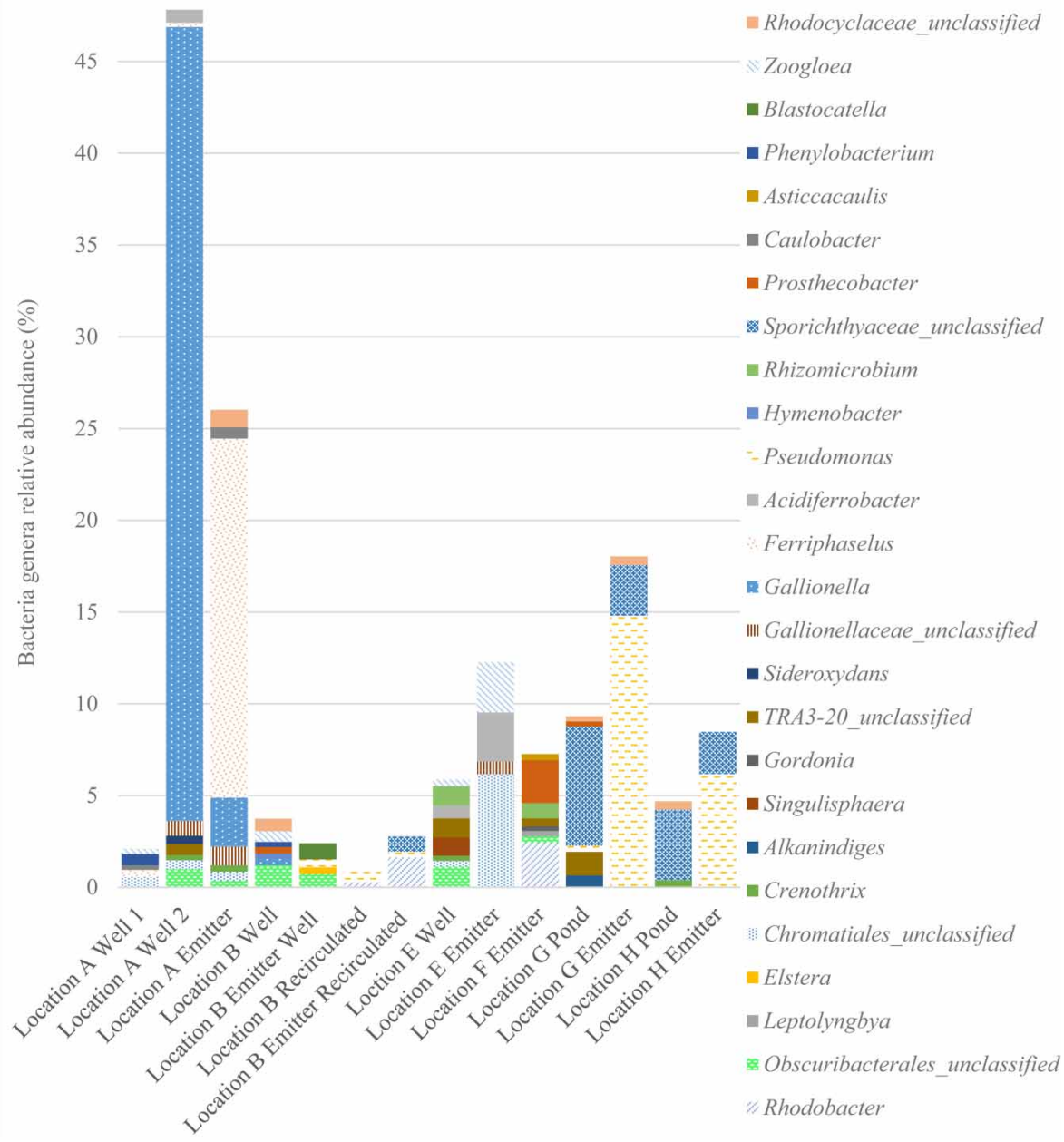


Figure 4 | Genus level relative abundance of bacterial communities with biological clogging potential in samples collected in 2017. The rest of the relative abundance percentage (not shown) consisted of other bacteria genera with no known clogging potential and operational taxonomic units that were not classified to the genus level. No DNA could be extracted from the public water source in location 6. Commercial greenhouse locations are described with letters from A to H (Table 1).

(*Crenothrix*, *Singulisphaera*, and *Zooglea*) (Figure 4). These observations suggest that the presence and abundance of specific bacteria in the irrigation water may be a more relevant indicator of clogging than the number of aerobic bacteria, which has been the sole indicator to assess the biological risk of clogging. The HPC method quantifies only culturable organisms and gives no indication of bacterial phenotypic characteristics. Therefore, the number alone is not a reliable indicator to assess the risk of clogging. Finding a single molecular or biochemical marker that screens for biological clogging–related traits is challenging due to the redundancy and multiplicity of genes and pathways involved in iron oxidation (Bonnefoy & Holmes 2012) and biofilm formation (Beloin & Ghigo 2005; Karatan & Watnick 2009) in bacteria. Therefore, additional research is needed to determine common microbial taxa among a wide array of clogged systems, which could lead to the identification of potential genetic and phenotypic markers. Furthermore, this research can aid in the development of methods that can be used to quantify biological clogging risks in irrigation systems.

Management practices change the quality of irrigation water in the distribution system, which, in consequence, may affect the risk of emitter clogging. The risk of clogging in location F rated low and moderate at the source and emitter, respectively (Table 2). The rating changed at the emitter because the number of bacteria, TDS, and magnesium levels increased relative to the source water (Table 2 and Supplemental Material 3). This location had a constant injection of fertilizers, which explains the increase in the nutrient levels and consequential higher chemical risk of clogging rating at the emitter (Table 2 and Supplemental Material 3). The nutrient solution was prepared in an open container that was placed in a ground-level trench, pumped to storage tanks, and passed through a 60-mesh screen filter with a transparent housing. A green filamentous growth was visible inside the screen filter. The nutrient solution at the emitter contained photosynthetic, biofilm-forming (*Rhodobacter* and *Rhizomicrobium*), floc-forming (*Gordonia*), and surface-attaching (*Asticcacaulis* and *Prosthecobacter*) bacteria (Figure 4). The biological risk of clogging rating increased because of possible contamination in the open mixing tank and the transparent screen filter housing that allowed light transmission, resulting in the growth of photosynthetic organisms. These results show that inadequate management practices can decrease water quality and increase the risk of clogging.

Chemical clogging

We suspected that iron build-up was the cause of clogging in locations A and C because we observed rust stains on emitters and inside the housing of disk filters. However, the samples in location A rated low for chemical clogging, while samples in location C rated moderate for manganese clogging (Table 2). The results from the commercial laboratory test showed no iron present in the irrigation water in 2015 (Supplemental Material 3). In 2017, we measured total soluble (iron II) and insoluble (iron III) iron along with the commercial laboratory tests for all locations. The measured and laboratory-reported levels of iron were 0.8 and 0.3 $mg{\cdot}L^{-1}$ for location A, and 2.5 and 0.2 $mg{\cdot}L^{-1}$ for location B. With these concentrations of insoluble iron, the samples were classified as having a moderate to high risk of chemical clogging. We also detected iron-oxidizing bacteria (*Acidiferrobacter*, *Ferriphaselus*, *Gallionella*, *Sideroxydans*, and TRA3-20 unclassified) in the water samples from location A (Figure 4) at near-neutral pH (Supplemental Material 3). This is in accordance with observations made by de Vet *et al.* (2011) in which *Gallionella* spp. grew and accumulated inside oxidation filters at pH from 6.5 to 7.73 and in water with oxygen at near saturation. This suggests that iron-oxidizing bacteria play an important role in the precipitation of iron that results in clogging, highlighting the importance of more specific qualitative and quantitative assessments of water quality.

Iron precipitation depends on interactions between chemical and biological processes. The standard water suitability tests for irrigation water in horticultural operations only measure the available iron for the plants, not the total iron or biological oxidation of iron. Therefore, models capable of estimating the biological and chemical oxidation of iron should be tested to determine the clogging risk of iron in water.

In location D, a white mineral precipitate clogged the emitter in an irrigation boom. However, the irrigation water in location D was classified as having a low risk of clogging (Table 2). The water was classified as moderately hard based on the levels of $CaCO_3$ and HCO_3^- according to the US Geological Survey 2016 (Supplemental Material 3). This suggests that the degree of chemical precipitation depends on the interaction between multiple parameters rather than the concentration of individual elements. A single indicator that explains these interactions is needed to estimate the chemical clogging risks. For example, the Langelier saturation index (LSI) estimates the degree of saturation of water with respect to calcium carbonate by considering the temperature, alkalinity, ionic strength, TDS, and pH of a sample (Bower *et al.* 1965). LSI values between -2 and 0 indicate that $CaCO_3$ is likely to remain in solution, and values between 0 and 2 indicate that $CaCO_3$ precipitation may occur (Rafferty 1999). The LSI for this location was below 0, suggesting no $CaCO_3$ precipitation. However, the sample at the emitter had no dissolved fertilizers, and we do not know the temperature of the water inside the pipes at the moment of sample collection. The classification systems can include the LSI as an indicator of scale formation to assess the chemical clogging risk of irrigation water. It is important to determine the levels of LSI at which emitter performance is affected.

CONCLUSIONS AND FUTURE PERSPECTIVES

The classification systems recommended by major international organizations were a useful tool to compare the relative risks between samples in the same location (i.e., from source to emitter and between water sources). However, they were not effective as a standalone predictor of clogging or as a tool for identifying the specific

sources of clogging. The systems did not provide enough insight into the specific cause of the clogging or hazard level. The major limitations of the classification systems were that their assumptions do not consider interactions among chemical and microbial factors or the qualitative characteristics of microbial communities and their assumptions overemphasize the value of chemical clogging – even when levels within the *severe range* included levels typically applied in fertigation in greenhouses. A reliable classification system serves as a valuable decision-making tool for practitioners to assess water source suitability and develop water quality management strategies aimed at mitigating the risk of emitter clogging. This supports in minimizing the economic impact of clogged irrigation systems. The classification system can be effectively used in tandem with real-time on-field clogging detection methods, such as the evaluation of emitter performance data and operating pressure.

Gaps identified and further research

Our observations indicate that assessing clogging risk based solely on the concentration of physical, chemical, and biological indexes can lead to unreliable results. To improve classification systems, it is essential for researchers to develop new indicators that account for interactions between water quality parameters and environmental conditions that lead to clogging. It is crucial to establish the relationships between these new water quality indexes and performance indicators for various categories of emitters.

Furthermore, relying solely on HPC to assess biological clogging risk is not advisable. Our results highlight the need to identify methods that screen for specific phenotypes that contribute to clogging, such as microbial surface attachment, biological iron oxidation, filamentous growth, and production of flocs, EPS, and biofilm. Research should also determine the levels at which these indexes may affect irrigation performance and may impact the economic and technical viability of farms. Identifying the specific cause of clogging is important for growers who aim to prevent issues and minimize economic risks with targeted treatment options.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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