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Increasing functional diversity of the urban canopy for climate resilience: Potential tradeoffs with ecosystem services?

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ABSTRACT

Cities are home to an increasing number of people who depend on urban forests to provide ecosystem services such as temperature regulation, air quality improvement and storm water abatement. Climate change may challenge the capacity of urban forests to provide these services. Intensification of heat waves, droughts and strengthening storms could lead to tree die-offs. In Quebec City, work has suggested that the urban canopy is vulnerable to future projected climates, i.e. hotter and drier summers. Compounding this threat, the exotic emerald ash borer is expected to kill 11 % of municipal trees over the next decade. Together these pressures could lead to a significant loss of canopy cover and ecosystem service provisioning in the near-term.

We test whether replanting strategies for lost ash, which shift the forest community towards a more climate-tolerant canopy using a functional trait-based approach, can help to mitigate or improve ecosystem service provisioning in the near-term. Using a municipal database of urban trees, we simulate canopy growth and replacement over 20-years for three different replanting scenarios: i) 'business-as-usual', ii) 'stratified' or iii) 'conifer-focused' replanting strategy, and compare their delivery of ecosystem services.

Results from the simulations find clear trade-offs in ecosystem service provisioning within and between replanting approaches. The 'conifer-focused' scenario provides the highest level of air quality improvement, storm water abatement and reduced energy demands in winter, however there are limitations on where coniferous trees can be planted in cities. In contrast, the 'business-as-usual' scenario achieved greater canopy cover, carbon sequestration, and high summertime cooling, but remains vulnerable to climate change. Stratifying replanting across tree functional groups results in the greatest increase to canopy diversity, intermediate levels of ecosystem service provisioning and important reduction in vulnerability to future pests . We suggest that a replanting approach focused on increasing the functional trait diversity of the urban canopy will likely confer the greatest ecosystem service benefits to the urban population and improve the resilience of the urban canopy to pests and climate pressures in the future.

1. Introduction

Urban forests play a critical role mitigating the impacts of climate change for city residents (Read et al., 2009) through their provisioning of ecosystem services, i.e. the benefits nature provides to people (Millennium Ecosystem Assessment (MEA, 2005). Urban trees make important contributions to storm water abatement (McPherson et al., 2000, 2002), air quality improvement (Hirabayashi, 2014; Hsieh et al., 2018; Nowak et al., 2018) and mitigation of urban heat island effects (Heisler and Grant, 2000; Akbari, 2002), all of which have important benefits for human health (Donovan et al., 2013) and municipal budgets (McPherson et al., 1997; Nowak et al., 2007; Elmqvist et al., 2015). Climate change is expected to increase the demand for these ecosystem services in cities via intensified storm events and hotter temperatures (Bower et al., 2008). At the same time, extreme events can put increased physiological pressure on urban ecosystems (Meehl et al., 2007). For example, increasing urban heat island effects can impact both tree growth (Martin-Benito and Pederson, 2015) and reduce resilience to stressors such as drought and pests (Cregg and Dix, 2001). Ensuring that urban forests remain resilient and continue to provide critical ecosystem

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services under future climate regimes is a mounting challenge for many cities.

The capacity of urban forests to mitigate the impacts of intensified weather events will depend on maintaining a healthy canopy cover (Fahey et al., 2013). Like any natural system, the function and resilience of the urban forest depends on the species composition of its community. More species- or trait-diverse communities are expected to have greater stability in ecological function (Yachi and Loreau, 1999) and greater resistance to pests (Civitello et al., 2015). These in turn support the provisioning of ecosystem services (Balvanera et al., 2006). For instance, Manes et al. (2012) showed that tree group functional diversity across the city of Rome, Italy exerted a complementary role in stabilizing air pollution removal throughout the year, and across different urban environmental conditions within the city, thereby improving overall ecosystem service provisioning. Understanding how species identity and diversity respond to future climatic conditions and affect ecosystem service provisioning will be needed for designing effective management approaches with an eye to the future (Kremen, 2005; Adams et al., 2012; Anderegg et al., 2015).

Like many northern cities, Quebec City in Canada is expected to experience significant changes in climate over the coming century. Regional projections predict an increase in summertime maximum temperatures by 2−5°C above an historical average of 23.5°C by 2100 and increase of annual rainfall of up to 150 mm by 2070–2080 (Logan, 2016), mostly in winter months. An assessment of the municipal urban canopy by Paquette and Messier (2016a) using a novel functional trait-based approach (Paquette and Messier, 2016b; Paquette et al., 2020) suggest the functional composition of the urban canopy in Quebec City may not be robust to these future climate pressures. The authors provide recommendations to help shift the composition of the canopy towards a more climate-tolerant structure and recommend a more even distribution of functional groups to improve the resilience of the canopy (Paquette and Messier, 2016a).

The urban canopy in Quebec City is also under threat from the Emerald Ash Borer (EAB), an exotic insect pest from Asia that arrived in 2017 (Ville de Québec, 2018). Across the city's managed trees, ash species make up ~11 % of all stems and constitute 13 % of the municipal canopy cover (Ville de Québec, 2018). Over the coming decade, all ash trees in the city are expected to succumb to the EAB, which attacks all 22 species of North American ash and kills virtually all infested trees (Poland and McCullough, 2006). This presents a significant challenge for urban forest planners who have a mandate to increase urban canopy cover across the city from 32 % to 35 % by 2030 (Ville de Québec, 2016). It also presents a significant opportunity to reconfigure the composition of the urban canopy to better cope with future stressors.

Selecting and strategically planting species based on anticipated future conditions and ecosystem service provisioning could improve the overall performance of the urban canopy in supporting human well-being. Tallis et al. (2011) show in their study of the Greater Los Angeles area that targeted planting of deciduous trees along streets in the most polluted areas would have the greatest benefit to future air quality. A similar study in New York City developed a prioritization map for planting based on human population density, expected pollution levels and existing tree cover to maximize the benefits from new tree planting (Morani et al., 2011).

In the case of Quebec City, shifting canopy composition away from the dominant broadleaf canopies that intercept rain, air pollution and UV light, (Lovett, 1994; Powe and Willis, 2004) towards slower growing, drought-tolerant species with smaller canopies may reduce ecosystem service provisioning across the city. Drought-tolerant species tend to have deep taproots with greater root-to-shoot ratios with less above ground biomass and smaller leaf areas (Korn, 2015). Leaves of these species also tend to have thick cuticle and epidermic layers and low stomatal conductance that reduce evapotranspiration (Korn, 2015). These characteristics, which make them tolerant to drier conditions, may limit their ability to provide equivalent levels of ecosystem services as large broadleaf species. Some drought-tolerant species, such as conifers, however, keep their needles year-round, potentially providing ecosystems services in parts of the year when broad-leafed deciduous species in northern latitudes cannot (Manes et al., 2012; Clapp et al., 2014).

In this paper we explore the potential for near-term trade-offs in ecosystem service provisioning that would result from shifts in species composition of the urban canopy in Quebec City towards more climate-tolerant species. Based on recommendations and the functional group classification of Paquette and Messier (2016ab, Table 1.) we develop and contrast three replanting approaches to replace the loss of ash to the EAB: i) a business-as-usual (BAU) approach where replanted species are selected at random from the existing species pool (apart from ash species), ii) a stratified replanting approach which selects species across tree functional groups to improve evenness and representation of all functional groups, including more drought-tolerant and flood-tolerant species, and iii) focused replanting of under-represented conifer species which tend to be more drought-tolerant. We hypothesize a trade-off in ecosystem service provisioning with the increased predominance of drought-tolerant conifer species in the urban forest community due to the loss of large-leafed deciduous species.

2. Materials and methods

2.1. The urban forest of Quebec City

Quebec City, Canada (52.9°N, 73.5°W) experiences a strong continental climate averaging 4.8°C annually with average highs in January and July of -7°C and 25°C, respectively, and receives annual rainfall of 1250 mm evenly distributed across all seasons. The city has a population of ~532,000 inhabitants and its land use is characterized by low-density urban structures with a number of large highways and green spaces cutting across the city (Communauté Métropolitaine de Québec, 2018). In recent decades the degree of urban sprawl has increased 9-fold in Quebec City (Nazarnia et al., 2016), extending the built up area from 132 km^2 in 1996 to 219 km^2 by 2011 and reducing the amount of urban green space. Within the city's urban perimeter of 75 km^2, the forest canopy accounts for 32 % of the land cover (Ville de Québec, 2016). The majority of forest cover is trees on private residential lots, wooded parklands and forest patches. Street trees and open parkland trees, managed by the Quebec City account for 6.7 % of urban forest cover (Wood et al., 2018).

In this study, we rely on the municipal inventory of street trees and parkland trees in 2017 provided by Department of Horticulture and Urban Forestry, which is publically available (https://www.donneesquebec.ca). This municipal canopy is composed of 103 269 trees from 187 species with over 390 varietals listed in the municipal inventory.

Table 1
Functional group classification of tree species in Quebec City.

Group	Functional group	Representative and abundant species
1	Shade-intolerant pine species, tolerant to drought	Black pine, red pine, pine (except for white pine)
2	Shade-tolerant conifer species	Spruce, fir, cedar, white pine
3	Pioneer species with rapid growth, low-density wood and flood-tolerant species	Cottonwood, willow, birch, larch
4	Large-seeded species with fast growth, medium-density wood, tolerant to drought	Oak, horse-chestnut, ginkgo, cherry, leguminous species
5	Small stature species with slow growth, dense wood and tolerant to drought	Lilac, elm (except American), hawthorne, apple, small serviceberry, small maple
6	Shade-tolerant species with, moderate growth, medium-high wood density	Maple, ash, linden, large serviceberry, American elm

Source: Adapted from Paquette and Messier (2016)

For each stem in the inventory data was available on the species name, diameter at breast height (DBH), geo-location, estimated date of planting, whether it was a street tree, and if so, its relative placement, and a unique identifier. This data was used as the baseline dataset for further analysis.

Following their classification approach in Gatineau, Quebec (Paquette and Messier, 2016b; Paquette et al., 2020), Paquette and Messier (2016a) applied a trait-based approach using species' sensitivity to environmental stressors (shade, drought and flood tolerance) and traits related to ecosystem services (seed weight, wood density, specific leaf mass, leaf nitrogen concentration, maximum photosynthetic capacity) to develop a functional group classification for the 187 species in the Quebec City municipal inventory (Table 1). This approach identified an over-dominance of shade-tolerant species with large leaves (group 6: maple, ash, linden, elm) and a severe under representation of drought and heat-tolerant conifers (groups 1 and 2). The authors recommend the adoption of such a functional-group based approach when developing planting lists to improve the diversity and evenness of species across the city. In particular they recommend an approach favoring conifers in groups 1 and 2 (especially pines) and as well as species from functional groups 4 and 5 to improve drought-tolerance across the city in light of projected future climate change.

2.2. Scenarios of future tree replanting

We constructed three alternative scenarios of replanting for trees lost to the EAB based on recommendations from Paquette and Messier (2016a). Currently, there are 12 118 ash trees within the municipal canopy inventory that will need to be replaced over the coming decade. In our first scenario, '*business-as-usual*', we replace all dying ash with a randomized selection of individuals from current inventory (excluding ash) to replicate the current species and functional group distribution. The second scenario, '*stratified replanting*' is constructed by selecting even numbers of stems (n = 2424) from functional groups 1, 2, 3, 4 and 5 to replace ash, but not from group 6 in order to reduced its over abundance in the community. Species in groups 1, 4, 5 are more tolerant to drought, while species in group 3 are more tolerant to flooding. Our final scenario, *'conifer-focused replanting'* replaces ash with stems from species only in functional groups 1 and 2 to improve their strong under-representation in the canopy and boost overall drought-tolerance.

We simulated the loss and replanting of ash stems over a ten- and twenty-year period for each scenario. In each, 10 % of ash are lost each year and replaced by new stems until all ash trees are replaced (year 10). All newly planted trees are assigned a diameter of 5 cm (standard replanting size for municipal trees) and grow each year based on species-specific growth rates (SM Table 1) estimated from data in the USDA Urban tree database (McPhearson et al. 2016) and rescaled around a 0.75 cm average annual growth rate estimated by iTree Eco model for Quebec City (see Supplemental Material for details). We assume a community-wide mortality rate of ~2% per year above the loss of ash to reflect typical non-EAB related tree mortality based on estimates provided by the Department of Horticulture and Urban Forestry for Quebec City (*pers. comm., Jérôme Picard*). To achieve this, each year of the simulation we select 2000 trees at random from existing and newly planted stems to remove and replant according to the replacement rules of each scenario. We extend our simulation of canopy dynamics (growth, death, replanting) 10 years beyond the loss of ash to cover a 20-year time horizon. Three simulation runs were generated for each replanting scenario. In each run, annual tree specific mortality was standardized across scenarios by using a random number generator in each year with a common seed set value across runs to select trees to remove.

2.3. Species composition, diversity and vulnerability

For all scenarios we assess the structural and functional group composition of the canopy at year 20 based on both the stem number and basal area. Using the x- and y-coordinates for each tree from the municipal canopy database, we calculate rarefied richness, Shannon's diversity, and Simpson's evenness of the replanted trees on a 300m × 300m (9 ha) grid across the city using the iNEXT package in R (Hsieh et al., 2016). We base these calculations on the species identity as well as functional group, and exclude grid cells where no public trees are planted. These values were then mapped and averaged across the city. In addition, we examine the number of stems and total canopy area susceptible to regional known pest threats as assessed by iTree v6.0 (i-Tree Eco v6, 2018), as an indicator of canopy vulnerability.

2.4. Estimating ecosystem services

We used the United States Forest Service UFORE urban tree model (i-Tree Eco v6, 2018) to estimate the provisioning of ecosystem services from the current municipal canopy and across runs for each of the three replanting scenarios. The i-Tree Eco model relies on a minimum set of parameters to estimate ecosystem service provisioning by individual trees, i.e. species identity and diameter at breast height (DBH), which were available from the city inventory. In addition, we collected field measurements for a subset of municipal trees to develop species-specific allometric equations for supplementary variables in the model that improve estimation accuracy. We selected the 70 most abundant species or varieties from the inventory to sample, which together represent 85 % of all planted municipal trees. For each species we generated a random sample of 40 stems stratified across their DBH range to sample. Trained technicians from the Department of Horticulture and Urban Forestry collected field measurements following i-Tree sampling protocols from May 11th through June 29th 2018, sampling 2352 trees across Quebec City.

For each sampled species we used field collected data to derive species-specific allometric equations to estimate measures of canopy structure from DBH and apply derived equations to remaining trees in the municipal dataset as well as to the constructed scenarios following closest-relative rules (see SM2). In select cases, tree diameters in the scenarios exceeded the applicable range of the species-specific allometric equations resulting in decreasing or negative values for canopy metrics (n = 2 species) in large diameter trees. In these cases, we applied the maximum estimated species-specific canopy metric value estimated by our allometic equations to all trunks beyond this size. This approach is conservative and may lead to slight underestimates of the true canopy size for these large individuals.

The inventories for the baseline and the three simulations for each replanting scenarios were then uploaded to i-Tree Eco to estimate processes related to five key ecosystem services: carbon storage, carbon sequestration, air pollution removal, avoided run-off and energy savings produced by municipal trees. We relied on built-in urban population estimates for Quebec City and meteorological data for ValCartier airport in 2015, located 15 km from downtown Quebec City. Due to the need for hourly climate data in i-Tree Eco, we were unable to include simulated weather data under future climatic conditions, as these are not unavailable at such a fine temporal resolution. Instead, we evaluated the provisioning of ecosystem services in each scenario at year 10 and 20 of the replanting simulation with weather data from 2015 to examine trends in the evolution of ecosystem service provisioning resulting from changes in canopy composition and structure, but not climate change *per se*. The model was also re-run for all scenarios and time periods with meteorological data for 2010, the only year in which built-in air quality data are available in i-Tree Eco for Canada. We report mean values and standard errors calculated across the three simulation runs for each scenario. All analyses were carried out in R Studio v1.0.43 and R (R Core Team, 2017).

3. Results

3.1. Canopy structure

Over the 20-year time horizon, all scenarios of replanting first lost and then recovered basal area, canopy cover and carbon storage, surpassing the baseline levels by the end of the simulation (Table 2). Differences between scenarios related to differences in growth form, captured by the allometric equations, wood density and species-specific growth rates. The greatest level of carbon-storage was achieved in the stratified replanting scenario. By the end of the simulation, all scenarios resulted in a loss of tree species and varieties, due to the loss of ash and rare species that were not selected in replacement planting (Table 2). The Business-as-usual (BAU) and coniferous replanting scenarios experienced the greatest species loss.

3.2. Species diversity

All scenarios represent an improvement in the spatial diversity and evenness of the municipal canopy across the city. Overall, the stratified replanting strategy achieved the highest averaged levels of rarefied richness, Shannon's entropy and Simpson's diversity scores of functional groups (Fig. 1, Table 3). The BAU replanting strategy performed second best for improving rarefied richness of functional groups across the city as it selected from all possible species present, while the conifer-focused replanting scenario achieved higher levels of rarefied Shannon's entropy and Simpson's diversity scores of functional groups by increasing presence of highly under-represented species across the city. Species-level results were similar and are not shown.

Based on the relative abundance of tree species, the three replanting scenarios resulted in strong differences in functional composition of the municipal canopy by the end of the 20-year simulations (Fig. 2a-d). The BAU scenario resulted in a composition that closely resembled the baseline community in terms of functional group representation, with the continued dominance of group 6. In contrast, the stratified replanting scenario achieved a more balanced composition across all six functional groups, while conifer-focused replanting scenario resulted in a strong shift in dominance towards coniferous species. However, when we look at the functional group composition weighted by the basal area (Fig. 2e-h), we see that despite changes in the number of stems per functional group, after twenty years there is little change in the basal area distribution across functional groups due to the relatively small diameter of the newly planted trees and the dominance of large remnant stems. With time, we would expect basal-area composition to shift to more closely resemble the stem-based composition as the canopy matures. As ecosystem service provisioning is linked to tree size, we would also expect that the ecosystem service bundles associated with each scenario would evolve through time in parallel.

Table 2
Comparison of simulated canopy structure of public trees across three scenarios of replanting over a 20-year time horizon as compared to the baseline. Values presented are means of three simulations for each scenario and standard errors (SE).

Scenario	Basal Area (m^3)	Canopy Cover (ha)	Carbon Storage (tn)	No. Species (Varieties)
Baseline	8 195.4	498.9	26 355.7	183 (391)
Business-as-usual replanting				
10 yrs	7 813.2 ± 12.3	464.5 ± 0.6	25 522.0 ± 42.3	165.3 ± 0.3 (354.7 ± 0.7)
20 yrs	8 962.5 ± 18.9	532.8 ± 0.3	29 113.3 ± 115.2	163.7 ± 0.3 (351 ± 1.5)
Stratified replanting				
10 yrs	7 840.2 ± 12.5	464.0 ± 0.6	25 502.5 ± 42.6	166.0 ± 0.6 (356 ± 1.2)
20 yrs	9 098.6 ± 20.4	531.5 ± 0.5	29 314.0 ± 76.9	165.7 ± 0.9 (353.7 ± 2.0)
Conifer–focused replanting				
10 yrs	7 818.2 ± 12.5	455.9 ± 0.6	25 430.4 ± 42.8	165.7 ± 0.9 (355.7 ± 1.8)
20 yrs	8 993.1 ± 20.4	507.0 ± 0.5	28 769.7 ± 76.9	162.3 ± 0.7 (348.3 ± 1.8)

3.3. Ecosystem services

3.3.1. Current canopy

Estimates from the initial run of the iTree Eco model with the baseline inventory data suggest that municipal trees in Quebec City currently store ~26,360 tons of carbon in their biomass and sequester ~689 additional tons per year. The model estimates that the municipal canopy traps and removes ~16 tons of airborne pollutants and helps to avoid ~96,970m^3 of storm water runoff through interception, evaporation and transpiration annually. Finally, municipal trees located next to residential buildings were estimated to reduce heating and cooling energy requirements by ~8.0 MWH and ~16,130 MBTU per year. Together, these energy savings are estimated to result in potential avoided carbon emissions of ~421 tons annually. Since only a single run was possible with the baseline inventory data, the lack of uncertainty around these estimates requires that we interpret them as approximate values of the true service provisioning of the urban canopy.

3.3.2. Replanting scenarios

All replanting scenarios experienced an initial decline in ecosystem service provisioning across all services over the first 10 years of replanting due to the loss of large ash trees in combination with the background mortality rate. In all scenarios, ecosystem service provisioning levels are restored to, and in most cases surpass baseline, levels by year 20 of the simulations (Fig. 3a-l). The rate of loss and recovery of services is strongly dependent on the background mortality rate used. We also tested a 3% mortality rate that showed similar patterns, but which barely regained baseline service provisioning levels by the end of the simulation time horizon (results not shown), which may in fact be more realistic mortality rate. Thus the absolute, but not the relative values in our results are sensitive to assumptions of background mortality rates.

Across all scenarios, the BAU scenario provided the highest levels of carbon sequestration and removal of carbon monoxide (CO) at all evaluated time points. However, overall the BAU provided lowest level of service provisioning for avoided run-off, reduction of heating costs, and removal of all other airborne pollutants. In contrast, conifer-focused replanting showed the highest level of avoided run-off, rainfall interception, air pollutant removal (apart from CO), as well as avoided heating and overall energy reduction. In general, the stratified replanting scenario had an intermediary performance for most ecosystem services, but provided the highest level of evapotranspiration and avoided cooling. The one service that no scenario was able to fully recover to baseline levels was reduction in summer cooling costs. At the end of the 20-year simulation there was still a 16–22 % reduction in the provisioning of this service, likely due to the small stature of most newly planted trees near buildings. Across the full suite of ecosystem services evaluated, the BAU replanting showed an average 2.3 ± 0.2 (SD)% improvement in overall provisioning over baseline levels, stratified replanting 6.9 ± 1.2 (SD)% and conifer-focused replanting 19.3 ± 0.3 (SD)% by the end of the 20-year simulation.

3.4. Vulnerability to pests

In addition to ecosystem services estimation, the i-Tree Eco model also cross-references the species composition of the canopy with known regional pest threats. In the case of Quebec City 22 potential insect threats were identified in addition to EAB. Replanting scenarios varied

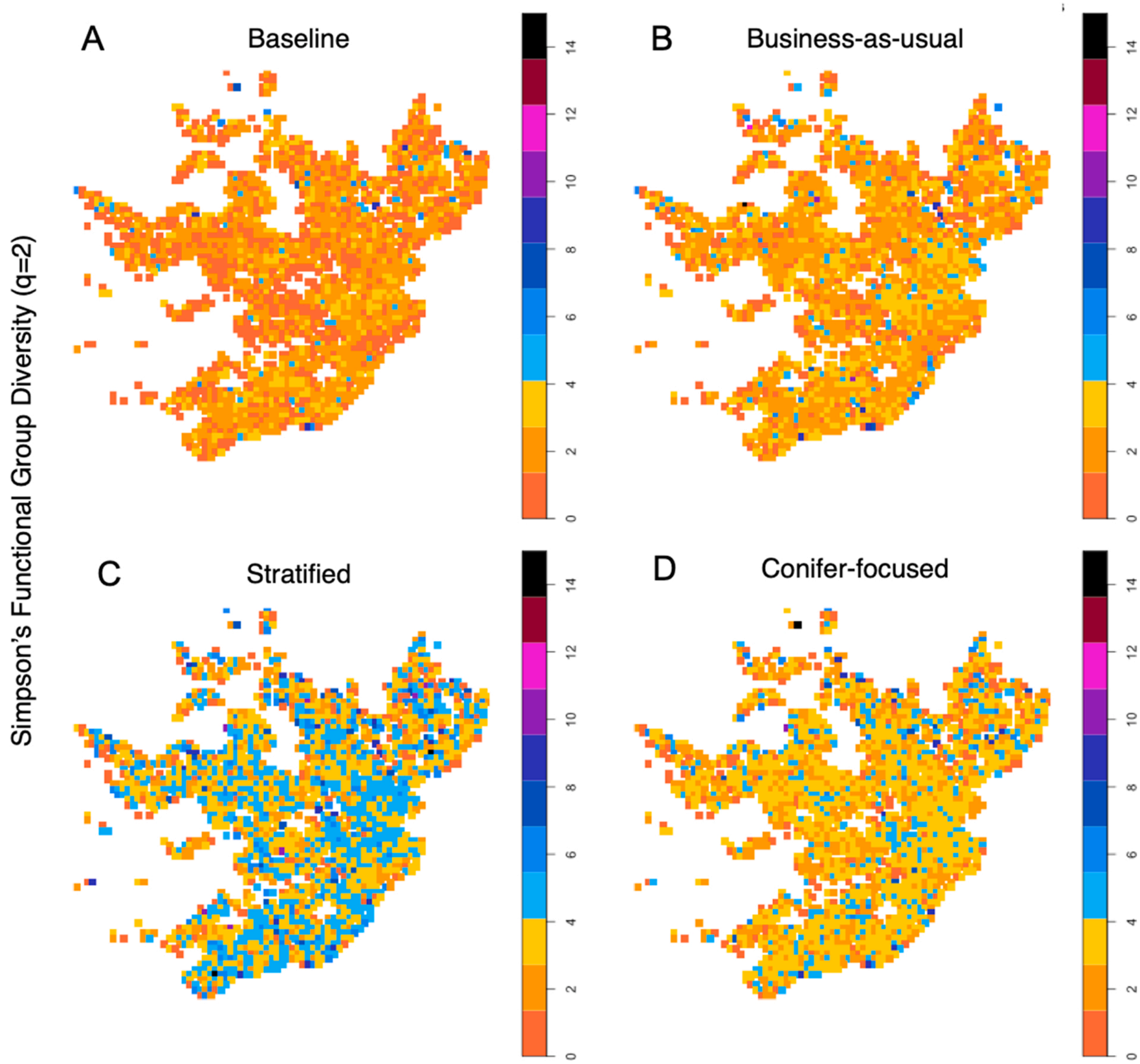

Fig. 1. a-d. Rarefied metric of inverse Simpson's index of diversity (Hill's q = 2) of municipal tree functional groups in a 300 × 300 m (9 ha) grid across Quebec City for the same simulation run in the (A) baseline, (B) business-as-usual, (C) stratified and (D) conifer-focused replanting scenarios. Red tones indicate lower diversity of functional groups and blue tones indicate higher diversity of functional groups per pixel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Averaged rarefied richness, Shannon's entropy and Simpson's diversity of functional groups of municipal trees per 9 ha-sampled grid across Quebec City in the baseline year = 0 and of the three replanting scenarios at year 20 of the simulation. Presented values are the average of means calculated for each of the three runs of per scenario ± average SE of runs.

Scenario	.Mean rarefied richness	Mean rarefied Shannon's entropy	Mean rarefied inverse Simpson's diversity
Baseline	3.39	2.36	2.08
Business-as-usual replanting	4.59 ± 1.15	3.09 ± 0.81	2.57 ± 0.79
Stratified replanting	5.33 ± 1.02	4.58 ± 1.03	4.08 ± 0.99
Conifer-focused replanting	4.38 ± 0.96	3.66 ± 0.84	3.34 ± 0.74

in the mean number of stems vulnerable to each known regional pest threats as well as the amount of canopy area potentially be affected (Table 4). All replanting scenarios reduced the total number of trees and percent of leaf area susceptible to regional pest as compared to baseline, as all ash were removed. The Asian long-horned beetle continued to present the largest threat in each of the replanting scenarios, potentially affecting ~65 % of the canopy in the BAU scenarios, and ~61 % and ~59 % of the stratified and conifer-focused canopies respectively, down from 69 % in the baseline. The greatest mean reduction in vulnerability was found in the stratified replanting and least in the conifer-focused replanting scenarios. In the conifer-focused scenario the southern pine beetle and pine shoot beetle threaten the greatest number of stems (~50,000 and ~32,000 respectively). Despite these high stem numbers, these pests only threaten ~16 % and 9% of the canopy respectively, as most susceptible pines would be recently replanted and still small. The threat posed to the canopy under this scenario would be expected to increase as these trees mature.

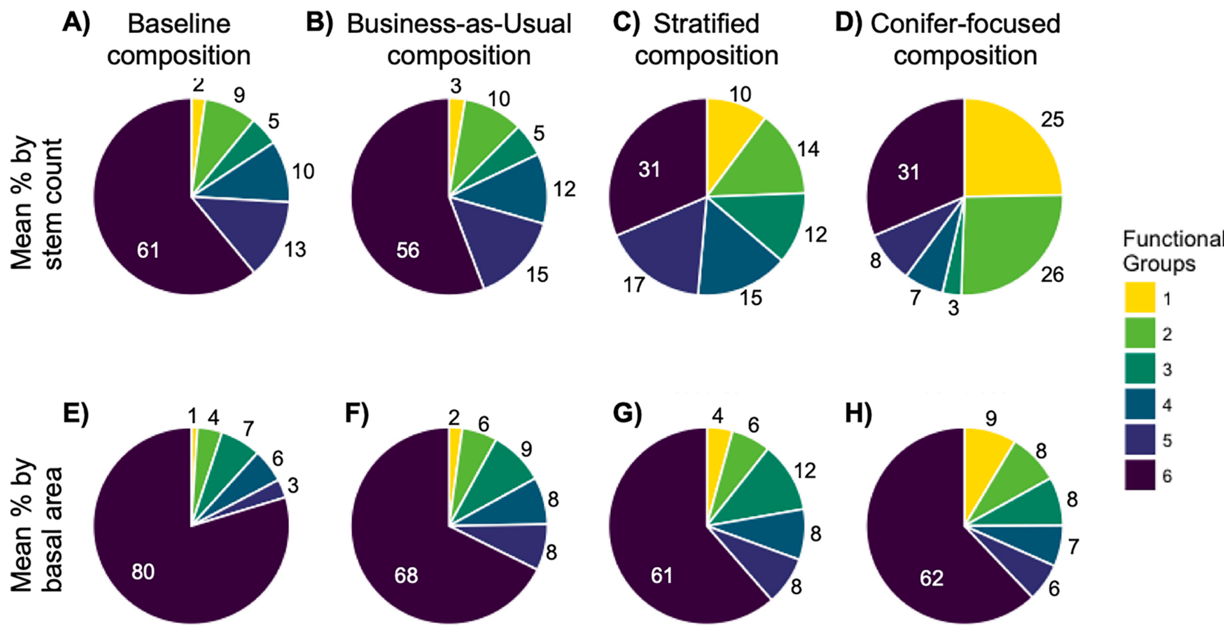

Fig. 2. a -h. Functional group composition of municipal trees of Quebec City by stem count (top row) and basal area (bottom row) in the 'business-as-usual', 'stratified', 'conifer-focused' replanting scenarios as compared to the baseline.

4. Discussion

The arrival of the Emerald Ash Borer (EAB) and the subsequent loss of ash trees are expected to have a significant impact on the provisioning of ecosystem services across Quebec City over the coming decades. Our scenarios suggest that service provisioning could change by +1.8 % to -66 % in the first 10 years after arrival of EAB, depending on the service and the replanting approach adopted (Fig. 3). While each of our three replanting scenarios restored most ecosystem services to initial levels after 20 years, there were significant differences between them in terms of the rate of restoration and the final provisioning levels achieved. The BAU replanting scenario achieved the most rapid restoration of canopy structure and carbon sequestration levels. In constrast, the conifer-focused replanting, designed to strongly increase the drought-tolerance of the canopy, achieved the greatest improvement in avoided run-off, air quality, and reduction in energy costs from residential heating. The stratified replanting scenario, which aimed to improve the evenness of the urban canopy while including more drought- and flood-tolerant species, was intermediate in its levels of ecosystem service provisioning. However, this scenario also helped to reduce the vulnerability of the canopy to regional pest threats and potential impacts of heat islands through higher evapotranspiration rates. While the relative levels of provisioning between scenarios were significantly different for the most part, the absolute degree to which services would be provided by the canopy will depend on their true growth and mortality rates of urban trees under climate change, pest and development. These results suggest urban forest managers may face important trade-offs when planning the future canopy composition for multiple functions, including future climate-tolerance.

Although this study did not explicitly test the capacity of different canopy compositions to provide ecosystem services under future climate conditions, the results provide an indication of how alternative replanting approaches, put in place today, will perform over the near-term as canopies transition to compositions with a greater number of drought- and flood-tolerant stems. Consideration of how canopies will perform under the new climate normals of 2050 or 2100 remains to be tested.

4.1. A rational for more conifers

On a per stem basis, conifers may provide a higher annual level of service provisioning than deciduous species in temperate climates as they keep their needles year-round (Clapp et al., 2014). In Quebec City, this is important as a significant proportion of the current annual rainfall (~75 %) occurs outside of the summer season when the canopies of deciduous trees are no longer in leaf. Moreover, because conifers respire under most weather conditions, they may also increase the water-holding capacity of soils in colder wet seasons by drawing water out of the ground through transpiration, promoting infiltration and further reducing run-off (Clapp et al., 2014). Looking towards the future, the role of conifers may become increasingly important for storm water management given that precipitation levels are expected to increase in Quebec significantly over the next 50–60 years, predominantly during the winter (Logan, 2016).

Conifers similarly provide year-round benefits for air pollution removal as a result of their dense foliage and needles. Manes et al. (2012) found in Rome, Italy that over the period of a year, conifers out-performed deciduous as well as evergreen broadleaf species in the absorption of ozone (O_3), a key air pollutant forming smog, when normalized by area of tree cover. The dense structure and foliage of conifers also makes them uniquely suited to act as windbreaks in cold climates, helping to reduce household heating needs. In a study by Donovan and Butry (2009), the authors found that by planting conifer species on the north side of a house (in the northern hemisphere) they thermally benefit the building by acting as a windbreak, without inhibiting heat gain from winter solar radiation from the south. In contrast, deciduous trees are recommended on south facing sides to shade houses in the summer and allowing solar radiation to pass through leafless branches in the winter (Heisler, 1986).

Currently, only 6.7 % of municipal trees planted next to buildings and 5.1 % of street trees are conifers. Increasing the proportion of these species in the urban canopy would not only increase drought-tolerance of the municipal forest, but could also provide significant increase in certain ecosystem services. Indeed, in our study we found that the conifer-focused replanting scenario improved storm water run-off reduction by an average of 11.7 ± 0.2 %, air pollution removal by 14.2 ± 0.4 % as well as reduced heating needs by 45.6 ± 0.3 % over the baseline after 20 years.

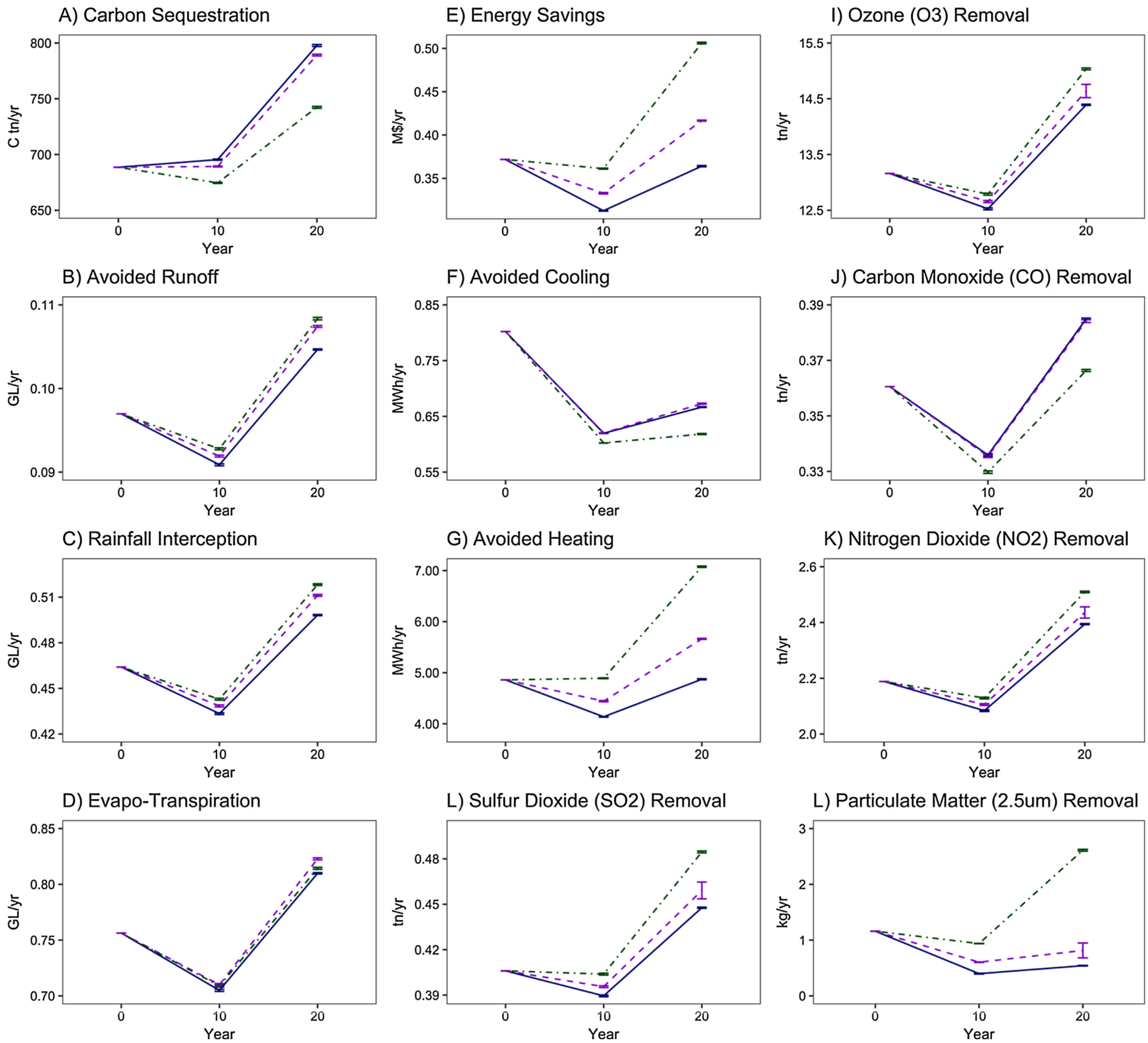

Fig. 3. a-l. Mean estimated levels of ecosystem service provisioning for 12 modeled services at 10 and 20 years after replanting. Lines represent the three modeled replanting scenarios: Business-as-usual (solid blue line), stratified (dashed purple line) and conifer-focused (pointed green line) replanting. Error bars represent calculated standard errors (SE). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
The number of stems, percent and maximum leaf area of municipal trees susceptible to regional pest threats in the baseline (year = 0) and in the three replanting scenarios at year 20 of the simulations for Quebec City, and top three dominant pests by number of stems. Values are means ± SE of the three simulations runs per scenario.

Scenario	No. Stems Susceptible across all pests	Percent of total leaf area susceptible across all pests (%)	Max susceptible leaf area per pest	Dominant Pest Threats
Baseline	88,252	96 %	69.4 %	Asian longhorned beetle Winter moth Gypsy moth
Business-as-usual replanting	86,199.7 ± 18.9	90.7 ± 0.03 %	64.7 %	Asian longhorned beetle Winter moth Gypsy moth
Stratified replanting	86,105.0 ± 9.8	90.6 ± 0.03 %	60.9 %	Asian longhorned beetle Winter moth Gypsy moth
Conifer-focused replanting	92,680.0 ± 26.2	92.0 ± 0.06 %	58.7 %	Southern pine beetle Pine Shoot beetle Asian longhorned beetle

4.2. Planning for resilience

As in many cities, the urban canopy in Quebec City faces multiple, possibly synergistic, environmental stressors (Logan, 2016). Traditional strategies to cope with multiple, known and unknown stressors in cities have been to diversify species composition, increase native species representation and avoid over-dominance by one species, genus or family (Ordonez and Duinker, 2013). While useful for increasing species and phylogenetic richness, these prescriptions do not look at the distribution of species functional traits, which are likely to be stronger predictors of responses to stress and ecosystem function (de Bello et al., 2010). Increasingly ecologists argue that it is not the number of species *per se*, but the diversity and type of functional traits which species express that drive ecosystem function (Tilman et al., 1997, Dıaz and Cabido, 2001, Diaz et al., 2004). Communities with both high functional diversity and high functional redundancy are expected to be more resilient to changes in their environment (Flynn et al., 2009; Laliberte et al., 2010).

To date, most studies using a functional trait-base approach (Knapp et al., 2008, 2012;Nock et al., 2013; Schütz and Schulze, 2015) have found that the strong selection pressure of the urban environment coupled with aesthetic preferences have homogenized urban plant assemblages, making them potentially more vulnerable to environmental change (McKinney, 2002; Kühn and Klotz, 2006). Despite the growing availability of trait-data, functional diversity is rarely used as a guide to help plan more resilient urban forest communities. Functional trait-based classifications, such as those developed by Paquette and Messier (2016b) and Paquette et al. (2020), can be instrumental in designing functionally resilient canopies. By taking a stratified replanting approach across functional groups, our replanting scenarios were able to achieve a more balanced and diversified functional composition in the urban canopy, with better representation of drought-tolerant (i.e. groups 1, 4, 5) and flood-tolerant (group 3) trees. In addition, stratified replanting retained the greatest number of original species and had the lowest number of stems vulnerable to regional pests. By selecting species across functional groups, urban planners may be best able to balance goals of improving canopy resilience to multiple stressors including climate change and pests, while providing a stable flow of ecosystem services throughout the city.

4.3. Selecting species that can grow today and thrive tomorrow

Due to the long-lived nature of trees, shifting the urban tree composition requires long-term thinking. Urban foresters are constrained in the selection of species to plant by a number of factors. The harsh conditions in the urban environment, i.e. unnatural hydrological cycling (Quigley, 2004), low quality of soil (Zhu and Carreiro, 2004), exposure to pollutants (Miyamoto et al., 2004) and direct disturbances (Florgård, 2000), all limit which types of species grow well in cities (Sieghardt et al., 2005). Species must also fulfill criteria regarding their form and function. Many trees are planted along streets where their base canopy height must be sufficiently high to allow pedestrians to pass below and permit adequate visibility for motorists, while also growing in constrained soil spaces.

In our study, we selected only species that already existed in the municipal tree inventory, and thus assumed they are sufficiently adapted to stressors in the urban environment. However, we assumed any particular tree across the city could be replaced by any other species existing in the inventory, regardless of site-specific considerations. This assumption is likely inaccurate, as conifers are rarely preferred for street trees in busy urban roadways as they block pedestrian passage and/or motorists view. These considerations may affect the feasibility of following a conifer-focused replanting scenario, as there are may be too few suitable sites to replant large numbers of conifers.

Secondly, urban planners must take into consideration how conditions are expected to change over the lifespan of tree. In many cases native species are often preferred in urban planting policies as they are assumed to be adapted to local climatic conditions, to make the best use of available resources, to control invasive species and to regulate the gene pool (McKinney, 2002). In addition, they maintain associated indigenous biodiversity (McKinney, 2002) and ecological integrity (Noss, 1990). However, native species may not necessarily be adapted to all future climate conditions. New climate extremes may exceed the tolerance of native species, making them vulnerable to dieback and/or pests. Urban foresters will need to look further field to identify regional species whose range shift and climate envelop will become suitable with future climate change, and consider how pests and pathogens are likely to spread (Yang, 2009). In our scenarios, we only consider trees already planted in Quebec City. It is possible that other species will become important in urban planting and for ecosystem services as conditions change in the coming decades.

Finally, local residents also have strong preferences regarding the types of trees and other vegetation planted in public spaces. In particular, urban foresters must consider the possible disservices that particular tree species provide. For instance, many urban plantings can increase allergens, promote invasive species, and host pathogens or pests (Lyytimäki et al., 2008). Urban plants can also be a source of pollution precursors, namely volatile organic compounds (VOCs), which when emitted in large enough quantities can influence urban ozone concentrations (Chameides et al., 1988). Despite all of these considerations, more often than not the final determinant of species selection is controlled by the supply from regional nurseries (Conway and Vander Vecht, 2015). In many cases the selection offered does not coincide with urban foresters needs (Sydnor et al., 2010), but rather residential consumers preferences. In such cases, it is essential that urban foresters work with the nursery industry to better communicate their needs in order to build a supply of locally appropriate species to help increase the diversity and resilience of urban forests.

5. Conclusions

We find that improving the functional diversity of municipal street trees and parkland trees in Quebec City, with an eye to improving climate-tolerance of the canopy, could have important near-term impacts on the delivery of ecosystem services. Overall, replacing ash trees lost to EAB with coniferous species provided the greatest recovery in provisioning of many ecosystem services, however it is likely an unrealistic scenario given aesthetic considerations and restrictions on planting sites. Adopting a stratified replanting approach across functional groups was most effective in increasing the spatial diversity of trees and reducing vulnerability to pests, while still maintaining higher levels of service provisioning than a business-as-usual approach. Stratified replanting is likely a more feasible option for urban foresters as it provide greater flexibility in selecting species to match site conditions while importantly increasing the resilience of the canopy to future stressors. Together these results suggest that over the short term the EAB will cause significant loss of ecosystem services to local residents, it will however, also create an important opportunity to improve the structure of the urban canopy to better meet the challenges of tomorrow.

Data availability

Datasets for this study are made available through the Open Science Foundation and can be found at: DOI 10.17605/OSF.IO/M36JD.

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CRediT authorship contribution statement

S.L.R. Wood: Conceptualization, Data curation, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **J. Dupras:** Conceptualization, Funding acquisition, Project administration, Writing - review & editing.

Declaration of Competing Interest

We declare there is no conflict of interest in regards to the publication of this manuscript.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ufug.2020.126972.

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