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ORIGINAL PAPER

Establishment and development of ornamental grasses on green roofs and living walls

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Abstract

Ornamental grasses are often used in gardens to improve biodiversity and as additional aesthetical resources. However, their use in green roofs (GR) and living walls (LW) is not so widespread and it has not been studied extensively. The aim of this work is to assess the performance of seven grass species (*Imperata cylindrica 'Red Baron'*, *Acorus gramineus*, *Stipa tenuissima 'Pony Fails'*, *Carex flagellifera 'Bronzita'*, *Carex oshimensis 'Evergold'*, *Uncinia rubra 'Everflame'* and *Miscanthus sinensis*) for their use in GR and LW. The growth of the plants was evaluated (i.e. biomass production, dimensions), as well as their visual quality and survival. *C. flagellifera* and *C. oshimensis* showed coverage levels greater than 75% and good visual quality, while *A. gramineus* reached 55–60%. *I. cylindrica* and *M. sinensis* showed coverages slightly below 50% in the LW, however, both performed well in the GR, though with a lower visual quality. *U. rubra* did not develop well, reaching the lowest coverage (below 45%) but maintaining a high visual quality. *S. tenuissima* also attained low coverage in the LW and presented high mortality, especially in the GR. In LW, *C. oshimensis* stood out in flowering, while *S. tenuissima* showed the highest flowering rate in GR. The species should be selected considering their characteristics and performance in order to achieve a correct appearance and development. Interspecific interactions are especially important in LW, as species with upward growth should be placed above species with fallen leaves, not below.

Keywords Vertical greening system · Green walls · Building integrated vegetation

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Introduction

Nowadays, some cities are so densely built that it is difficult to introduce new green spaces. For this reason, building-integrated vegetation systems are proliferating. Green roofs (GR) and living walls (LW) allow the use of the building envelope (roof and walls, respectively) for the placement of vegetation. Both GR and LW provide many ecosystem services, such as mitigation of the heat island effect, improvement of air quality, stormwater retention, or habitat creation (Collins et al., 2017; Milliken, 2018; Lin et al., 2021; Teotónio et al., 2021). They can be used for growing food, though they usually have an ornamental purpose (Fernández-Cañero et al., 2013; Mårtensson et al., 2016).

The typology of these greening systems is extensive and allows for the use of a great deal of plant species. For instance, GR range from far-reaching systems, including small plants with low maintenance, to intensive ones that support larger plants such as shrubs or trees (Cook-Patton and Bauerle, 2012). LW involve a supporting structure with different attachment methods (felt, panels or boxes) and a waterproof backing to isolate the LW from the building in order to avoid moisture problems (Fernandez-Cañero et al., 2018).

Different ornamental species with various planting designs are employed to create attractive vegetation systems with a long-lasting good appearance, playing with colours, sizes, and textures. But each constructive system has different characteristics that affect the selection of the plants species, not only based on aesthetic traits.

The careful selection of plants is critical to the success of the installation of greening systems. This must consider the microclimate, including exposure to the sunlight, wind, shade, and temperature fluctuations, as well as the intended use, aesthetic purpose, the ecological relationships between all the species and the fauna that could be associated with them (Snodgrass and Snodgrass, 2006; Sutton and Lambrinos, 2015).

As Snodgrass and Snodgrass (2006) point out, the most successful GR plants are low-growing, superficial-rooted perennials that are tolerant to heat, cold, sun, wind, drought, salt, insects, and diseases. They should also have the ability to self-propagate, a certain longevity expectancy, and ought to require minimal nutrition and maintenance. Following these characteristics, ornamental grasses (a term that refers to grasses planted in gardens and other amenity landscapes as opposed to those growing in natural places) could be a good option that also contributes to increase the diversity of plant species available for the GR industry instead of the standard succulents (*Sedum acre* and *Sedum spurium*) and grass species (*Poa compressa*) plants commonly used in them. A wide range of grasses are used for gardening, as they adapt to many growing conditions and their shapes, sizes, colours, and textures can complement beautifully (Hawke, 2018).

Since most ornamental grasses do not require intensive management and are closer to natural grasslands, the design and establishment techniques with those alternative types of grass bring more economic and environmental benefits, as suggested by Ignatieva et al. (2015). Another advantage of ornamental grasses, since they are not cut, is the movement of the plant with the slightest amount of wind, bringing a new dynamic element to garden compositions (Pudelska, 2008).

While ornamental grasses have actually become significantly popular for conventional landscaping (Davidson and Gobin, 1998; Pudelska, 2008; Thetford et al., 2011, 2009; Ignatieva et al., 2015; Tomaškin et al., 2015; Tomaškin and Tomaškinová, 2020), they are still relatively new to GR and LW. Regardless of turfgrasses being recommended for extensive GR since they have a low growth height, rapid cover capacity, and meadow appearance, they require deeper soil and need more maintenance of supplementary watering and pruning (NPS, 2009). Maclvor and Lundholm (2011) studied 15 species and observed that grasses and grass-like plants, known as graminoids, performed better with respect to their development and functions on extensive GR and could be suitable to improve their functioning, aesthetics, and longevity. Nagase and Dunnett (2012) reported that grasses (i.e. *Anthoxanthum odoratum*, *Festuca ovina*, *Koeleria macrantha*, and *Trisetum flavescens*) were the most effective for reducing water runoff, in comparison to different sedums and other herbaceous species in extensive GR.

In the case of LW, ornamental grasses are also becoming an alternative in the choice of species for vertical garden design. They should be selected not only based on aesthetic aspects but also on multiple factors such as the system of cultivation, the microclimatic conditions, and the sun exposure (Fernández-Cañero et al., 2018).

At the research level, the use of ornamental grasses has been much less studied for LW. Cheng et al. (2010) investigated the thermal effects of a vertical greening system planted with *Zoysia japonica*, a species that was selected due to its great versatility in terms of cultivation conditions, as it is resistant to high temperatures and drought, in addition to tolerating exposures of medium shade, although it prefers full sun, and stands out for its ability to provide a uniform vegetative cover. A few other researchers have also included grasses in their research, such as Marchi et al. (2015), who developed a model that simulates carbon dioxide sequestration in vertical gardens, taking into account different herbaceous species, finding that perennial grass (*Zoysia matrella*) captured the most carbon in its tissues. Riley et al. (2019) evaluated the growth and development of plants (*Lolium perenne* and *Festuca rubra*) in different concrete-based systems.

Both GR and LW usually have a marked ornamental component that implies approaching the research from a landscaping perspective focussed on the final visual result obtained, as opposed to other studies in agriculture and horticultural science, which prioritise production and final quality.

The assessment of ornamental grasses in terms of adaptation to very unique cultivation environments such as GR and LW has not been previously approached. GR are usually characterised by a limited depth (especially in extensive ones) and require the use of light substrates with good drainage properties (Eksi and Rowe, 2019). In LW, the growth in a vertical plane with a very reduced thickness available for the development of the roots constitutes a challenge.

The intra- and interspecific interactions are almost inevitable factors in LW composition. Designers, to guarantee total coverage of the system, should select the species considering the volume (width and height dimensions) of the plant, minimising the competition and maintaining the complete LW coverage. For example, combining in an LW species with an upright development with others which tend to arc down is not easy if the former is placed below the latter. Therefore, analysing the interactions between different species is of utmost importance to achieve a good result in the landscape design of these greening systems.

Another aspect to consider is the complete change in the position of plant growth from a horizontal to a vertical type of growth. Therefore, observing the differences in growth characteristics and their performance between GR and LW is also interesting and has not been studied before.

With the hypothesis that the development and growth of ornamental grasses can be conditioned by the characteristics of a GR or LW and in order to understand the potential of different species and identify the most important traits for their use in GR and LW, the objective of this work was the evaluation of different species of ornamental grasses to:

(1) determine which species exhibited better performance;
(2) compare their development between both greening systems;
(3) establish their particularities and interactions with the other species.

The species were selected considering their ornamental aspects (e.g. colour, flowering, height) and growth characteristics to guarantee the coverage of the structures. The availability of species in nurseries was also taken into account. Therefore, species with upright growth were combined with others with tufted, arching or mounding habits.

Materials and methods

Location and climatic conditions

The experiment was carried out at the School of Agricultural Engineering (University of Seville, Seville, Spain; 37°21′6.45" N, 5°56′12.35" W) for 7 months, from November 5th 2019 to June 3rd 2020. The LW modules were located on one of the walls facing south. The GR modules were placed close to them, above a concrete surface, to be subjected to the same conditions (i.e. sun exposition, temperature and humidity).

During the test, the temperature and relative humidity were monitored by means of a HOBO U23 Pro v2 Temperature/Relative Humidity Data Logger (Onset Computer Corporation, Bourne MA, USA), placed between the GR and the LW modules. The average temperatures ranged from 12.4 to 26.8 ºC, with maximum values of 39.8 ºC and a minimum of 3.4 ºC (Fig. 1). The average relative humidity was 69.1%, with maximum values of 99.8% and a minimum of 34.7%.

Plant species and experimental setup

A total of eight ornamental grass species were initially chosen (Table 1). The species were selected, among those available in nurseries of the area, according to different criteria. First, species with different characteristics (some upright, others hanging; interesting colours and textures in the foliage, etc.) were chosen. They had to also have a clear ornamental value. For example, *Imperata cylindrica* and *Miscanthus sinensis* were considered to have high aesthetic value (Tomaškin et al., 2015). Most species are used in 'conventional' landscape design, but they are hardly used in GR or LW.

Previous research experience in GR and LW was also valued. Hence, some of the selected species were already used by other authors in GR: *Stipa tenuissima* (Nagase et al., 2017), *Carex flagellifera* (Shim et al., 2011), or *I. cylindrica* (Hwang & Yue, 2015). However, they have not been used in LW, so comparing their development and assessing their potential is interesting. *Acorus gramineus* was previously used in an experiment with LW by Nan et al. (2020) and *Carex oshimensis* by Segovia-Cardozo et al. (2019).

Fig. 1 Evolution of maximum and minimum temperatures (ºC) in the experimental site during the test

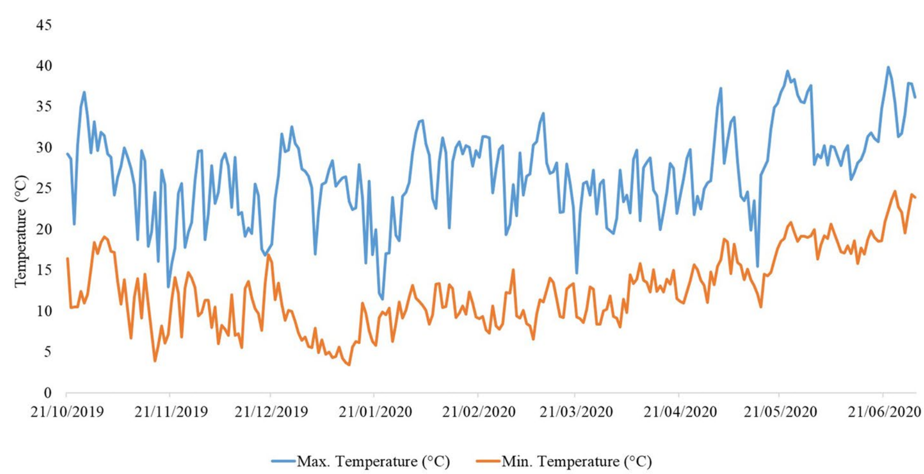


Table 1 Ornamental grass species used in the experiment

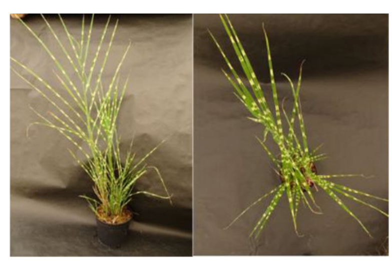
#	Scientific name	Abbreviation	Growth habit	Traits of interest	Side and top photo
1	*Uncinia rubra 'Everflame'*	Unc	Mounding growth	Bronze to bright red leaf	
2	*Stipa tenuissima 'Pony Fails'*	Sti	Upright erect growth	Hair-like green leaf	
3	*Festuca glauca**	Fes	Tufted growth	Green–blue leaf and fine texture	
4	*Carex flagellifera 'Bronzita'*	Car-fla	Mounding growth	Bronze leaf	
5	*Acorus gramineus*	Aco	Upright erect to arching growth	Variegated green and yellow leaf	
6	*Miscanthus sinensis*	Mis	Upright erect growth	Green and pale-yellow leaf	

Table 1 (continued)

#	Scientific name	Abbreviation	Growth habit	Traits of interest	Side and top photo
7	*Carex oshimensis 'Evergold'*	Car-osh	Arching growth	Green and central part of the leaf yellow	
8	*Imperata cylindrica 'Red Baron'*	Imp	Upright arching growth	Red, yellow, and green leaf	

**Festuca glauca* did not survive, it was replaced with *Zoysia japonica* (it was not taken into account in the data analysis because it was not planted simultaneously with the other species)

Festuca glauca was successfully used in other studies, both in GR (Nagase et al. 2017; Dusza et al., 2017; Yoon et al., 2021) and in LW (Cortês et al., 2021). However, none of the plants of this species survived in the early stages of our study (after 15 days from planting), so the plants could have been already damaged in the nursery, or they were not properly transplanted. In order not to modify the experimental design with the already ongoing test, this species was replaced by *Z. japonica* (characterised by its easy maintenance and low water and fertiliser requirements), which was not considered in the study. Therefore, only seven of the initially selected species were monitored.

A total of six plastic trays (0.75 m by 0.75 m by 0.12 m) were filled with a substrate mixture of 30% coconut fibre, 30% pumice, 20% perlite and 20% expanded clay up to a depth of 0.11 m in order to be used as extensive GR test modules. This substrate mixture was selected based on previous studies (Kotsiris et al., 2012; Pérez-Urrestarazu et al., 2019) and adapted with the main aim of serving for both GR and LW.

Another six LW modules (0.75 m by 0.75 m) were installed using a felt-based commercial system (Fytotextile®, Terapia Urbana S.L, Spain) composed of three synthetic layers: an outer polyamide layer, a geotextile intermediate layer and a waterproof back layer. The layers were sewn together, forming a grid of 25 pockets (0.14 m by 0.14 m each pocket) where the plants were inserted with the same substrate mixture described above.

The irrigation events took place twice a day, for 10 min each. This irrigation schedule was decided in order to avoid any stress for the plants due to water shortage. Shorter irrigation events with higher frequencies are recommended (especially in felt-based LW) (Perez-Urrestarazu et al., 2014). The duration of the irrigation event was set to prevent excessive drainage from the modules, based on previous experiences (Kaltsidi et al., 2020). The water was applied by means of three drip irrigation lines placed on the GR modules and one drip irrigation line placed in the upper part of the LW modules. Plants were fertilised once in mid-May using 3 g of Nutricote® (Projar Spain Ltd; N–P–K ratio 18–06–08) per plant. There was no pruning maintenance for the plants throughout the experiment, only the dry dead plants that tended to bend down (mainly *Miscanthus*) were removed two months after planting with no replacement. The weeds were manually removed.

Figure 2 shows the experimental design with species disposition in each of the GR and LW modules. Three replications were performed, each of them including two modules with the eight species. Given that the species disposition and neighbouring plants would affect irradiance and other cultivation environments, they were randomly distributed for each replication. Therefore, four plants of each species were planted for each replication, forming 8 species groups (4 in each module).

Plant development monitoring and maintenance tasks

The development and appearance of the plants was monitored every 2 weeks. The variables measured were related to the growth of the plant (coverage and dimensions) and the ornamental state (appearance). The number of dead plants (mortality rate) and those presenting inflorescence (flowering rate) was also recorded. At the end of the experiment, the generated biomass (dry weight) was obtained.

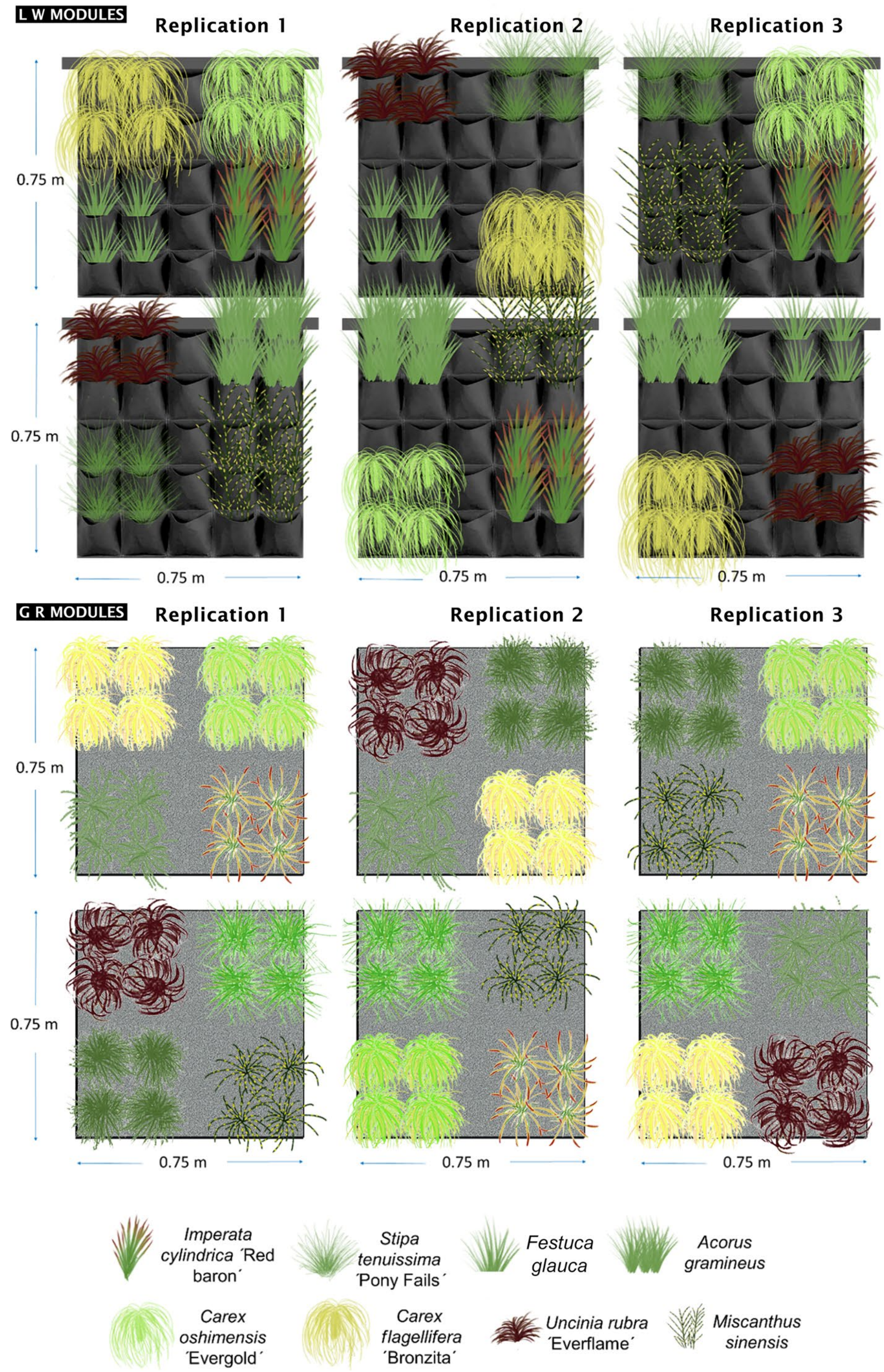


Fig. 2 Experimental design and species disposition in each of the living wall (LW) and green roof (GR) modules. Unc—*Uncinia rubra* 'Everflame'; Sti—*Stipa tenuissima* 'Pony Fails'; Fes *Festuca glauca**, Car-fla *Carex flagellifera* 'Bronzita', Aco *Acorus gramineus*, Mis *Miscanthus sinensis*, Car-osh *Carex oshimensis* 'Evergold', and *Imp Imperata cylindrica* 'Red Baron'. **Festuca glauca* did not survive, it was replaced with *Zoysia japonica* (not considered in the data analysis)

RGB images of each species group in the GR and LW modules were taken in order to assess the evolution of the vegetation cover during the experiment. The coverage (i.e. fraction of the module covered by vegetation) was determined by separating the pixels corresponding to the vegetation from the background of the modules (in the LW and in the GR) using ImageJ 1.52a image processing software (Rueden et al., 2017).

The dimensions of the species were obtained for the complete group of four plants of each species, as it was not possible to discriminate a single plant, mainly during the last two months of the experiment. In the LW modules, the dimensions of the plants were measured considering the growth of the plant to the front (horizontally), up and down (measured from the substrate surface in the pocket to the flag leaf) and its width and height. In the GR modules, the plant growth was measured by width-X, width-Y, and height (measured from the substrate surface in the plastic trays to the flag leaf) (Fig. 3).

A GreenSeeker handheld crop sensor (Trimble, Sunnyvale, CA, USA) was used to measure the Normalised Difference Vegetation Index (NDVI) in each species group. NDVI values the health and vigour of the plants (Turvey and Mclaurin, 2012) as well as the grass colour and density (Trenholm et al., 1999). A visual evaluation system, based on the one developed by the National Turfgrass Evaluation Program (NTEP) (Morris and Shearman, 1998), was also employed. For that, an Overall Visual Quality (OVQ) indicator was determined for each plant by rating its general appearance and the amount of dry leaves. The OVQ values ranged from 0 (100% of the leaves were dry) to 4 (less than 10% of dry leaves). This indicator was not recorded for Car-fla, as it was impossible to determine whether the leaves were actually dry due to the leaf colour of the species.

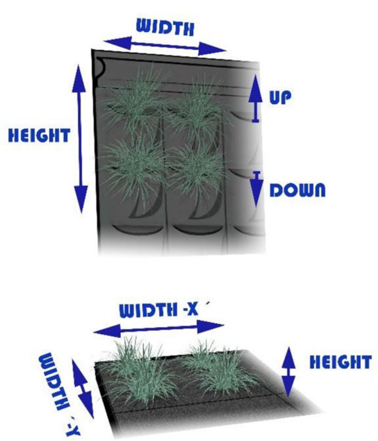


Fig. 3 Dimensions (width and height) measured in the species group, two per two plants, in the **a** LW and **b** GR modules

The total biomass production of each species was obtained by carefully separating, for each of the plants, the aerial part from the root system, drying it in an oven for 48 h at 80 ºC and registering the dry weights by means of an AH-300 precision scale (I.C.T., S.L., La Rioja, Spain).

Statistical analysis

The data collected were analysed with SPSS® Statistics (version 26.0.0.0; IBM Corp.). Variables complied with the assumptions of normality (Shapiro–Wilk test) and homoscedasticity (Levene test). Five analyses of variance were carried out: 1—comparing the final coverage of the species in the LW and GR modules; 2—comparing the total dry weight of the species in the LW and GR modules; 3—comparing the species dimensions in the LW and GR modules; 4—comparing the visual quality of the same species planted in the LW and GR modules in different months; 5—comparing the NVDI of the same species planted in the LW and GR modules in different months. Tukey post hoc tests at a 5% probability were also performed for each analysis of variance.

Results

The different species of ornamental grasses were monitored throughout the study and all the indicators calculated. Table 2 shows the coverage (average and final), visual quality, mortality and flowering rate, and biomass produced (as dry weight).

Figure 4 shows the changes of the coverage for each species in (a) LW and (b) GR. The average coverage values during the study ranged from 40.4 to 70.1% in LW and from 39.8 to 65.9% in GR. The species showing lower coverage were Unc (both in LW and GR) and Sti and Mis (in LW). Car-fla and Car-osh showed the highest coverages.

Table 2 Average coverage values during the study (COV_{av}), coverage at the end of the study (COV_f), overall visual quality (OVQ), Normalised Difference Vegetation Index (NDVI), mortality rate, and flowering rate for each ornamental grass species in the LW and GR modules

Indicator	Coverage (%)				Visual quality				Mortality rate (%)		Flowering (%)	
	COV_{av}		COV_f		OVQ		NDVI					
Species	LW	GR	LW	GR	LW	GR	LW	GR	LW	GR	LW	GR
Imp	48.2	40.7	49.6	64.9	2.5	2.3	0.24	0.26	0	0	8	0
Aco	52.4	51.6	55.4	60.2	3.5	3.7	0.30	0.37	0	0	8	17
Sti	46.7	48.3	46.0	67.4	2.1	1.4	0.24	0.29	25	42	8	42
Car-fla	70.1	65.9	79.0	68.9	–	–	0.21	0.25	0	0	0	0
Car-osh	69.0	55.9	78.0	79.4	3.6	3.5	0.30	0.37	0	17	67	17
Unc	46.1	39.8	40.5	43.1	3.5	3.7	0.30	0.36	8	33	0	0
Mis	40.4	50.7	48.8	74.8	2.4	2.5	0.24	0.34	0	0	0	0

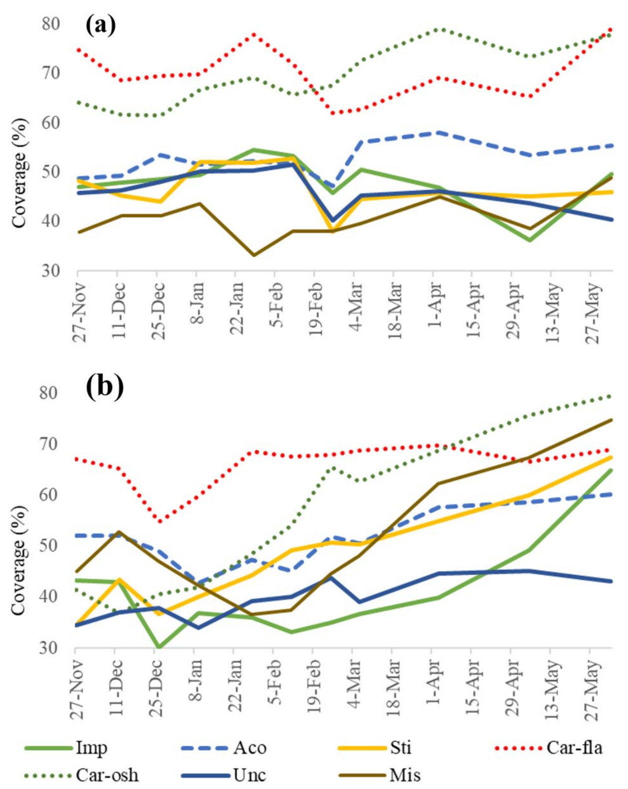


Fig. 4 Evolution of the coverage for the seven species of ornamental grasses in **a** LW and **b** GR modules

Curiously, Mis had a low value in LW but one of the highest in GR.

The final coverage ranges from 40.5 to 79.0% in the LW and 43.1 to 79.4% in the GR, but no significant differences were found (p value = 0.094) among them considering all species. Significant differences between LW and GR were only observed in the final coverage of Mis (p value < 0.05).

Taking into account the different species planted in the LW, Imp, Aco, Sti, Uns, and Mis did not show differences in coverage among them. However, differences were observed between Car-osh and Imp, Sti, Uns, and Mis. Car-fla presented differences with all species except Car-osh. In the case of GR, the differences were significant for all the species.

Few plants produced flowers (Table 2). Sti and Car-osh had the highest percentage of plants producing flowers, while Car-fla, Unc, and Mis did not flower at all.

Most of the plant species in this study survived during the entire experiment (Table 2). Figure 5 shows photographs of some of the GR and LW modules tested. The mortality rates of Sti were 25 and 42% and of Unc, 8 and 33%, in LW and GR, respectively. Car-osh had plant mortality only in GR (17%).

The average dimensions of each of the species' groups in the modules are shown in Table 3. In relation to the LW, the width variable was the only variable that did not show significant differences between species, and similar results were obtained in the width-Y variable in the GR. Mis and Sti showed, in LW, higher values for front growth (horizontally), Imp and Mis had higher values of up growth, and Car-fla had higher values for down growth and height. In the case of GR, Car-osh and Mis had higher width-X values, and Mis had higher height values.

The average dry weight per plant was 10.9 ± 7.1 for LW and 24.7 ± 24.3 for GR, therefore significantly different (p value < 0.05). When comparing the dry weight of the same species planted in LW and GR, all species show significant differences with a p-value < 0.05 (Table 3).

Sti was the species with a higher average biomass production in GR, followed by Car-osh and Mis, although there were no significant differences but with Unc. There was a high variation in weights between plants of the same species. In LW, Car-osh had the highest biomass, and there were no statistical differences compared with Sti and Car-fla. Unc was the species with the lowest dry weight both in LW and GR, followed by Imp.

The average values of OVQ were 3.01 ± 1.03 for LW and 2.87 ± 1.28 for GR (Table 2). In general, in terms of visual quality, the species studied had a similar behaviour in LW and GR. Figure 6 shows the OVQ values recorded monthly during the study. There were significant differences in OVQ values between months for all the species in the LW, except Car-osh. In the GR, differences were also observed except for Sti, Car-osh, and Unc. Sti shows the highest variation in time both in LW and in GR. Car-osh and Unc OVQ remained quite invariant during the months studied for both systems. As the months passed, the OVQ of Imp, Aco, and Mis species worsened in both LW and GR, and for Car-osh and Unc, it remained the same. However, OVQ improved for Sti in LW but remained the same in GR. This indicator was not recorded for Car-fla, due to the colour of the leaves of this species.

The average NDVI values of 0.26 ± 0.07 and 0.29 ± 0.11 were recorded in LW and GR, respectively. Figure 7 shows the variation in NDVI in the different months within each species. Significant differences (p value < 0.05) in NDVI were observed in LW for Imp, Aco, Car-fla, Car-osh, Unc and Mis, except for Sti (p value = 0.230). In the LW, for Imp, Aco, Car-fla, Car-osh, and Unc species, the NVDI values tended to decrease over time, while for Sti and Mis these values remained the same. In contrast, the NVDI values of all GR species did not present statistically significant differences due to the high variability of the data obtained, although changes over time were also observed.

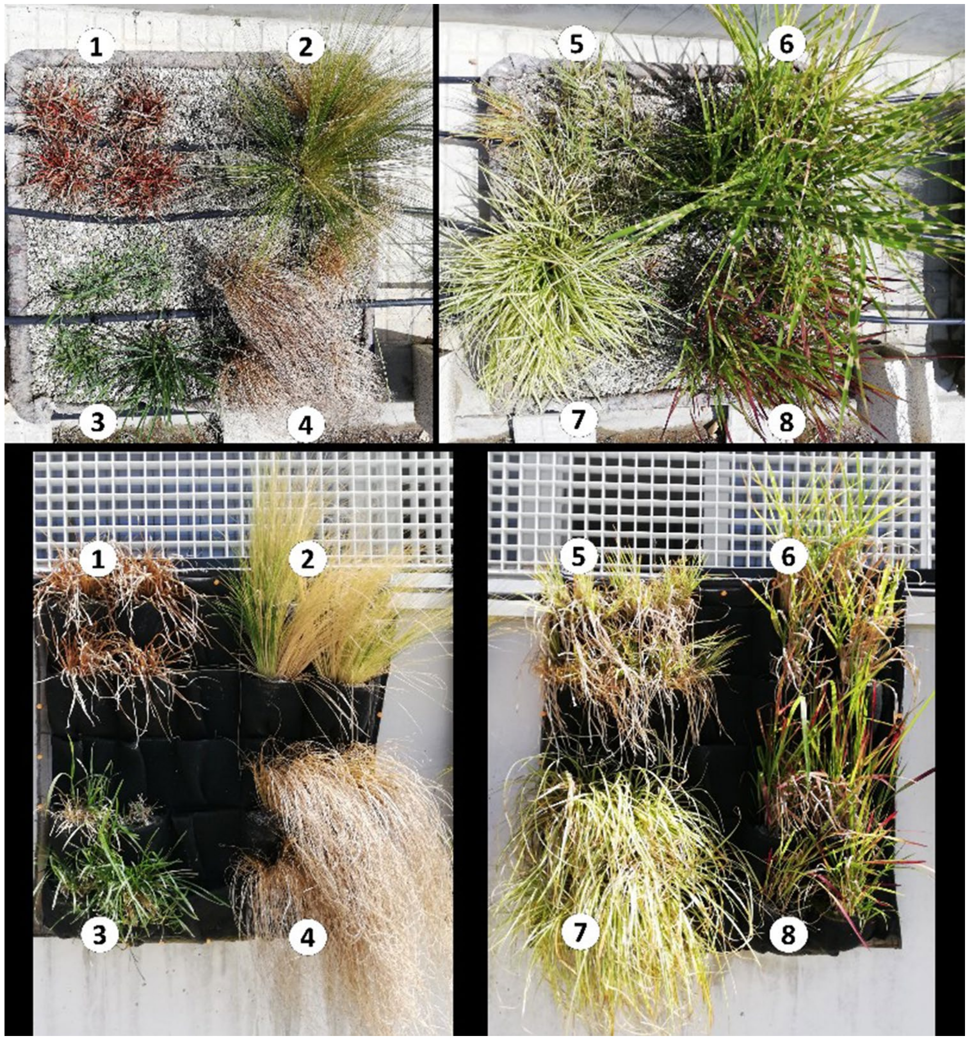


Fig. 5 Photographs showing some of the GR and LW modules tested. (1) *Unc Uncinia rubra 'Everflame'*, (2) *Sti Stipa tenuissima 'Pony Fails'*, (3) *Zoy Zoysia japonica* (replacing the original *Festuca glauca* that did not survive and not considered in the data analysis), (4) *Car-fla Carex flagellifera 'Bronzita'*, (5) *Aco Acorus gramineus*, (6) *Mis Miscanthus sinensis*, (7) *Car-osh Carex oshimensis 'Evergold', and* (8) *Imp Imperata cylindrica 'Red Baron'*

Table 3 Average dimensions of species groups in the LW and GR modules at the end of the study and dry weight per plant. Different small letters in the same column denote significant statistical differences between the different species in the same cultivation system (LW or GR)

	LW						GR			
	F*	U***	D***	W^ns^	H***	DW**	W-X**	W-Y^ns^	H***	DW**
Imp	29 ± 4^{ab}	41 ± 1^{a}	0 ± 0^{c}	45 ± 11	56 ± 1^{ab}	5.7 ± 2.4^{d}	47 ± 2^{ab}	52 ± 15	48 ± 6^{bc}	12.2 ± 5.9^{ab}
Aco	15 ± 5^{b}	15 ± 1^{c}	0 ± 0^{c}	40 ± 2	30 ± 2^{c}	7.7 ± 2.1^{cd}	54 ± 2^{ab}	46 ± 3	19 ± 3^{d}	14.1 ± 5.3^{ab}
Sti	30 ± 7^{a}	34 ± 10^{ab}	0 ± 0^{c}	47 ± 8	52 ± 10^{ab}	14.0 ± 6.9^{abc}	58 ± 16^{ab}	72 ± 29	64 ± 20^{ab}	57.7 ± 41.1^{a}
Car-fla	28 ± 2^{ab}	17 ± 2^{c}	33 ± 7^{a}	39 ± 3	62 ± 6^{a}	15.4 ± 2.4^{ab}	48 ± 14^{ab}	58 ± 6	22 ± 1^{d}	18.7 ± 5.0^{a}
Car-osh	26 ± 6^{ab}	23 ± 7^{bc}	15 ± 6^{b}	52 ± 9	51 ± 11^{ab}	18.6 ± 10.9^{a}	71 ± 6^{a}	63 ± 11	29 ± 5^{cd}	38.9 ± 26.4^{a}
Unc	18 ± 1^{ab}	13 ± 3^{c}	14 ± 3^{b}	38 ± 4	40 ± 2^{bc}	5.6 ± 2.5^{d}	41 ± 2^{b}	44 ± 5	16 ± 3^{d}	8.0 ± 1.7^{b}
Mis	30 ± 7^{a}	38 ± 4^{a}	0 ± 0^{c}	47 ± 11	53 ± 6^{ab}	9.9 ± 5.3^{bcd}	69 ± 11^{a}	60 ± 12	75 ± 9^{a}	38.7 ± 29.2^{ab}

F Front (cm), *U* Up (cm), *D* Down (cm), *W* Width (cm), *H* Height (cm), *DW* Dry weight (g)

ns not significant, $p>0.05$. $*p<0.05$; $**p<0.01$; $***p<0.001$

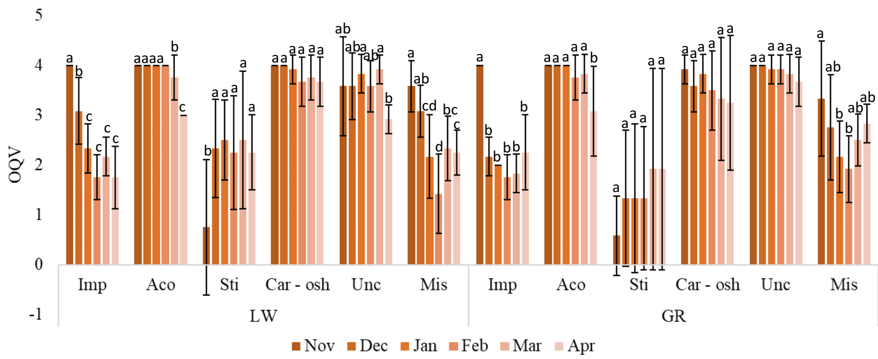


Fig. 6 Overall visual quality (OVQ) for six species of ornamental grasses from November 2019 to April 2020. Different letters denote significant statistical differences between OVQ values of the same species in different months per planted module, according to the Tukey test (p value < 0.05)

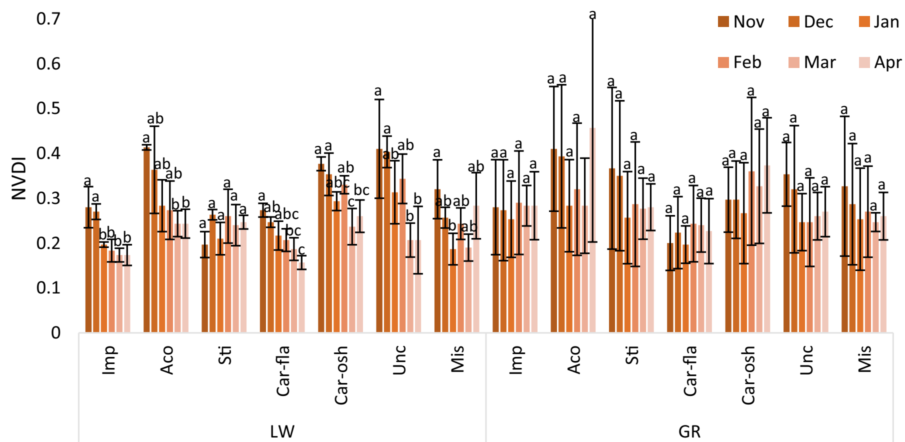


Fig. 7 NDVI values for the seven species of ornamental grasses from November 2019 to April 2020. Different letters denote significant statistical differences between the NDVI values of the same species in different months per planted module, according to the Tukey test (p value < 0.05)

Discussion

This work gives valuable information on the ability of ornamental grasses to survive and grow on GR and LW in Mediterranean climates, with dry summers and wet winters, as observed in Seville.

The species tested showed different degrees of performance. In general, all the species worked better in GR than in LW. This is understandable given the growing conditions in these systems, as the available space for rooting was much larger in GR than in LW. Though grasses can grow in shallower growth media, they thrive in depths ranging from 0.15 to 0.20 m (Luckett 2009). In addition, the amount of water that can be stored by the growing medium is usually much lower in LW modules (especially in those which are felt-based). Therefore, any problem with the irrigation system that provides water to plants will have more undesired consequences in the LW. The water distribution should also be considered, as the lower parts of the LW will be wetter than the top (Pérez-Urrestarazu et al., 2014).

In addition, plants are subjected to intraspecific and interspecific competition from others around them (Jørgensen et al., 2018). In LW, the competition for light tends to occur due to high plant densities, and its degree depends on the species. For example, the species with upright growth could shadow those planted above them (e.g. Mis and Imp) or, likewise, the species whose leaves tend to grow down could affect other plants located under them (e.g. Car-fla and Car-osh). This tends to be less likely to occur in GR than in LW.

These reasons can also explain the significant differences observed between the dry weight per plant in GR and LW. In the former, the weight more than doubled that of the latter, as we could mainly observe in Sti, Car-osh, and Mis.

Regarding the survivability of the plants, only Sti, Car-osh, and Unc (only 1 dead plant) showed problems, the former having the highest mortality in both LW and GR. In LW, the plants that did not survive were usually located at the bottom of the species group, but the growth of the surrounding plants did not suggest causes related to the competition for light. In addition, root interactions and competitiveness for resource uptake could determine the survival of the plants (Jayamanna et al., 2022), especially in environments where space and resources (i.e. water and nutrients) are limited. In GR, the mortality rate was much higher than in LW. This could be related to the greater development (more coverage and height) some species showed in the former, leading to a higher intra and interspecific competition.

The amount of surface covered by each species is important in both growing systems, but it is particularly essential in LW, where having a continuum with plants all over the black vertical surface (the outer polyamide layer) is usually desired. In this sense, the coverage finally reached was higher in all species for GR than for LW (except for Car-fla), although significant differences were only observed for Mis. While the coverage obtained in GR was greater than 60% (excepting Unc), in LW only three species exceeded 50%. A seasonal variation of coverage was observed (Fig. 4).

In the LW, coverage remained constant during the first months. In most species, it decreased at the end of January or during February, periods with the coldest temperatures, and then slightly increased again. This did not occur in Unc, which showed a lower coverage, overall visual quality (OVQ), and NDVI values at the end of the experiment than at the beginning. The low coverage values observed in Unc indicates that it is less suitable for use in LW.

In the GR, a slightly decreasing trend was also observed during winter, though from February onwards the coverage clearly increased in most species. Again, only Unc remained with low coverage values until the end of the experiment. This slight difference between the behaviour of the different species in LW and GR, especially during winter, is understandable given that in the former system the root zone is more exposed, so the air temperature affects them more. The thicker substrate layer present in the GR somehow insulates the roots from the cold.

In LW, there were no significant differences in the dimensions of 'front' (except between Unc and Car-fla) and 'width'. For Car-fla, Car-osh and Unc, the leaves grew up and fell below the planting level of these species. Though this favours the achievement of a dense and continuous cover, it could influence the development of the species located below them, especially in the case of Car-fla. The same can occur with tall species such as Imp, Mis or Sti since the plants were cultivated in pockets with approximately 0.15 m of height between one and the other and those plants grew more than 23 cm up. The 'up' and 'down' dimensions of the species (above and below the pocket) provide important information about the plant ability to cover the LW system. Furthermore, the 'front' growth gives an idea about the horizontal space (separation from the wall) occupied by the plants and the LW system. For these species (i.e. Imp, Mis or Sti), with a marked development in height, an important difference was observed between plants grown in LW and GR, being much taller in the latter. It must be considered that the dimension 'height' in GR corresponds to the dimension 'up' in LW (see Fig. 3).

Tall species such as Mis (which can reach heights of more than 1.5 m) are very appropriate for open spatial-like gardens, parks, lawns (Tomaškin and Tomaškinová, 2020), which also include GR. However, in LW they can be somewhat difficult to manage due to the higher planting density that is usually employed in them. Therefore, the planting design must consider the dimensions of these plants in order to avoid causing shadowing problems to other species planted around them.

Other studies reported heights for Imp of 28 cm (Davidson and Gobin, 1998), 30–40 cm (Tomaškin and Tomaškinová, 2020) and 65 cm (Thetford et al., 2009). In our study, this species reached between 41 and 48 cm. For Mis, however, the average heights observed in our study were 38 and 75 cm (for LW and GR, respectively), in the range of those observed by Davidson and Gobin (1998) (20–60 cm), but lower than those reported by other authors: between 70 and 119 cm (Thetford et al., 2011), 134 and 164 cm (Thetford et al., 2009) or an average of 83.6 cm (Yuan and Dunnett, 2018). No references for the other species tested were found. Therefore, it is worth mentioning that the LW system has limited the growth of most species, mainly the upgrowth. The vertical position of both shoots and roots and the reduced thickness and space available for the development of the roots may be the reason for this limitation of growth in height. An excessive upward growth with a lower root anchoring capacity could cause the plant to fall down.

The aesthetic value of ornamental grasses is not only provided by their foliage (e.g. Imp, Mis), but also by the stems and/or inflorescence and fruits (e.g. Sti) (Tomaškin and Tomaškinová, 2020). Flowering species also improve the appearance of the GR or LW. In our study, flowering was limited. Only Car-osh showed a higher percentage of plants (8 out of 12) flowering in the LW, while only one plant flowered for Imp, Aco and Sti. The latter two showed better flowering in the GR. Car-fla, Unc, and Mis did not have any flowering. Davidson and Gobin (1998) observed no flowering either for Imp and Mis. In contrast, Thetford et al. (2009) reported flowering for both species.

In terms of visual quality, Aco, Car-osh and Unc showed the best OVQ values, Sti and Mis being those with lower values. On the contrary, Thetford et al. (2011) reported an acceptable visual quality for Mis after two seasons. Tomaškin and Tomaškinová (2020) recommended *Stipa* species for GR. In our study, the one used (*S. tenuissima 'Pony Fails'*) worked well, reaching good coverage, though the OVQ was not high, especially one month after planting. In LW the coverage was lower, but had better OVQ values. The main flaw observed in this species was the high mortality rate, especially in GR where nearly 50% of the plants died before the end of the study. This difference may be due to the higher development of plants in GR that led to higher competition for the limited resources, to which Sti showed itself to be particularly affected. Car-osh and Unc also presented dead plants in GR (2 and 4, respectively) and only one dead Unc plant in LW. Therefore, the survival in the short term was high except for Sti. Although we did not test plant survival in the long term, other studies showed that Mis survived between 1 and 4 years (Davidson and Gobin, 1998; Thetford et al., 2009). Thetford et al. (2011) also reported a high level of survival for Mis after two seasons. In the case of Imp, while Davidson and Gobin (1998) observed a plant survival of 4 years, Thetford et al. (2009) indicated that less than half of the Imp plants they tested survived beyond a second year. No information was found on the other species.

The use of ornamental grasses in GR and LW can also present some problems, as they usually produce high amounts of pollen, which can pose a health risk for people with a predisposition to these allergens (Cariñanos and Casares-Porcel, 2011). The invasive nature of some species of ornamental grasses can be considered a drawback as well, and this should be taken into account when selecting species for planting. For instance, Tomaškin and Tomaškinová (2020) described Imp as one of the most aggressive invasive species of ornamental grasses. On the contrary, Davidson and Gobin (1998) reported that this species (along with Mis.) has low invasiveness.

Conclusions

The potential of using ornamental grasses in LW or GR is high due to their aesthetic value, as the different colours, sizes and flexibility of the leaves provide unique textures, volumes, and movements to plants in the green system. They also have low maintenance requirements (it was only necessary to prune the dead plants of few species that tended to bend down, manually remove weeds and fertilise once), which is interesting in growing systems that usually present access constraints and require working in heights. In addition, their resistance to climate conditions with high variability in ambient temperature (during the months of the experiment, the species were in Seville, Spain, with an ambient temperature between 3.4 and 39.8 ºC) allows their use in a wider spectrum of locations.

The selection of possible species to be used in GR and LW is usually made according to different criteria that allow creating interesting landscape compositions using different types of leaves, colour, flowering, etc. However, the designer needs to know the type of growth and behaviour that the species will have to fit it into the design and avoid possible problems with neighbouring species. To guarantee the total coverage of the GR and LW composition system, the species should be selected and placed considering all those aspects and also the intra and interspecific interactions, since the planting density in these systems (especially in LW) is very high. For example, in LW, species with upward growth (such as Aco or Mis) should be placed above species with falling leaves (such as Car-fla or Car-osh), not below.

In our study, Car-fla and Car-osh showed the best performance in terms of coverage and visual quality, followed by Aco, Imp and Mis also performed well in the green roofs, though coverages slightly below 50% were obtained in living walls. Unc showed poor development and the lowest coverage. However, it maintained a high visual quality, although some plants did not survive. Sti grew well, although it had low coverage in the LW and high mortality, especially in GR. More studies are needed to test the long-term survival of these species grown in GR and LW.

Author contributions GPSC: conceptualisation, data curation, formal analysis, investigation, resources, software, supervision, visualisation, roles/writing—original draft, and writing—review and editing. DKM-S: data curation, investigation, methodology, project administration, resources, supervision, validation, roles/writing—original draft, and writing—review and editing. RF-C: conceptualisation, data curation, investigation, methodology, project administration, resources, supervision, validation, roles/writing—original draft, and writing—review and editing. VL: conceptualisation, investigation, project administration, resources, validation, roles/writing—original draft, and writing—review and editing. LP-U: conceptualisation, investigation, methodology, project administration, resources, supervision, validation, roles/writing—original draft, and writing—review and editing.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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