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Seasonal variation in preference for green roof vegetation

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Green roofs are vegetation systems that are particularly well-suited to dense urban environments, and can contribute multiple ecosystem services that support biodiversity, human health, and well-being. Several health benefits are dependent on the way that people perceive the characteristics of the vegetation on the green roof, that is, their environmental appraisal. In this study we set out to explore the effects of different types of green roof vegetation, along with seasonal and successional variations, on visual aesthetical experiences, as well as perceived biodiversity. An online photo elicitation survey was conducted using standardised photographs of a selection of green roofs in Malmö, Sweden, during three different seasons. In the survey, members of the public were asked to evaluate different aesthetic qualities, and to estimate biodiversity and the stress reducing capacity for each photograph. Results showed statistical differences among roof types and by season and successional stage in terms of perceived colour, perceived biodiversity, aesthetic quality, and restorative effects, where the observed differences in perceived values were largely driven by the colour frame of the green roof. Lower scores were associated with a high percentage of red or brown-red shades ($p<0.001$), while higher scores were associated with a high percentages of green or white ($p<0.001$). The results of the study therefore have the potential to inform green roof management strategies.

KEYWORDS
urban biodiversity, ecosystem services, aesthetics, restorative effect, colour

Introduction

There is a wide movement to regreen our cities in order to tackle the environmental and societal challenges facing urban environments across the globe (O'Sullivan et al., 2020). Urban green infrastructure, including street trees, urban parks, and rain gardens, have become important tools in helping build resilience to climate change threats (e.g. Kabisch et al., 2017; Buffam et al., 2022). The options for establishing new ground vegetation in cities are often space-limited, so green roofs and green walls provide an important approach for enhancing urban vegetation. While the contribution to various ecosystem services from green roofs and walls is often more limited compared to green spaces and large street trees, they do provide vital ecosystem services that could contribute towards improving quality of life for the urban population (Oberndorfer et al., 2007; Bousselot et al., 2020). This is particularly true for densely built areas where space is limited for other types of vegetation, and green roofs and walls provide the only means for regreening.

One of the main ways that green roofs can contribute to urban liveability, health, and well-being is through their aesthetic effects, primarily visual. However, studies exploring visual effects, and cultural ecosystem services in general from green roofs, have been limited. An intensification of cultural ecosystem services in planning and building green installations could lead to an increase of place identity (Eliasson et al., 2018). Some studies have explored the potential role of green roofs for restoration and mental health, and others have considered preferences for green roof vegetation. Williams et al. (2019) pointed out that green roofs have limitations compared to ground vegetation in the form of restricted space and limited access, which reduces possibilities for physical exercise and the potential volume of vegetation. However, studies do show that green roofs have the potential to provide a restorative and appreciated environment that could contribute towards well-being and improvement of psychological health (e.g. Loder, 2014; Mesimäki et al., 2017; Williams et al., 2019). A recent study by Matos et al (2023). showed a general preference for green roofs with more lush vegetation, as well as those with better accessibility. According to Vanstockem et al. (2018), positive preferences for aesthetic qualities are related to a combination of sedum and herbaceous species in sedum-dominated vegetation. Visual characteristics related to vegetation structures on green roofs do seem to have an impact on aesthetic judgement, where natural meadow-like vegetation is more associated with positive preferences compared with lower-growing succulent vegetation (White and Gatersleben, 2011; Lee et al., 2014; Ode Sang et al., 2022). Important visual characteristics for delivery of cultural ecosystem services and positive preference for green roofs are structural variation, species diversity and composition, and visual features such as colours (e.g. Vanstockem et al., 2018; Ode Sang et al., 2022). Flower colours in meadow-like green roofs have been shown to increase restorative effects compared to sedum-dominated green roofs with a colour palette of mainly red and brown shades (White and Gatersleben, 2011).

Green roofs are expected to change over time in their vegetation community, including their visual attributes, but relatively little is known about how they change over time, and even less about how those changes affect people's perception of green roofs. It is well understood that terrestrial ecosystems change as they age – commonly with predictable shifts in plant communities, plant productivity, and soil properties – and the associated ecosystem services can be expected to change as well, since soil and plant characteristics underpin ecosystem service provision (Chapin et al., 2011; Lundholm et al., 2015). However, most of the existing knowledge on green roof performance has derived from studies using newly constructed roofs, small roof plots, or models (e.g. Sutton, 2015; Johnson et al., 2016). In a review of green roof research relevant for northern climates, only three out of more than 100 identified studies used full-scale green roofs that were more than two years old (Andenaes et al., 2018). That study identified the lack of measurements on older roofs as the single biggest knowledge gap in understanding green roof performance. The limited research has suggested that important changes likely occur over time in the green roof soil and plant characteristics that influence ecosystem service provision. Variation in green roof plant communities over time has emerged as a clear theme across studies (e.g. Gabrych et al., 2016; Lönnqvist et al., 2021), with some studies suggesting a negative relationship between roof age and species richness (Köhler and Poll, 2010; Thuring and Dunnett, 2014) and others a positive relationship (Catalano et al., 2016; Gabrych et al., 2016) or no relationship (Mitchell et al., 2021).

Studies into the perception of the same vegetation under different seasonal or successional stages are so far limited, but those found show a seasonal effect for preference (e.g. Buhyoff and Wellman, 1979; Junge et al., 2015; Wang and Zhao, 2020; Xu et al., 2022). In a study on evergreen trees, Wang and Zhao (2020) showed that season had an impact both on preference and potential for restoration. Xu et al. (2022) examined urban green spaces in China and found a preference for autumn vegetation, while winter was the lowest rated. In their study of agricultural landscapes, Junge et al. (2015) found a strong influence of seasonality when landscape elements were rated, with flowering elements strongly preferred. In studies by Buhyoff and Wellman (1979) and Thorpert and Nielsen (2014), the effect of landscape seasonality on preference was suggested to be caused by changes in vegetation colours.

Seasonality and lighting conditions have a strong impact on human perception, where visual perception and weather/light differ between seasons observed (Pótrolniczak and Kolendowicz, 2023). From that perspective, light and perceived colours occupy a central role in the visual landscape experience (Küller et al., 2009). According to Berlyne (1971), changes in lighting conditions and visual colours affect the arousal level, where intense colours such as red are associated with high arousal, more so than cool colours (blue, green) (Hanada, 2018; Wilms and Oberfeld, 2018).

Assessment of visual beauty and experiences of harmony have been reported to be connected to perceived colour effects, such as colour contrast in the outdoor environment (Arriaza et al., 2004; Eroğlu et al., 2012; Oleksiichenko et al., 2018; Huang and Lin, 2019). In particular, colour constancy in landscape environment affects the perceived contextual situation, with foliage and flowers having multiple absorbance peaks and inconstant and changeable illumination intensity (Foster and Amano, 2019). The effect of colour contrast in landscape situations has proved to be an important parameter in the assessment of visual beauty and experiences of harmony (e.g. Arriaza et al., 2004; Eroğlu et al., 2012; Oleksiichenko et al., 2018), where the right proportions and distinct differences are crucial in creating a positive contrast effect (Itten, 2003).

In the study we have divided the experience of green roofs into three dimensions: aesthetic qualities, perceived biodiversity, and restorative effect. The aim of the study is to assess the degree to which type of vegetation, age (stage of succession) and seasonality affect the different dimensions of experience of green roofs, but also to test the degree to which colour could explain these variations. The objective is to deepen the understanding of how people experience seasonality and time in relation to vegetation structures on green roofs, which could contribute towards guidelines for their establishment and management.

Materials and methods

In this, study different types of green roof vegetation were photographed and later used in an online survey completed by members of the public in Sweden. Six green roofs, varying in type of vegetation, succession, and seasonal variation, were used in the study (Table 1). The data material were collected in 2021 from green roofs situated on different buildings in the centre of Malmö, Sweden.

Type of vegetation, succession, and seasonal variation

Two types of vegetation were used in this study – sedum-dominated vegetation and biodiverse vegetation. For the sedum-dominated vegetation we explored the influence of succession using roofs representing three stages: 1) newly established (2–3 years old), 2) established 5–10 years ago, and 3) >10 years since establishment. The sedum-dominated vegetation consisted of sedum mat with hardy and drought-resistant deciduous plants adapted to the Nordic climate, together with and underlying moss layer which establishes over time. For these three roofs, vegetation cover surveys were carried out in the field during summer 2020 using 8 or more randomly placed 0.25 m^2 quadrats for each roof, with the % cover quantified for all vascular plant species (cf. Mitchell et al., 2021), as well as total moss % cover including both actively growing and dormant mosses. The newly established green roof consisted of low-intermediate moss cover underneath (30%) and a very high coverage of the field layer (vascular plant cover) of 89%, with very few bare patches. The field layer was dominated by *Sedum album* (84% cover) which forms a uniform carpet, with a very low cover of *Phedimus* sp (5%) and other succulents (1%). The green roof established 5–10 years ago had moderate moss cover underneath (39%) and a 55% cover of vascular plants along with substantial bare patches (21%). The vascular plants included *Phedimus ellacombianus* (28%), which forms distinct mounds, other *Phedimus* species totalling 23%, and other shorter sedum carpet-forming species totalling 11% cover. The oldest green roof (>10 years since establishment) contained a near complete moss layer underneath (76%) and a 55% cover of vascular plants. This included a substantial cover of several different succulents, primarily *Sedum Album* (24%) which forms a carpet, *Phedimus ellacombianus* (17%), which forms distinct mounds, and other *Phedimus* species totalling 16% cover. All sedum-dominated green roofs were exposed to the sun throughout the day.

We included three types of biodiverse green roof vegetation, where perennials and grasses were the dominant vegetation structure. The biodiverse green roofs are categorised after vegetation type and divided into dryland vegetation, grass-dominated vegetation, and silver-toned dryland vegetation. The first green roof had dryland perennials, e.g. *Petrorhagia saxifrage*, *Iris pumila*, *Iberis pruittii*, *Lavandula angustifo*lia, and *Verbascum* sp., with partly visible red substrate. The second green roof had grass-dominated vegetation containing different species of ornamental grasses and perennials, e.g. *Achillea* sp., *Eryngium planum*. The third green roof contained silver-toned dryland vegetation dominated by e.g *Festuca* sp., *Artimisia ludoviciana*, *Hylotelephium spectabile*, and *Alchemilla* sp. The biodiverse green roofs were all exposed to the sun, and had been established for different lengths of time. The green roof containing dryland perennials was set up in 2019, the grass-dominated green roof around 2012, and the silver-toned green roof in 2018. Due to the large variation in species used between different biodiverse roofs, it was not possible to identify green roofs with the same original vegetation type but at different stages of succession.

In order to capture seasonal variations, the six green roofs in the study were photographed on three occasions during the same year (2021). The first photography session was during spring (beginning of May), the second in the summer (August), and third in the autumn (beginning of October). Our aim on all photography occasions was to find the same light and weather conditions to ensure equivalent colouring for all photographs used in the study. Using Adobe Photoshop, all photos of the green roof vegetation were superimposed on the same background, ensuring less influence of background structures and colours on the preference scoring. The background used was a standardised setting with modern house architecture. A total of 18 images were thus generated and used in the online survey and image analysis (see Figure 1).

TABLE 1 Respondent's preference for green roof vegetation: research themes and questions used for online questionnaire.

Research theme	Questionnaire measures – questions
Aesthetic qualities	The green roof vegetation is **attractive**
	The **colours** of the green roof are attractive
Perceived biodiversity	The green roof vegetation looks **varied**
	The green roof is positive for **butterflies, bumblebees, bees, and other insects**
Restorative effect	I feel **relaxed** looking at the green roof vegetation

Online questionnaires to assess human preferences

An online questionnaire was developed to assess aesthetic preferences, perceived biodiversity, and restorative effect for the generated images of green roof vegetation, based on similar studies of perennial vegetation (Ives and Kendal, 2013; Hoyle et al., 2017; 2018) for each image. The response was assessed on a 6-point Likert scale (1 = totally disagree; 6 = totally agree). The questionnaire was distributed through the use of on-line panels of volunteer respondents through a Swedish provider, resulting in 120 respondents. The survey included comprehensive demographic

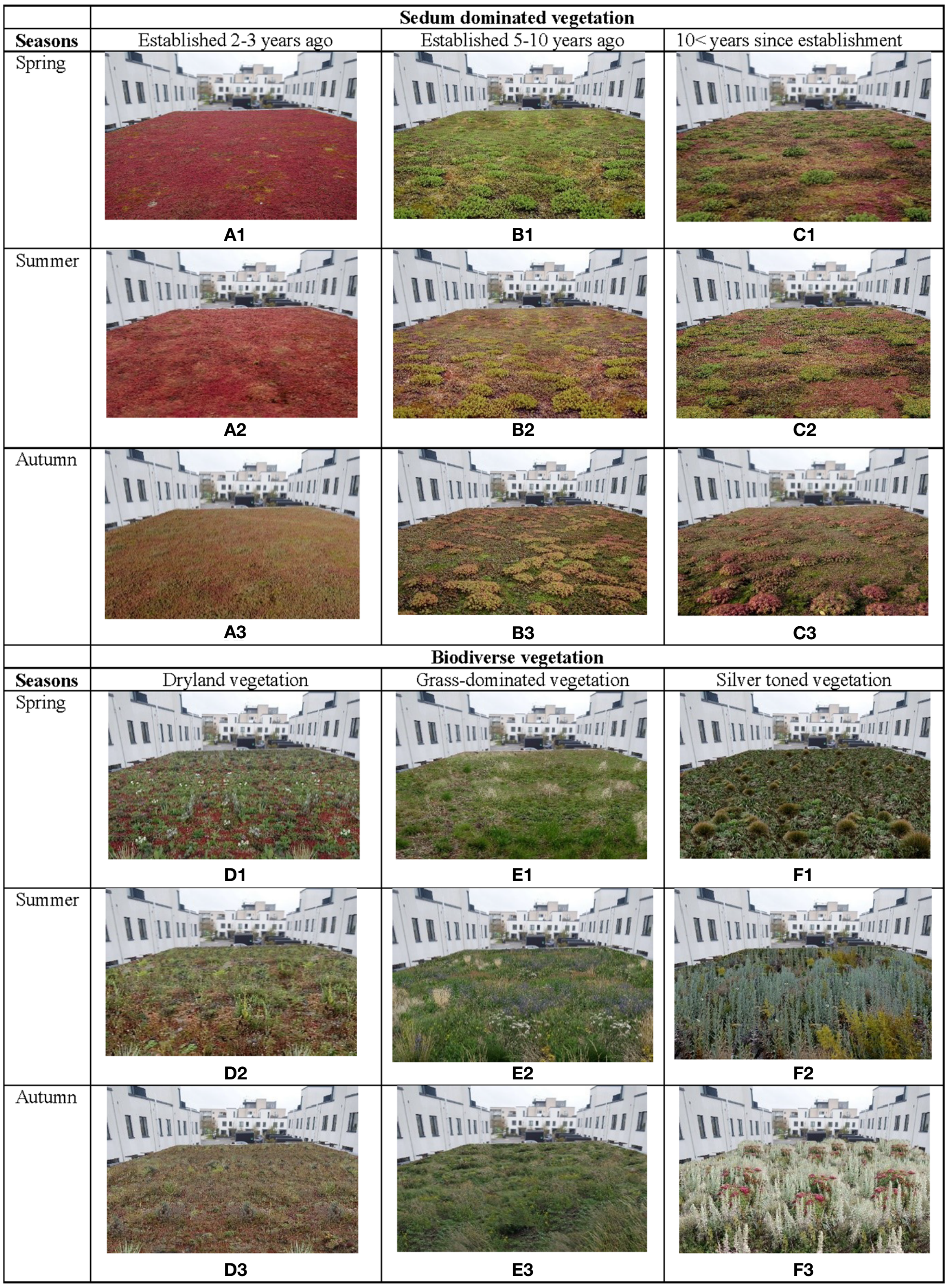

FIGURE 1
Photos used in the study. Each image in the figure corresponded to a specific vegetation type, time of succession and seasonal variation. Young sedum dominated vegetation in spring **(A1)**, summer **(A2)**, autumn **(A3)**. Medium sedum dominated vegetation in spring **(B1)**, summer **(B2)**, autumn **(B3)**. Old sedum dominated vegetation in spring **(C1)**, summer **(C2)**, autumn **(C3)**. Biodiverse-Dryland vegetation in spring **(D1)**, summer **(D2)**, autumn **(D3)**. Biodiverse-Grass dominated vegetation in spring **(E1)**, summer **(E2)**, autumn **(E3)**. Biodiverse-Silver toned vegetation in spring **(F1)**, summer **(F2)**, autumn **(F3)**.

characteristics of participants and nature/environmental interest profile (Table 2).

Three research themes formed the basis of the questionnaire, and five questions addressed the participant's perception of aesthetic qualities, perceived biodiversity, and restorative effect for each of the images (Table 1). The aesthetic qualities and perceived aesthetic preference of the green roof vegetation were tested against the variables 'attractiveness' and 'colours'. Using colours and variation in landscape design projects is essential in the development of attractive design solutions, and is one of the driving forces for increasing aesthetic qualities in urban green contexts. The variables 'attractive' and 'colour' relate to a fundamental dimension of human arousal experiences and can shape our experiences and emotional behaviour (Hoyle et al., 2017; Thorpert, 2019). Perceived biodiversity values were measured against the variable 'varied', testing perceived plant diversity

TABLE 2 Demographic and nature/environmental interest profile of participants responding to the survey (n=120).

Gender	Male	49%
	Female	51%
	Other gender identity	0%
Age	18–20	2%
	21–30	7%
	31–40	21%
	41–50	22%
	51–60	17%
	61–70	18%
	> 70	13%
Highest level of education	Primary school	4%
	Upper secondary school	41%
	University	52%
	Other	3%
Present accommodation	Apartment	41%
	Terraced house (townhouse)	11%
	Independent house	47%
	Other	1%
Main upbringing environment	Rural area	26%
	Suburb area	17%
	Residential area	34%
	City centre	23%
Active in a nature conservation or environmental association or have a nature-related hobby	Yes	27%
	No	73%
Membership in environmental organisation	Yes	8%
	No	92%
Landscape/Environment/ Garden interest	Yes	63%
	No	37%
Colour-blindness	Yes	2%
	No	98%

(Hoyle et al., 2017) and connecting degrees of arousal to pleasantness through the collective variable complexity (Berlyne, 1971; Palmer et al., 2013). We also tested the correlation between the value of the plantings for perceived value to pollinators and perceived attractiveness. Pollinators in this study are defined as pollinating butterflies, bumblebees, and bees, but also other insects that indicate perceived biodiversity. To measure human relaxation and restorative effect, the variable ‘extent’ of the attention restoration theory (ART, Kaplan, 1995) addresses human experiences of being comfortable and at ease and refers to the restorative quality of the environment.

Statistical analyses of human preference

Respondents’ preferences for the images, as well as a specific type of vegetation (sedum-dominated or biodiverse), succession (with regards to sedum-dominated vegetation), and season were analysed using analysis of variance with a block design, followed by Tukey’s *post-hoc* test with a 5% significance level. The block factor was the identity of the participant, and the treatment factor was the research themes and associated questions. Correlation was additionally used to detect linear relationships between the variables used in the study: ‘attractive’, ‘colour’, ‘varied’, ‘insects’, and ‘relaxed’.

Colour image statistical analyses and image segmentation

Previous studies have shown that consciousness in the design of colour combinations can be a way of improving aesthetic qualities and human psychological benefits (Thorpert et al., 2023). Colour analyses of the data material are therefore a major part of this study. Image segmentation with image colour clusters were used as the main colour analysis method, to enable participants to discern colour differences between the data material. All 18 images used in the online survey were analysed in the Image Color Summarizer program - RGB and HSV Image Statistics (Saveanu et al., 2022). The colour clusters in the program were calculated using central points of clusters for the K-means algorithm (Basar et al., 2020). Descriptive colour statistics for each image were obtained at 100-pixels resolution, clustered into six groups (k-means), respectively. To see the effect of vegetation colour on the variables used in the study collectively, a multivariate analysis (Redundancy Analysis, RDA) was performed using the program Canoco (v. 5). In addition, partial correlation analysis, with participant as the controlling variable, was used to explore linear correlations between the respective response variables (‘attractive’, ‘colour’, ‘varied’, ‘insects’, and ‘relaxed’) and each colour segmentation variable. For the partial correlation, the package ppcor in R was used.

Results

Human visual response to the green roofs

The demographic profile of participants (n=120) is shown in Table 2. All respondents are included in the results in order to reflect a representative sample of a total population. This means that the 2% of respondents that are colourblind were included in the results and in the calculations. The respondents in the online survey were gender balanced. The age distribution of the sample was mainly towards adults and older persons, whose main upbringing environment was an urban context. One-third of the respondents were active in a nature conservation or environmental association or had a nature-related hobby. None of the respondents actively worked with design or installation of green roofs.

The influence of demographic and nature/environmental profile on the result was tested through a mixed effect model, which showed no statistical significance ($p<0.05$) for any aesthetic qualities or perceived biodiversity. For restorative effect, a significant effect in preference related to landscape/environment/garden interest ($p=0.016$) was detected.

Components of green roof vegetation affecting human response to aesthetic qualities and restorative effect

For the images of green roofs tested in this study, the variables 'attractive' and 'colour' used to measure aesthetic qualities were correlated. 'Attractive' and 'colour' showed the strongest significant relationship compared with the other tested variables (Figure 2). Perceived aesthetic qualities and the variables 'attractive' and 'colour' are important for whether restorative effects are experienced when observing the green roofs. Restorative effects are correlated with aesthetic qualities and the variables 'attractive' and 'colour', where 'colour' was significantly more important for restorative effects and perceived aesthetic qualities than perceived biodiversity and the variables 'varied' and 'insects'.

Components of green roof vegetation affecting human response to perceived biodiversity

Perceived biodiversity (butterflies, bumblebees, bees, and other insects) had a low correlation with restorative effect. Green roofs positive for perceived biodiversity had lower correlation with visual aesthetic qualities and the variables 'attractive' and 'colour'. In contrast the variable 'varied' had a more positive impact on perceived biodiversity and green roofs were positive for 'insects'.

Impact of seasonal variation and vegetation type on perceived biodiversity, aesthetic qualities, and restorative effects

Seasonal variation and type of vegetation affected human experiences significantly, especially in biodiverse green roofs, see Table 3. In spring, the green roof with flowering dryland vegetation (D1) had the highest mean value for the five variables (Figure 3, Table 3), and was significantly different from the two other biodiverse green roofs, grass-dominated (E1) and silver-toned green roof vegetation (F1). In autumn, most positive preferences were reported for silver-toned flowering vegetation (F3). In summer, the green roof with grass-dominated flowering vegetation (E2) had the highest mean values for perceived biodiversity, aesthetic qualities, and restorative effect, and differed significantly from the other two biodiverse roofs (D2, F2).

The impression of the Sedum-dominated vegetation on the green roof established 2–3 years ago (A1–3) was experienced as relatively stable in relation to seasonal variation. The green roofs with sedum-dominated vegetation with an establishment period of five years and upwards (B1–3 and C1–3) followed the same pattern in terms of seasonal variation, generating the highest mean values, and were significantly different from the sedum roof established 2–3 years ago in terms of perceived biodiversity, aesthetic qualities, and restorative effects in the spring (Figure 3, Table 3). The older sedum-dominated green roofs in spring and autumn (C1 and C3) are experienced as more positive for butterflies, bumblebees, bees, and other insects compared with the other two sedum-dominated green roofs.

The biodiverse green roof with grass-dominated vegetation in summer (E2) was preferred relative to all the other green roof images in the study. This was reflected in significant differences in experienced biodiversity, restorative effect, and perceived aesthetic quality.

Differences in colouring between the green roofs

Quantitative analyses through the use of image segmentation illustrated the main colour differences between the images (Table 4). The sky and surrounding building facades, which includes the colour shades of the front part and faced details, accounted for approximately 38% of the visual images. The remaining percentage was counted as vegetation colour structures.

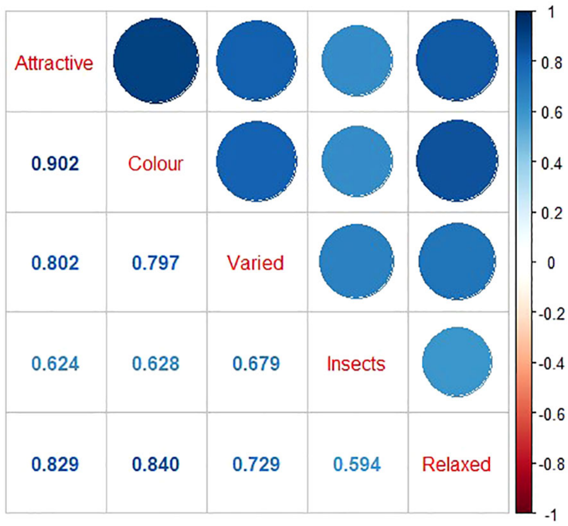

FIGURE 2
Correlation for the variables 'attractive', 'colour', 'relaxed', 'varied' and ' insects', with a significant correlation between the five variables, $p < 0.001$. The correlations are based on all 18 images including both sedum-dominated and biodiverse vegetation. No difference in the correlation and p-values between the variables occurs when the tested green roofs are calculated separately in each category (sedum-dominated and biodiverse vegetation).

TABLE 3 Average scores given by respondents (n = 120) and standard deviation for each green roof image.

	Image	Mean	StDev	Grouping									Image	Mean	StDev	Grouping									Image	Mean	StDev	Grouping								
Attractive	A1	3.00	1.69					e	f				B1	4.09	1.47		b	c							C1	4.11	1.41		b							
	A2	3.17	1.68				d	e	f				B2	3.45	1.67				d	e					C2	3.37	1.56				d	e	f			
	A3	2.91	1.57						f				B3	3.45	1.58				d	e					C3	3.59	1.59				d					
	D1	4.10	1.47		b								E1	3.35	1.58				d	e	f				F1	3.28	1.63				d	e	f			
	D2	3.62	1.49			c	d						E2	4.66	1.38	a									F2	3.62	1.60			c	d					
	D3	2.93	1.67						f				E3	3.50	1.56				d						F3	4.20	1.60	a	b							
Colour	A1	3.18	1.65					e	f	g			B1	4.05	1.44		b	c							C1	4.08	1.41		b	c						
	A2	3.27	1.73				d	e	f				B2	3.38	1.68				d	e					C2	3.44	1.56				d	e				
	A3	2.83	1.50						f	g			B3	3.44	1.50				d	e					C3	3.65	1.59			c	d					
	D1	4.16	1.44		b								E1	3.38	1.55				d	e					F1	3.26	1.63				d	e	f			
	D2	3.63	1.55			c	d	e					E2	4.70	1.26	a									F2	3.65	1.48			c	d					
	D3	2.79	1.60							g			E3	3.55	1.46				d	e					F3	4.22	1.60		b							
Relaxed	A1	2.85	1.67					e					B1	3.90	1.56		b								C1	3.95	1.56		b							
	A2	2.94	1.68					e					B2	3.44	1.64			c							C2	3.43	1.61			c	d					
	A3	3.00	1.62				d	e					B3	3.41	1.57			c	d						C3	3.59	1.62		b	c						
	D1	3.91	1.57		b								E1	3.38	1.51			c	d						F1	3.24	1.65			c	d	e				
	D2	3.56	1.63		b	c							E2	4.48	1.53	a									F2	3.44	1.60			c						
	D3	2.95	1.61					e					E3	3.55	1.54		b	c							F3	3.92	1.68		b							
Varied	A1	2.32	1.43					e					B1	3.50	1.52				d						C1	4.27	1.35		b							
	A2	2.61	1.60					e					B2	3.36	1.51				d						C2	3.46	1.55				d					
	A3	2.39	1.36					e					B3	3.63	1.43			c	d						C3	3.62	1.51			c	d					
	D1	4.21	1.37		b								E1	3.22	1.46				d						F1	3.42	1.59				d					
	D2	4.05	1.43		b	c							E2	4.91	1.16	a									F2	4.15	1.48		b							
	D3	3.25	1.64				d						E3	3.55	1.44				d						F3	4.49	1.40	a	b							
Insects	A1	3.38	1.77								h	i	B1	3.96	1.47					e	f	g			C1	4.71	1.17		b	c						
	A2	3.56	1.66							g	h	i	B2	3.80	1.64					e	f	g	h		C2	3.80	1.59					e	f	g		
	A3	3.30	1.67									i	B3	3.93	1.44					e	f	g			C3	4.19	1.44				d	e				
	D1	4.62	1.34		b	c							E1	3.81	1.62					e	f	g			F1	4.00	1.55					e	f			
	D2	4.46	1.34			c	d						E2	5.32	0.92	a									F2	4.65	1.30		b	c						
	D3	3.70	1.65						f	g	h	i	E3	3.93	1.47					e	f	g			F3	5.01	1.11	a	b							

Grouping information means that images that do not share a letter are significantly different, based on Tukey's post-hoc test. The table shows the results from the tested variables 'attractive', 'colour', relaxed', 'varied' and 'insects', divided into three categories of sedum-dominated vegetation: newly established (A1–3), established (B1–3) and >10 years since establishment (C1–3), and three categories of biodiverse vegetation: dryland vegetation (D1–3), grass-dominated vegetation (E1–3), and silver-toned dryland vegetation (F1–3). 1=spring image; 2= summer image; 3= autumn image.

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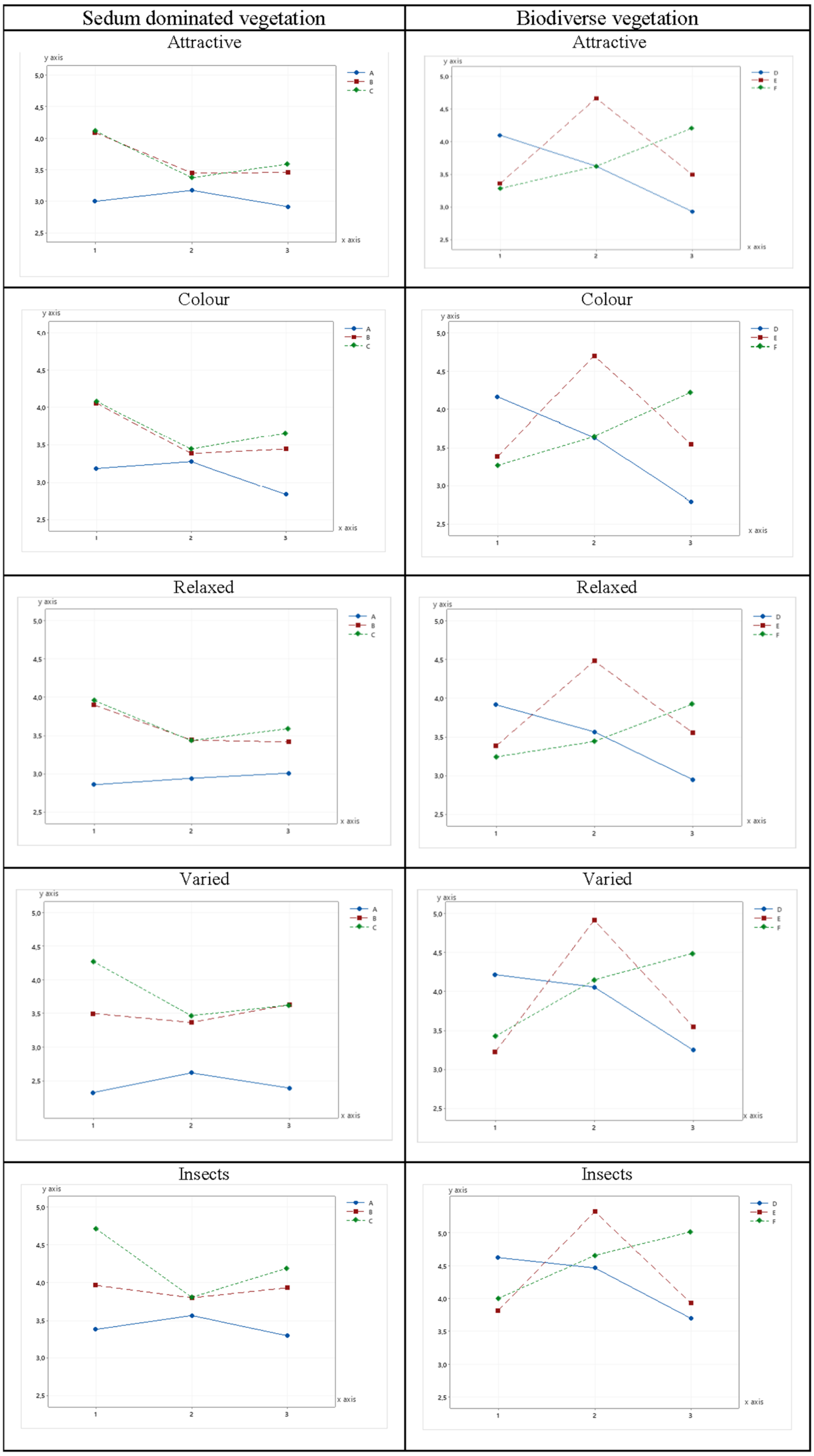

FIGURE 3
Interaction plot of the variables ‘attractive’, ‘colour’, ‘relaxed’, ‘varied’ and ‘insects’ illustrating the factors: season (1–3), time of succession on sedum-dominated green roofs (A–C), and three categories of biodiverse green roofs (D–F). Y-scale shows the mean values, and numbers on the x-scale refer to the seasons spring (1), summer (2) and autumn (3). Capital letters and lines refers to type of vegetation.

TABLE 4 Eight categories of colour division in the roof images tested.

Vegetation type		Vegetation colour in percentage							
		Red shades	Brown-red shades	Green shades	Yellow-green shades	Blue-green shades	White shades	Blue-grey shades	Buildings & Sky shades in %
Sedum-Young/Spring	A1	62%	0%	0%	0%	0%	0%	0%	38%
Sedum-Young/Summer	A2	62%	0%	0%	0%	0%	0%	0%	38%
Sedum-Young/Autumn	A3	18%	44%	0%	0%	0%	0%	0%	38%
Sedum-Medium/Spring	B1	0%	16%	20%	26%	0%	0%	0%	38%
Sedum-Medium/Summer	B2	17%	16%	0%	29%	0%	0%	0%	38%
Sedum-Medium/Autumn	B3	0%	16%	3%	43%	0%	0%	0%	38%
Sedum-Old/Spring	C1	12%	22%	15%	13%	0%	0%	0%	38%
Sedum-Old/Summer	C2	15%	23%	2%	22%	0%	0%	0%	38%
Sedum-Old/Autumn	C3	17%	23%	12%	10%	0%	0%	0%	38%
Bio-Dryland/Spring	D1	13%	0%	46%	0%	0%	3%	0%	38%
Bio-Dryland/Summer	D2	0%	18%	22%	20%	0%	2%	0%	38%
Bio-Dryland/Autumn	D3	0%	40%	0%	22%	0%	0%	0%	38%
Bio-Grass/Spring	E1	0%	0%	59%	0%	0%	3%	0%	38%
Bio-Grass/Summer	E2	0%	0%	44%	11%	0%	4%	3%	38%
Bio-Grass/Autumn	E3	0%	0%	0%	35%	27%	0%	0%	38%
Bio-Silver/Spring	F1	0%	14%	0%	16%	32%	0%	0%	38%
Bio-Silver/Summer	F2	0%	10%	0%	8%	0%	0%	44%	38%
Bio-Silver/Autumn	F3	3%	0%	8%	20%	0%	31%	0%	38%

The eight colour categories with respective approximate percentage values were calculated from the colour image segmentation based on k-means cluster initialisation, see Appendix 1. Colour image statistical analyses and image segmentation.

In the newly established green roof with sedum-dominant vegetation, shades of red colours were in clear majority. In spring and summer a variety of red shades were the overall dominant colour of the visually coloured vegetation surface (A1-A2). During autumn, the vegetation colours change towards a majority of brown-red shades (A3). The sedum-dominated green roof established 5–10 years ago had a clear visual appearance of a variety of green and yellow-green shades in springtime (B1). During summer, the majority of the colours changed towards yellow-green shades and red/brown-red shades (B2). In autumn, yellow-green shades were in a clear majority and dominated the visual appearance. Colours of red and brown-red shades and a variety of green shades were in majority in the sedum-dominated green roofs with more than ten years of establishment (C1–3). The green roofs progressed towards redder vegetation shades as the season progressed, with yellow-green shades dominating during summer and green shades during spring and autumn.

The green roof with dryland perennials with partly visible red substrate showed a relatively similar colour increase during the season, so the redness on the green roofs darkened from red shades in spring (D1) into brown-red shades as the seasons progressed (D2–3). The grass-dominated biodiverse green roofs showed consistency in the green shades in spring and summer (E1–2). In autumn (E3), yellow and blue-green shades dominated the visual appearance. The biodiverse green roof consisting of silver-toned vegetation displayed a wide colour palette during the season. In spring a clear majority of blue-green and yellow-green shades dominated the visual appearance (F1). During summer, the vegetation colours changed into dominating blue-grey shades (F2), and during autumn, white and yellow-green shades with red shades as accents were most common (F3).

General associations of aesthetic qualities and restorative effect according to roof type, season, and colour palette

From the multivariate (RDA) analysis, 59% of the variance in perceived aesthetic and restorative values could be explained by the vegetation colour (Figure 4). Of this, the vast majority (55%) was explained axis 1, which represents a gradient between roofs that score low on all of the perceived aesthetic and restorative values, and roofs that score high. The lower scores were associated with red-brown and red shades, while the higher scores were associated with green and white shades. In general, low-scoring (red or red-brown) characteristics were associated with the young sedum roof and roofs during the autumn season. High scores were associated with Bio-grass (grass-dominated vegetation), Bio-silver (silver-toned vegetation), and to a lesser degree, Sedum-old (>10 years since establishment), and the summer season. The Bio-dryland (flowering dryland vegetation) roof, sedum-medium (established) roof, and spring season were associated with intermediate scores and colours.

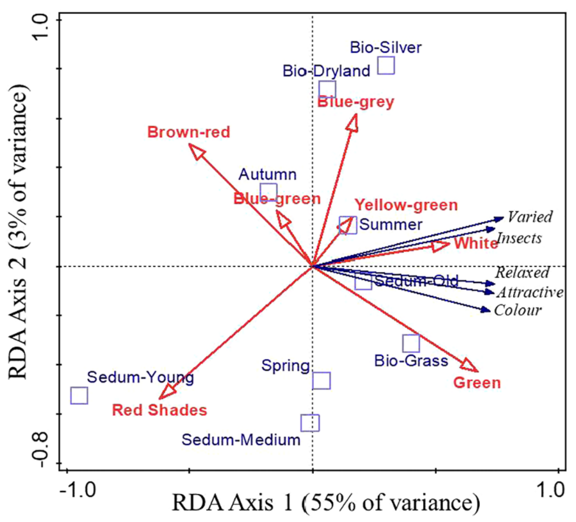

FIGURE 4
Redundancy analysis (RDA) with mean perceived aesthetic and restorative values for 5 different aspects (Varied, Relaxed, Attractive, Colour, Insect) as response variables, % colour within 7 different colour types as predictor variables, and roof characteristics (roof type, season) shown in the background as supplementary variables. Colour type and perceived aesthetic and restorative values were significantly correlated (pseudo-F=2.6, p=0.042).

A secondary gradient in the data, axis 2, could explain an additional small amount (3%) of variance in the perceived aesthetic and restorative values. Here, perceptions of varied and insect-supporting qualities were associated with blue-grey and brown-red shades, the Bio-Dryland (flowering dryland vegetation) roof, the Bio-Silver (silver-toned vegetation) roof, and the autumn season. Relaxed, attractive, and especially colour attributes were associated with green and red shades, the Sedum-Medium (established) and Sedum-Young (newly established) roofs and the spring season.

The importance of the visual characteristic colour for how people experience green roofs

The partial correlation analysis showed that image colour had a significant impact on measured human experiences. Specifically, there were significantly higher values for all five response variables (measuring aesthetic qualities, restorative effects and perceived biodiversity), for roofs with a high proportion of green ($P<0.001$) or white shades ($P<0.001$), and for roofs with a low proportion of red ($P<0.001$) or brown-red shades ($P<0.001$). The correlation coefficients (Pearson's r) ranged between $r = -0.130$ and -0.367 for red shades; $r = -0.130$ and $r = -0.220$ for brown-red shades; $r = +0.141$ and $+0.253$ for white shades; and $r = +0.224$ and $+0.247$ for green shades. The other colour shades (blue-green, blue-grey, yellow-green) did not show as strong or consistent results, with most relationships being insignificant and a few weakly significant for isolated response variables.

Discussion

In this study, observed differences in perceived values were largely driven by aesthetic features, where restorative effects were significantly correlated with colour and attractiveness, indicating the powerful impact colour has on human experiences. This observation is supported by a recent review (Ode Sang et al., 2022) which highlighted the importance of visual characteristics for delivery of positive preferences, and especially the visual feature colour, which was found to be important in supporting cultural ecosystem services.

The green roofs in this study showed a broad palette of colours, where the colour combinations extended from a majority of red and brown-red shades to a mix of green, yellow-green, white, and blue-grey shades. Some of the results from this study are in line with previous studies, showing that red and brown-red sedum-dominated vegetation on green roofs is less preferred than meadow-like greenish roof vegetation (White and Gatersleben, 2011). This current study indicates that, regardless of the materiality of the red shades (vegetation or substrate colour), a reduction in percentage of red shades of green roofs is related to increased experiences of aesthetic enjoyment and relaxation. This indicates that colour combinations and related colour contrast play an essential role as a driver in human experiences of green roofs.

This study indicated that seasonal and successional changes may influence ecosystem service provision from green roofs, since the experienced colour in the vegetation community for a given roof changes seasonally and over successional time. The results are in line with recent studies showing a seasonal effect for positive preference (e.g. Xu et al., 2022). Furthermore the results from this study indicate that green roofs with a visual aesthetic performance of a high proportion of green and green roofs with a high percentage of white shades coupled to a low percentage of red shades, have the potential to be highly appreciated. A colour composition with these qualities might lead to perceived pleasurable experiences, relaxation and positive expectations for butterflies, bumblebees, bees, and other insects. Earlier studies have shown the importance of a well-balanced understanding of colour theory and awareness of related human experiences to reach positive visual aesthetic outcome and restorative effects (Neale et al., 2021; Thorpert et al., 2022). This indicates that the link between human visual perception, aesthetic and restorative qualities, and colour characteristics should not be neglected in design issues and planning programmes.

The limited research to date has suggested that important changes are likely occurring over time in the green roof plant communities, changes that may influence ecosystem service provision (e.g. Lönnqvist et al., 2021, Gabrych et al., 2016). After establishment, temporal variation in green roof plant communities is to be expected, and shifts in the plant community have been observed when young and old roofs are compared (e.g., Köhler and Poll, 2010; Gabrych et al., 2016; Mitchell et al., 2021). Some studies have suggested a negative relationship between roof age and species richness (Köhler and Poll, 2010; Thuring and Dunnett, 2014) and others a positive relationship (Catalano et al., 2016; Gabrych et al., 2016) or no relationship (Mitchell et al., 2021). Based on the results presented in the current study, a shift in the dominant colour composition will likely have an impact on the perceived values people obtain from viewing the roof. Other factors, like patchiness or perceived messiness (Loder, 2014), may also play a part, but have not been the focus of this study.

The nature of the long-term changes we can expect for a given green roof depends on a number of factors that can influence the development of the vegetation community over time, including (i) the original species mixture, (ii) the type of substrate used and other aspects of green roof construction, (iii) the regional climate, (iv) local climate and within-roof microclimates, including roof shading and temperature conditions, and (v) management interventions like fertilisation, irrigation or weeding. These can all vary from roof to roof, so no single long-term trajectory can be expected for all green roofs. However, one common theme observed in much of Fennoscandia, including the region covered by this study, is that shallow-substrate sedum-based green roofs tend to shift over time from being dominated by the intended vascular vegetation (succulent plants in the *Sedum* and *Phedimus* genera) to a high coverage of mosses, coupled with a reduced cover of vascular plants (Emilsson, 2008; Gabrych et al., 2016; Lönnqvist et al., 2021; Mitchell et al., 2021). Furthermore, thin-substrate green roofs commonly experience environmental stress, most commonly water deficiency, during extended dry periods. Stressful conditions can lead to a decrease in leaf size and change in leaf colour for some sedums, commonly with a loss of greenness (e.g., Cotoz et al., 2023). Both of these observations have implications for the colour palette and the patchiness in appearance of green roofs, but it is not possible to generalise about the likely impact on environmental appraisal aspects without more detailed research.

Previous studies have shown that in private urban green settings, warm flower colour diversity influences altered heart rate variation and restorative effects (Neale et al., 2021), A conscious use of colour design in landscape planning can influence aesthetic qualities and the viewer's aesthetic satisfaction, and evoke positive restorative effects (Hoyle et al., 2017). Our study found a negative relationship between high amount of red shades and aesthetic enjoyment and relaxation, as well as a positive relationship between high amount of green shades or white shades (flowers) and the tested variables. This would favour use of the more greenish meadow-like roof vegetation, or a sedum roof under conditions that maintain a more greenish character over time. Intentional use of colour and colour contrast in the design of urban green installations could improve human experiences of pleasantness, as indicated in previous studies by Huang and Lin (2019); Thorpert (2019) and Oleksiichenko et al. (2018). An argument could be made here to choose sedum species with fewer red shades and/or attempt to influence the way which the roofs undergo succession, which could improve how the public experience green roofs. This approach would be in line with the ambition to create and improve harmony between physical environment, human experiences and ecosystems (Bhadouria et al., 2023). The results from this study build on recent studies (Yilmaz et al., 2018; Thorpert et al., 2023), showing that from a cultural ecosystem perspective, landscape professionals have an opportunity to influence the visual expression of green installations through conscious planning and design and thereby influence the viewer´s aesthetic satisfaction.

Methodological considerations

Visual context and colour composition can influence human perception and how the surroundings are interpreted. Variation in daylight intensity, vegetation and built structures, and other elements are part of the visual experience. Colour constancy in outdoor environments particularly affects the perceived contextual situation. The visual stimulus thereby influences the human perception and related experiences of changed attitudes and preferences towards the perceived environment. The results from this study could be affected by the contextual colour situation. This means that attention should be paid to the overall colour characteristics in which the green roofs are placed and designed.

A strength in this study is that we photographed the green roofs under similar light and weather conditions and used a standardised architectural background as the visual frame. An additional strength is that we tested different successional ages of the sedum roofs as well as different types of biodiverse roofs. However, a weakness is that we only tested one of each type of green roof vegetation. The use of more varieties of biodiverse roofs, and replicates of the sedum-dominated roofs in different age classes, would be a good next step to test whether the observed patterns can be generalised across a broader range of green roofs.

The methodology used in this study gives an understanding of how people experience green roofs, based on a specifically chosen situation and time interval, and using photographs. A more profound understanding about human judgements and green roof vegetation *in-situ* could help to ensure a well-balanced outcome and increase the understanding of human psychological benefits in relation to green roof vegetation. Previous studies have reported differences in preferences, related to age and gender (Van den Berg and van Winsum-Westra, 2010; Ode Sang et al., 2016; Southon et al., 2017) as well as environmental/garden interest (Hoyle et al., 2018). In this study, a significant influence of landscape/ environment/garden interest was found with regards to the responses for restorativeness. No other statistically significant influence of demographic or environmental profile on the responses regarding aesthetic qualities, perceived biodiversity and restorative effects was detected.

Conclusion

This research shows that the role of aesthetic qualities connected to seasonality and successional aspects on green roofs should be considered as a parameter for human restorativeness. Positive perceived biological diversity was also connected with specific colour characteristics, showing the potential of aesthetic features to influence perceived biodiversity. Our results can support how public attitudes and values in urban green contexts can be improved through aesthetic features and awareness of colour characteristics in design and planning processes. This include for instance the consideration of specific sedum species to minimize red shades and increase the amount of green vegetation and flowering vegetation when introducing green roofs as a means for restoration.

Integration of the results could support design processes in ecosystems for green built environments, urban planning decisions and communication regarding biodiversity qualities on green roofs, though the relationship between perceived biodiversity and actual biodiversity in relation to green roofs needs further study. The results of the study support the use of vegetation dynamic as a design concept when introducing green roofs in an urban context, accommodating and allowing for changes over season and successional time.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the study involving humans in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was not required from the participants in accordance with the national legislation and the institutional requirements.

Author contributions

PT: Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. ÅO: Conceptualization, Investigation, Methodology, Writing – review & editing. IB: Funding acquisition, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2024.1346397/full#supplementary-material

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