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Ecosystem structure influences human health outcomes as the basis for green prescriptions

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The role of Nature ** in supporting human life, health, and well-being has been recognized and appreciated since ancient times, and has become a topic of scientific investigation with early studies dating back several decades. In recent years, this field has gained renewed attention and methodological refinement, driven by interdisciplinary frameworks and advances in environmental psychology, ecology, and health sciences, including new ecosystem-based approaches that highlight the deep human dependence on Nature for both mental and physical health. Among Nature-based Interventions that aim at exposing people to the natural environment, Green Prescriptions (GRx) represent a promising strategy to address human health challenges in ways that can also support environmental sustainability, in line with the Planetary Health framework. However, significant gaps remain in our understanding of the specific ecological factors that influence health outcomes during therapeutic activities in natural settings; in particular, it remains unclear how ecosystem structure and functions modulate health responses in individuals. This nine-month pilot study examined the therapeutic efficacy of GRx within a Mediterranean woodland ecosystem, to assess if and how variations in ecosystem structure influence health outcomes in individuals with complex chronic conditions. Using a novel aggregated index to characterize four distinct woodland patches, we identified a gradient in structural complexity where greater ecosystem functionality was consistently associated with greater alleviation of psychological and physical symptoms. Notably, health outcomes were independent of weather conditions and participants' baseline connectedness to Nature, whereas temporal dynamics and the presence of peaks in the productivity of some species influenced both perceptions and physical responses. This underscores the intrinsic role of ecosystem properties and dynamic functions in modulating human health responses, while also suggesting the potential presence of a complex set of signals pervading complex ecosystems that is worth further exploration. The results demonstrated cumulative health benefits, including significant reductions in medication use over time, particularly among individuals with respiratory challenges and chronic pain. Furthermore, participants showed improved environmental awareness and behavior, embracing the interconnectedness principle, which is integral to effective environmental conservation. This study highlights the potential of well-functioning ecosystems to serve as co-effectors in healthcare interventions, advancing the goals of Planetary Health while reinforcing the importance of preserving ecological integrity. (**In this paper, "Nature" is written with a capital "N" to indicate the living biosphere and the abiotic matrices (soil, air, and water) in which life is embedded, including the ecological processes they sustain. This capitalization reflects the scientific perspective of Nature not merely as a passive backdrop, but as an active ecological system that interacts and influences human health. It also avoids confusion with "nature" as the intrinsic quality of a phenomenon**).**

Keywords Green prescriptions, Ecosystem structure and functioning, Human health, Nature and humans interdependence, Nature-based interventions, Planetary health

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The benefits provided by Nature** in supporting human life, health, and well-being have been known since ancient times and have been documented for decades of scientific investigation[1–3] . In recent years, this field has gained renewed attention and methodological refinement, supported by interdisciplinary frameworks and advances in environmental psychology, ecology, and health sciences. Moreover, the steadily rising popularity of outdoor activities in natural settings became even more pronounced after the COVID-19 pandemic, when humanity experienced unprecedented isolation and restrictions on going outdoors[4], catalyzing a surge of research and public awareness on the role of natural environments in health and psychological resilience[5–7]. In fact, in the aftermath of those periods of isolation, it became evident that not only had social isolation caused long-term harm [8], but also that the forced separation from the natural environment underscored the profound dependence of human well-being on the presence of, and personal connection to, Nature for emotional and psychological health[9–11].

Alongside the recognition of the importance of human relationship with Nature, it has also become apparent that traditional healthcare systems are under strain[12], struggling to manage the rising costs of treating a global population burdened by chronic health problems and the growing threat of epidemics triggered by environmental degradation, an issue to which the healthcare sector itself contributes[13,14].

As a result, the widespread interest in finding new ways to engage with the natural environment for maintaining and restoring human well-being and health has facilitated the exploration of various opportunities. Activities in natural environments range from solo or small group recreational hikes, which provide opportunities for outdoor physical activity, to experiences that go beyond recreation by focusing on disease prevention and treatment, supporting the conventional medical treatments in alleviating—or reversing—symptoms of both acute and chronic conditions[15]. While all these activities fall under the broad category of "Nature-Based Interventions" (NBI), those with specific therapeutic goals belong to a narrower subset known as Green Prescriptions (GRx). These are formalized therapeutic interventions, prescribed by doctors or healthcare professionals and supervised by qualified experts, tailored to address clearly defined health needs that have been formally diagnosed by a healthcare provider[16]. GRx involve structured and intentional activities in natural settings to improve patients' mental and physical well-being, with the parallel aim of improving health while reducing reliance on pharmacological treatments. The term Green Prescription was originally introduced in New Zealand in the 1990s to describe medical recommendations encouraging physical exercise[17], where the word "green" referred to the color of the prescription form rather than to Nature exposure itself[18]. Over time, the concept evolved to encompass structured interactions with natural environments, emphasizing the restorative and therapeutic potential of green areas and natural environment rather than physical activity alone[19,20]. Following this evolution, various models have emerged internationally: from individualized GRx clinical schemes in the U.S.[21], Canada[22,23], and Australia[24], to socially-mediated, group-based models within the UK's Green Social Prescribing framework[25,26]. In Europe, standardized clinical GRx protocols are still emerging, although Nature-based health practices are increasingly piloted or integrated into healthcare settings[27,28]. Despite variation in delivery models, these approaches commonly aim to harness the health-supporting potential of ecosystems through structured, evidence-based exposure to Nature.

In this way, GRx are seen as tools aligned with the principles of Planetary Health, contributing to their goals by promoting a non-pharmaceutical approach to enhance mental well-being and physical health, while also aiming at reducing the environmental impact of healthcare systems[29,30]. Though still in its early stages, GRx have indeed shown to play an important supporting role as complementary approaches for alleviating chronic pain[31], reducing respiratory challenges, and treating metabolic syndromes[32].

GRx and Nature-based health interventions conducted in forest ecosystems have been widely investigated for their positive impacts on mental health, including reduced stress[33], anxiety[34,35], and depression[36,37] as well as improved cognitive function[38,39]. Moreover, GRx involving structured exposure to Nature have been shown to be particularly effective in the treatment of diseases such as diabetes, obesity, hypertension, depression, asthma, and autoimmune disorders[40–42] through physiological and immunological benefits[43,44].

GRx experiences in natural ecosystems have also shown to be beneficial even for Complex Chronic Conditions (CCCs), namely those illnesses and chronic diseases triggered by multifactorial causes, many of which, when identified, require interventions involving changes in behavior and living contexts[31,32]. While pharmacological prescriptions that directly address the underlying causes of CCCs are rare and often leading to complications, exposure to environments like forests and woodlands has shown to influence CCCs outcomes by modulating physiological functions through interactions with plants Volatile Organic Compounds[33], with soil and environmental microbiome[45,46], and by synergizing with therapeutic activities conducted within them, e.g., by providing an appropriate variety of proprioceptive stimuli for motor rehabilitation[47].

Despite the well-documented benefits on mental and physical health, a significant gap remains in our understanding of the specific ecological factors that influence human health outcomes. In particular, it is still unclear if the characteristics of an ecosystem, such as ecosystem structure, habitat complexity, and biodiversity, modulate health responses in individuals. Furthermore, studies investigating the sustained effects of Nature exposure on health over time, in the context of GRx protocols, are relatively rare.

Here, we aim to address these gaps by presenting the results of a nine-month pilot study conducted in a woodland located in central Italy. The study explored the effects of a GRx protocol on both subjective and objective health outcomes of participants, focusing on how variations in ecosystem structure modulate these responses, and if vegetation stratification, patch structure, and species composition in the woodland mediated different effects. The aim of the study was to answer the following research questions: (1) Does the structural complexity of woodland ecosystem patches influence the health responses of individuals with chronic or stress-related health disorders? (2) Do ecosystem patches differing in structural attributes and species composition elicit distinct psychophysiological responses in participants? (3) Does biodiversity at the ecosystem patch level contribute to explaining variations in health outcomes?

Through this investigation, we aim to provide new insights into the ecological characteristics that optimize the therapeutic effects of GRx and deepen our understanding of the relationship between ecosystem structure and human health.

Materials and methods

The pilot study presented here was conducted in a woodland ecosystem called in Italian *Bosco di Puck*, located in southern Tuscany, Italy (Fig. 1). According to the definition by Grant[48], this deciduous woodland is a semi-natural environment, since the ancient forest has turned to coppiced woods and oak rows in the 1950s. Starting from 2012, the *Bosco di Puck* has been managed by a medical doctor who implements GRx as therapeutic interventions for her patients. Since then, the ecosystem has undergone a process of re-naturalization to restore its natural dynamics, where harvesting of biomass and activities like logging, mowing, and wood cutting have been halted as much as possible and limited to the cases when intervention is needed for the sake of visitors' safety. Despite its relatively small size (4.54 hectares), this woodland is representative of the typical biodiversity found in deciduous and mixed forests of central Italy, lying at an altitude between 375 and 600 m above sea level.

Most of the woodland area is represented by a mixed thermophilous oak-dominated woodland, with the downy oak *Quercus pubescens* and Turkey oak *Quercus cerris* as the dominant species[49]. As such, the ecosystem corresponds to the habitats G1—Broadleaved deciduous woodland, and G1.7—Thermophilous deciduous woodland (under the EUNIS European terrestrial habitat classification framework[50]) which represent the most evolved vegetation in the Italian peninsula from the lowland to the montane level.

However, the *Bosco di Puck* woodland comprises a series of patches that, while fitting the general habitat classification, exhibit distinct characteristics in terms of canopy cover, apparent structure, and ecological community composition. These differences make the patches ecologically heterogeneous and distinguishable from one another, enabling their identification and classification. To measure and map them, detailed field surveys, performed annually by trained ecologists from 2012 until 2023, were conducted to assess the dominant species and overall floristic composition. We combined aerial orthoimages from 2006, 2016, and 2023 (publicly available through the PCN of the Italian Ministry for the Environment and the Geoportale of the Regione Toscana), with ground-truthing collected field data. Digital mapping was then performed using QGIS software, version 3.34.4-Prizren[51]. Such a multi-year mapping approach verified the long-term ecological stability of the

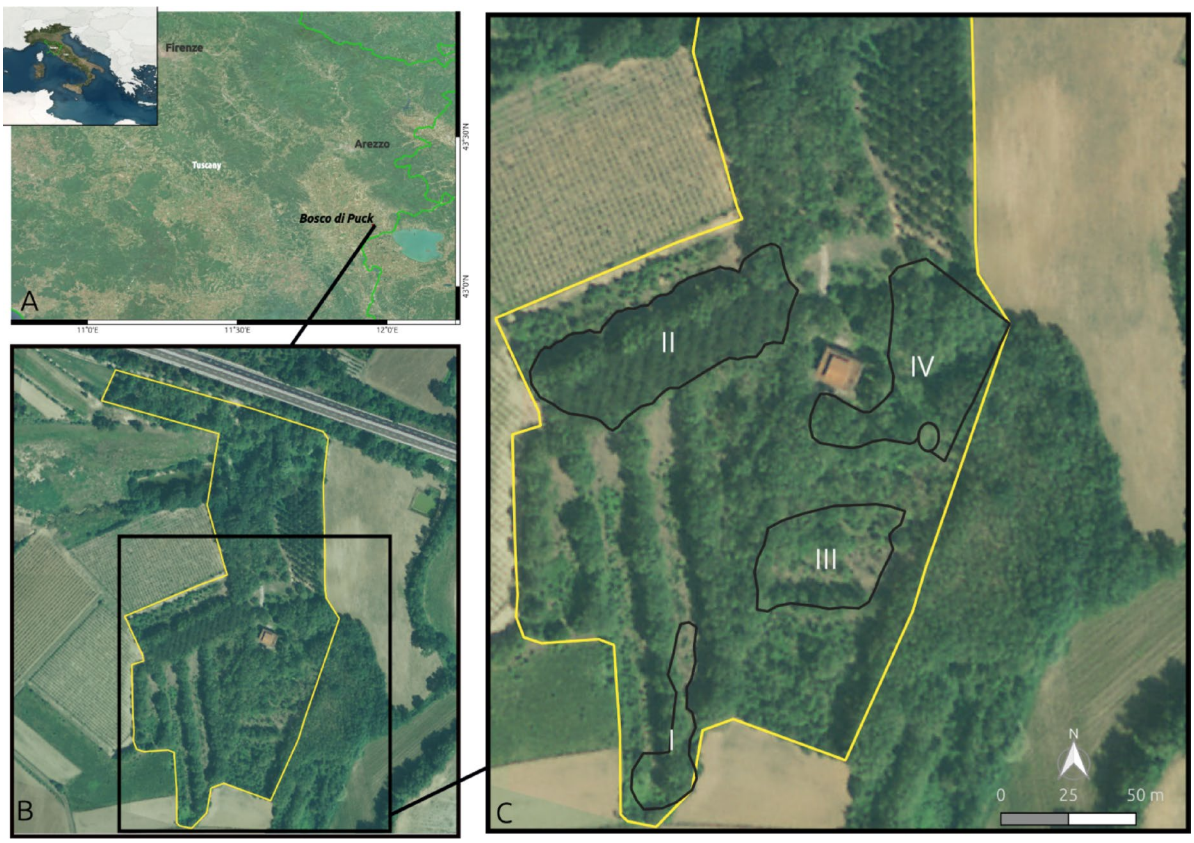

Fig. 1. (**A**) Location of the study area in Italy. (**B**) Aerial image of the woodland where the study took place. The yellow line represents the boundaries of the *Bosco di Puck*. (**C**) The polygons of the patches in the woodland where Green Prescription sessions took place. Map created by the authors with QGIS (version 3.34.4-Prizren), using as base layer the ortophoto from the WMS service of the Italian National Geoportal (PCN—Ministero dell'Ambiente, 2012).

woodland structure and ensured that the patches identified during the GRx protocol, achieved in 2015–2016, remained representative of the same ecological gradients over time.

Building on the general map, we identified the preferred observation points where participants engaged in Green Prescription activities, obtaining representative checkpoints in 4 different woodland patches (Fig. 2).

At the coordinates of these points, we established a 10-m buffer zone; within these buffer areas, we estimated the relative basal cover for the vegetation layers (herbaceous, shrubby, and canopy). Each layer was weighted by multiplying its cover estimate by 0.3, and the weighted values for all three layers were summed to provide an overall indicator of relative vegetation coverage on the horizontal plane. This indicator (x) ranges from 0 to 1, where 0 represents bare soil and 1 stands for complete coverage of the surface[52].

A second indicator (y) was developed to represent the vegetation cover on the vertical plane, accounting for vegetation stratification and plant density. To do so, a camera was positioned at breast height to capture a series of natural-color photographs, taken while rotating the camera clockwise ensuring consistent height from the ground. This method, inspired by the work of Hosoy & Omasa[53], allowed us to depict the vertical density as perceived from a human-eye perspective. Photographs were taken under different lighting conditions to simulate the visual experience as perceived by participants in the study.

The resulting images were analyzed using R language in the RStudio environment[54], with *magick* and *imager* packages. R, G, B channels in each image were split, thresholded, and converted into binary versions, enabling the determination of the number of pixels occupied by vegetation compared to non-vegetation elements. The ratio of vegetated to non-vegetated pixels defined the value of indicator y, for which $y = 1$ represents full vegetation coverage, and values decrease approaching $y = 0$ if no vegetation was present.

Additionally, the species of plants, liverworts, lichens, and mushroom fruiting bodies visible in the patch, over the course of a year, were counted. A normalized indicator (z) of relative species richness was calculated as the ratio of the total species detected in a patch to the maximum number of species recorded in the richest patch, which was assigned a value of 1 on the z indicator scale.

The three indicators x, y, z were combined to represent each patch in a 3D mathematical space, with the score for each indicator serving as coordinates. Equation 1 was used to calculate the Structural Combined Index (SCI), which determines the Euclidean length of the vector from the origin (0, 0, 0) to the point (x_i, y_i, z_i), where i identifies the patch.

$$SCI = \sqrt{x_i^2 + y_i^2 + z_i^2} \tag{1}$$

The SCI ranges from 0 to the diagonal length of a cube with side 1, namely $\sqrt{3} \cong 1.732$. A Normalized Structural Combined Index (NSCI) was derived by dividing the result of the SCI by its maximum value $\sqrt{3}$:

$$NSCI = \frac{\sqrt{x_i^2 + y_i^2 + z_i^2}}{\sqrt{3}} \tag{2}$$

The NSCI ranges from 0 to 1, where 0 indicates the poorest possible condition across all indicators, and 1 represents their best possible condition.

Green prescription protocol

This study was conducted as an exploratory retrospective analysis of a Green Prescription (GRx) protocol originally implemented between autumn 2014 and spring 2015. At that time, the GRx programme was offered

Fig. 2. Photos of the patches where participants engaged in Green Prescription activities.

within local healthcare services as a complementary therapeutic activity prescribed by medical professionals for patients with chronic or stress-related conditions.

The participants in the study were recruited among patients referred by general practitioners, local healthcare services, and other medical professionals involved in their care. After an interview with the medical doctor in charge of the GRx protocol design, participants who have at least two co-occurring chronic or psychosomatic conditions met the inclusion criteria.

The selected group consisted of 15 patients (9 female, 6 male) across different age groups, with a mean age of 44 years (± 13.4 s.d.), and highest frequency in the 41–50 age range (Supplementary materials I, Tab. S1-1). All participants had a confirmed Complex Chronic Condition, based on reports from prior specialist visits, medical reports, and hematological and clinical-chemical tests (that were not performed specifically for the present study). These clinical and diagnostic evaluations were documented as part of the standard GRx medical assessment. According to participants' medical history (anamnesis), they were classified into 4 groups:

- I_P: Patients with autoimmune conditions and pain;
- I_RP: Patients with autoimmune conditions, pain, and respiratory difficulties;
- M_P: Patients with mental health challenges and pain;
- M_PR: Patients with mental health challenges, pain, and respiratory difficulties.

Current and past symptoms were recorded, as well as ongoing pharmacological treatment, including the baseline prescribed dosages. Familiarity with natural environments was assessed as a general self-reported tendency to spend time and feel comfortable in natural settings. Additionally, the short Connectedness to Nature (CNS-6 scale) for adults was implemented to evaluate the personal traits of connectedness to Nature of the participants[55]. This scale was proposed once at the beginning of each trimester, since it evaluates a personality trait that is usually stable and not prone to change fast[56].

The study was conducted in compliance with the ethical principles of the Italian "Codice di Deontologia Medica" (Medical Code of Ethics[57]) and all applicable laws. Before starting the study, participants were informed about the potential benefits, risks, and limitations of the GRx protocol, and they were instructed to report any changes in symptoms or health status. Fully informed consent was obtained for participation in the GRx protocol, including adherence to the safety protocol, and permission for data collection under appropriate measures for anonymization and data protection, as approved by Regione Toscana. All personal, health-related and clinical data were anonymized and stored in password-protected files accessible only to the authorized research team.

The GRx protocol adopted in this pilot study aimed at a dual objective: improving the health of the patients while simultaneously maintaining the ecological integrity of the woodland. To achieve this, the protocol applied the *enactive ecological approach*, an extension of the biopsychosocial model[58–60] that emphasizes the dynamic, reciprocal interaction between individuals and their environments as part of the therapeutic process.

Rooted in enactivism, a theory of cognition that suggests humans "bring forth" the world through action and perception, the biopsychosocial approach integrates ecological principles to help patients explore, interact with, and adapt to their environment in ways that support their own healing process or their ability to cope with chronic symptoms.

Under this framework, participants in this study were encouraged to engage with the patches in the woodland, exploring strategies for adapting to the environment while gradually abandoning behaviors that hindered their health. This process helped them identify activities that were most manageable, reducing or preventing symptoms onset. In this way, participants were not only supported but also empowered by taking an active role in their therapy.

To ensure the ecosystem's protection, the framework was expanded to include animal and plant communities, aligning the purpose of this GRx protocol with the Planetary Health perspective. Thus, during both the planning and execution of GRx interventions for each patient, opportunities for physical interaction with the woodland were carefully assessed. Interactions that could pose any temporary or permanent risk to the woodland and its living beings were carefully avoided: examples include trampling on seedlings, lichens, and mushrooms, disturbing nesting birds, or engaging in other activities that might disturb other living organisms.

The study lasted 9 months and was divided into three periods, each spanning one trimester: it began in autumn (first trimester), continued through winter (second trimester), and concluded at the end of the following spring (third trimester).

The GRx consisted of two 2-h individual sessions per participant, twice each week. Participants attended the sessions separately, following their personalized therapeutic plan and under the supervision of medical staff. No collective or group activities took place, and no interaction occurred between participants, or between participants or other subjects, during the sessions. In the first two sessions, the healthcare professional guided each participant to help them orient themselves and assess their ability to perceive signals of distress in both their body and the woodland. In subsequent sessions, the healthcare professional continued to accompany the participants but no longer provided direct guidance. Instead, participants were encouraged to explore the woodland freely, while avoiding ecologically vulnerable areas. This approach allowed them to reach the woodland patches where they could pause to enjoy the environment's perceived benefits, or engage in activities such as observing, smelling, and touching elements around them. They could also experiment with self-directed movements like swaying, which provided opportunities to experience relief from pain and other symptoms.

At the beginning of each visit, environmental conditions were recorded, including weather, air temperature, and wind intensity, along with any disturbances or unique features observed in the woodland (e.g., animal presence, young trees sprouting, visible mushroom fruiting bodies, or flowering). Participants were encouraged to adjust their pace according to their comfort, with the freedom to stop, observe, or speed up as desired. They could also choose to share their impressions with the medical doctor or remain silent, ensuring a personalized experience for each session. During the study period, all participants visited the four woodland patches, one per session, ensuring within-subject comparability of perceived and physiological responses. The sequence of visits was counterbalanced across participants to minimize order effects, and each session was separated by at least three days, ensuring that each patch was visited in a period of two weeks. This design ensured comparability of perceived and physical responses while avoiding habituation or cumulative exposure effects.

Every three months, patients were invited to reassess their impressions and perceptions while visiting the patches of the woodland. A series of 4 questionnaires were proposed to gauge the interactions between the ecosystem and each of the participants, focusing on two macro-areas, namely i) their subjective preferences and perceptions; and ii) the objective effects on their mental well-being and physical symptoms.

The first questionnaire aimed at giving a background assessment of the appreciation of each woodland patch on a 10-point Likert-type scale[61], a tool commonly employed in environmental psychology to evaluate subjective preference (questionnaire A). A second questionnaire, adapted from the perceptual scales developed by Han (2003)[62], assessed how each patch was described by participants based on their perceptions. The wording of the original scale was slightly simplified to facilitate understanding, and the response format was expanded to a 10-point Likert-type scale to increase sensitivity and maintain consistency across all questionnaires the scales in (questionnaire B). The results allowed the comparison between the perceived characteristics of the patch and the NSCI calculated for the patch.

Additional surveys aimed to test the effect on the well-being of the patient, in terms of psychological (questionnaire C) and physical effects (questionnaire D), through a 0–5 Visual Analogue Scale. The final score of all the scales and evaluations was calculated as the sum of the scores to each item, considering the reverse items on a specular scale.

The items of the questionnaires are available in Supplementary Materials II.

To collect objective indicators alongside the questionnaire's responses, signs and symptoms (whether usual or newly acquired) experienced by the participant were recorded. If a participant appeared tired, upset, in pain, or showed signs of discomfort, the healthcare professional recorded and monitored these symptoms, in accordance with the safety protocol. Additionally, each participant kept a therapeutic diary, where they tracked the dosages of medications or treatments they were using to manage and cope with their chronic pain or discomfort in their daily life.

All psychological and physical self-report measures were derived or adapted from validated instruments widely used in studies on the restorative and therapeutic effects of natural environments [63–65]. Field surveys and data collection scheme is illustrated in Fig. 3.

Statistical analysis

Statistical analysis was conducted using R language[66] within the RStudio environment (version 2023.09.00 + 463[54]). Packages *tidyverse, dplyr, stats, broom, and dunn.test* (version 1.3.6) were used. Questionnaire results were analyzed to identify significant differences in responses across different patches in the woodland and across different time periods. For each multiple comparison, the normality of the data was assessed using the Shapiro–Wilk test, and homoscedasticity was evaluated using Bartlett's test; then, appropriate statistical test was chosen between repeated measures ANOVA with Tukey's post-hoc test, and Kruskal–Wallis with Dunn's post-hoc test, depending on the data distribution. If the Kruskal–Wallis test was required instead of ANOVA, p-values from

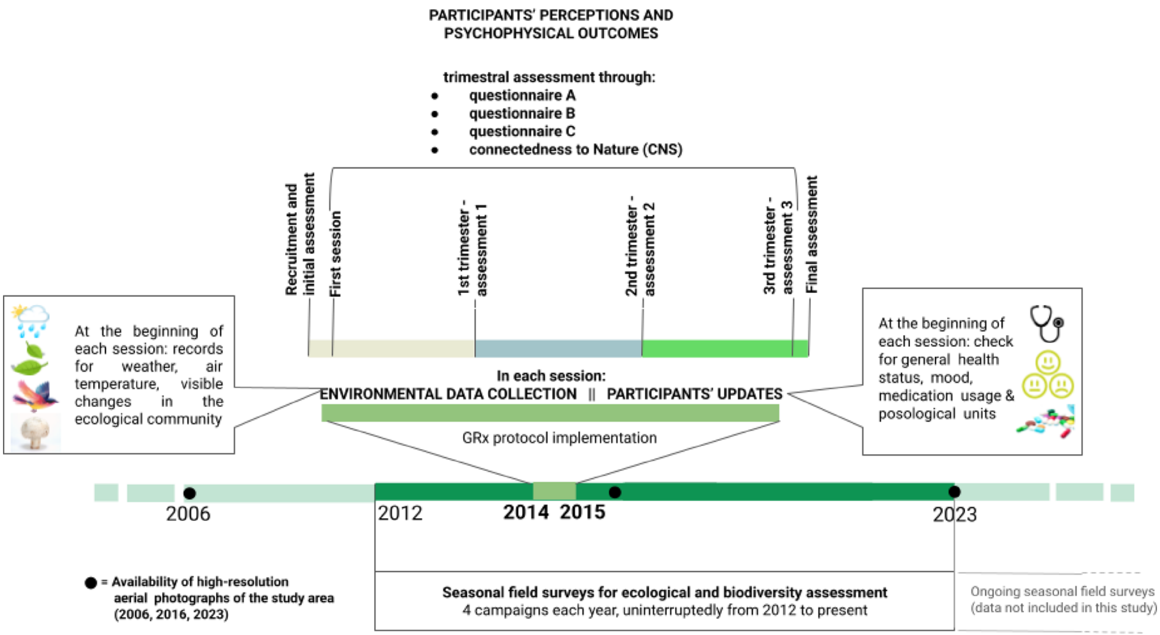

Fig. 3. Data collection scheme.

Dunn's post-hoc test were adjusted using Bonferroni's correction. Data visualization was performed using R packages *ggplot2, ggpubr, scatter3D,* and *plotly*.

Results

Ecosystem structure

The field assessments in the woodland allowed for the evaluation of the structure and complexity of the forest patches (Fig. 2). Table 1 shows the indicators for each patch tested during the GRx protocol, along with the SCI and NSCI results.

The results reveal that the four patches differ in terms of structural complexity as well as plant and mushrooms species richness. Specifically, the level of complexity and richness increases according to the NSCI, progressing from patch I, a grassy glade, to patch II, a pinewood, then to patch III, a transitional forest with young oaks, and finally to patch IV, a mature oak forest dominated by Turkey oaks and downy oaks, with a dense understory.

The positioning of the four patches in the mathematical space, based on the NSCI results, is shown in Fig. 4.

Overall participants' perception of the patches of the woodland

The results of questionnaire "A", which asked patients about their appreciation for the visited woodland patches, are shown in Fig. 5.

We used repeated measures ANOVA to analyze differences in the dependent variable as a function of woodland patch and time phase. Preferences among patches showed significant differences (ANOVA $F = 58.13$, $p < 0.0001$) across all the three trimesters, and were independent of weather conditions and air temperature. The lowest overall appreciation score was consistently assigned to patch I in all the periods; on the contrary, scores for patches III and IV were significantly higher than those for patches I and II.

As regards the temporal trends, the data dispersion tends to decrease in all areas. Yet, some trend differences can be noticed: the scores assigned to patch I and II remained stable throughout the first and second trimesters; nevertheless, both data dispersion and standard deviation gradually decreased from the first to the second trimester. On the contrary, patch III showed a slight decrease in its score in winter (2nd trimester) compared to autumn (1st trimester) but increased significantly and became less dispersed in spring (3rd trimester). Finally, patch IV was consistently regarded as the most favorite patch, with preference steadily increasing along with time, with a maximum in spring (3rd trimester). P-values and details on the statistical analysis are reported in Supplementary Materials III.

Questionnaire B, which collected the subjective descriptions of the patches, revealed that the participants were able to detect the different species richness level, despite they were not explicitly invited to focus on living beings heterogeneity. Their semi-quantitative assessment of the patch characteristics showed indeed a peak in the scores associated with the adjectives "variegated" and "rich in life forms" for patches III and IV. The same patches were associated with positive words, like "wonderful", "interesting", and "beautiful"; opposed to that, the words "monotonous" and "oppressive" were more frequently assigned to patches I and II (Fig. 6). Despite the overall fascination, the item "awe" was generally not reported in association with specific patches, except in a few cases spontaneously noted by the attending physician during GRx sessions, when participants' attention was drawn to the largest oak in Patch IV.

In addition to the responses to questionnaire B, participants frequently reported sensations that were difficult to describe. When attempting to explain these experiences, they often attributed them to the color(s) enhanced

Patch	Representative photograph	Description	Layer	Horizontal relative vegetation cover	Vertical relative vegetation cover	Number of observed species	Weighted horizontal vegetation cover	Weighted vertical vegetation cover	Normalized species richness index (n.species / max n. species of the richest patch)	SCI	NSCI
I		Glade with annual herbaceous species	herbaceous	0.8	0.66	9	0.27	0.47	0.67	0.86	0.49
			shrubby	0.1	0.47	3					
			canopy	0.0	0.42	2					
II		Pinewood	herba-ceous	0.4	0.52	9	0.39	0.52	0.67	0.93	0.54
			shrubby	0.2	0.58	3					
			canopy	0.7	0.62	2					
III		Young transitional oak forest	herbaceous	0.6	0.68	13	0.51	0.54	0.90	1.17	0.68
			shrubby	0.4	0.54	2					
			canopy	0.7	0.57	4					
IV		Mature oak forest with densely vegetated underwood	herbaceous	0.9	0.73	12	0.69	0.56	1.00	1.34	0.77
			shrubby	0.7	0.58	3					
			canopy	0.7	0.54	6					

Table 1. Results of x, y, and z indicators, Structural Composite Index, and Normalized Structural Composite Index for the analyzed woodland patches.

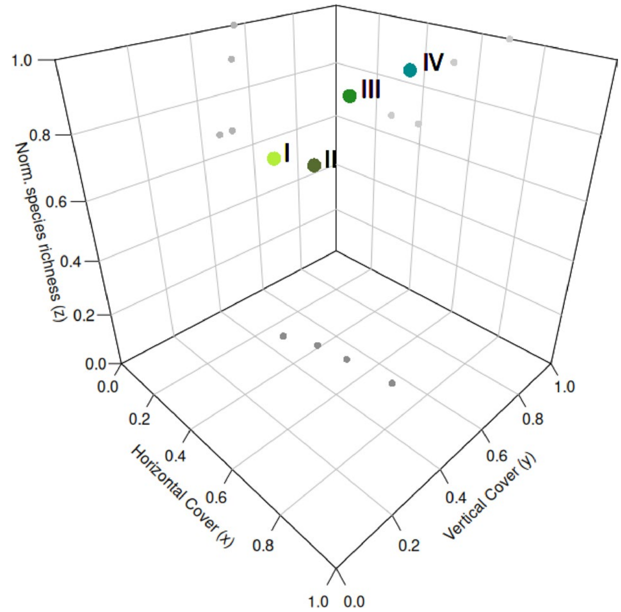

Fig. 4. Patches results for the NSCI, plotted in a 3D mathematical space.

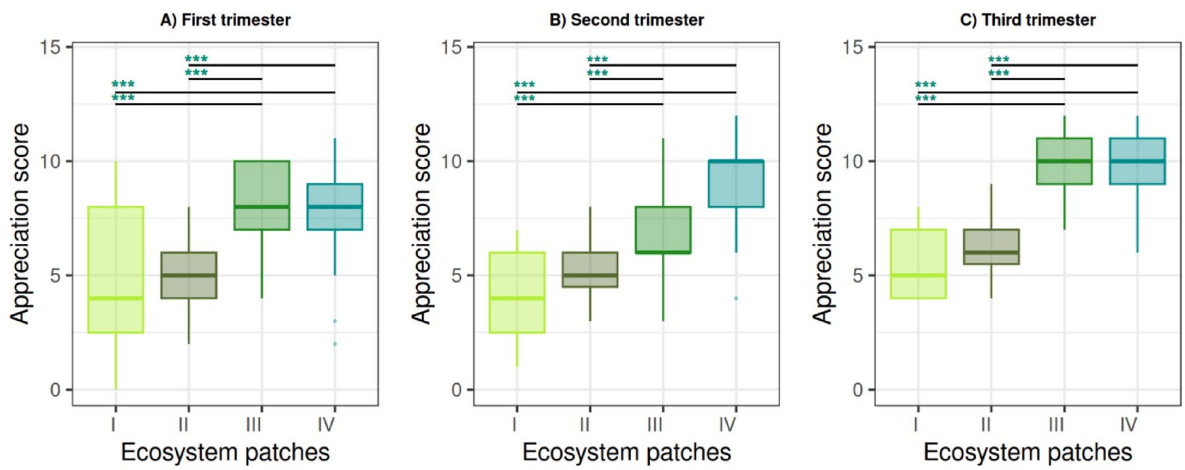

Fig. 5. Score of appreciation for each patch of the wood in the three trimesters of GRx intervention, obtained through the questionnaire "A" (Tab. SM2, A). Boxplots are grouped by trimester to allow direct comparison among woodland patches at each time point. The vertical bars represent the standard deviation of the responses; the thick horizontal bar represents the median of the group. Asterisks indicate level of significance at the Tukey post-hoc test with Bonferroni adjustment: * $p < 0.05$, ** $p < 0.01$, ***$p < 0.001$. Statistical tests results and p-values are shown in Supplementary Materials III.

by sunlight filtering through the foliage and reflecting on the ground, or to a subtle synesthetic sensation merging tactile and auditory elements.

Psychological effects

Figure 7 illustrates the scores obtained from Questionnaire "C" about improvement in mental well-being. Patches IV, as well as III, consistently show higher scores compared to patches I and II. Overall, across the three trimesters, median scores for all patches tend to stabilize and improve over time, indicating a gradual positive and cumulative impact of the interventions.

p-values are reported in Supplementary Materials III.

No association of the resulting scores and score trends were detected with weather conditions, nor with the participants' connectedness to Nature. Only a slight tendency to score higher in all the patches was reported for participants with prior familiarity with natural environments, that is, those more accustomed to or comfortable

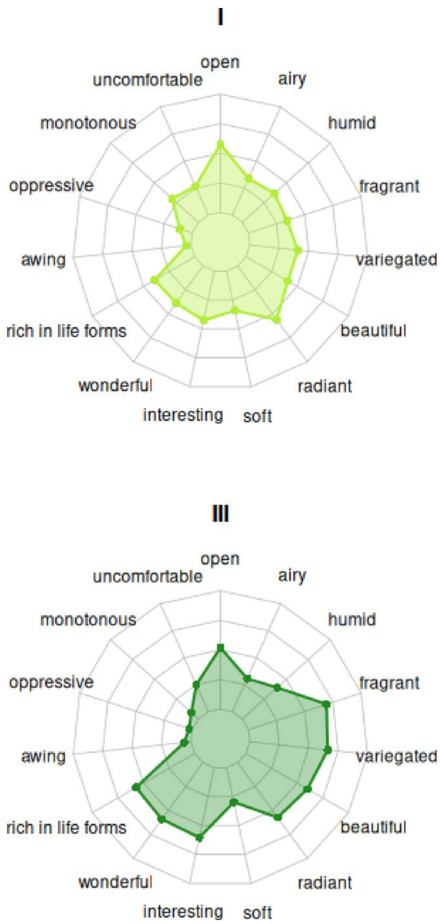

Fig. 6. Results of the questionnaire "B" (Tab. SM2, B). The points on the plot area represent the average score across the three trimesters.

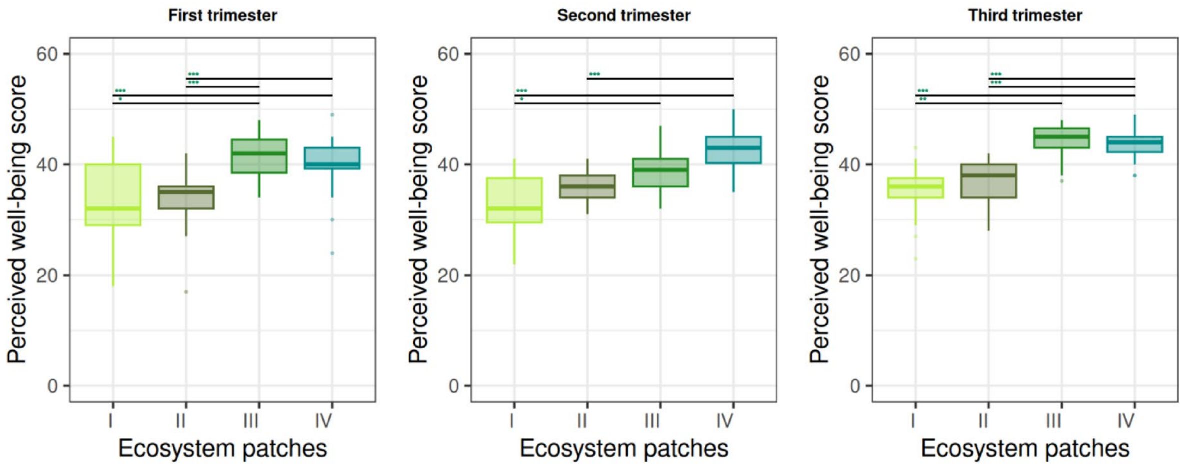

Fig. 7. Score obtained through the questionnaire "C" (Tab. SM2, C) across three trimesters of GRx intervention. The vertical bars represent the standard deviation of the responses; the thick horizontal bar represents the median of the group. Asterisks indicate level of significance at the Tukey post-hoc test with Bonferroni adjustment: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Statistical tests results and p-values are shown in Supplementary Materials III.

in natural settings. Nevertheless, even participants who initially reported aversion or disinclination towards natural elements were able to perceive the calming effect of the woodland patches.

Effects on physical symptoms

All the patients reported improvements in their symptoms while visiting the forest, although not all the areas showed the same effects (Fig. 8) and, more importantly, not always consistently across the trimesters.

In general, all the patches were able to alleviate at least some of the symptoms reported but with significant differences between them. The lowest effectiveness resulted in patch I, which was consistently associated with the reduction of no more than one symptom during the 1st trimester in autumn, when the GRx started. Patch II (pinewood) did not show significant differences from these results, although it was more frequently associated with the alleviation of two or more symptoms.

The highest number of consistently improved symptoms were recorded for patches III and IV during the first trimester, as well as during the third trimester; however, the effects were perceived as less beneficial during the second trimester, in winter. Statistical analyses results and p-values are reported in Supplementary Materials III.

These findings are more refined by distinguishing the effects based on the symptoms most alleviated by the different patches, in the different periods of GRx, for different subgroups of patients falling under the same clinic conditions and the most relevant symptoms they were taking medications for. Figure 9 shows the results in patients with autoimmune conditions and pain (IP), patients with autoimmune conditions, pain, and respiratory difficulties (IRP), patients with mental health challenges and pain (MP), and patients with mental health challenges, pain, and respiratory difficulties as well (MPR).

Across all groups, symptom relief generally increased over the three trimesters, despite no significant differences were detected between different phases, nor along the interaction between periods and patches. Similar to the overall results shown in Fig. 8, the relief outcomes vary significantly between patches (repeated measures ANOVA $F = 11.813$, $p < 0.0001$), with different patterns depending on the participants group.

Patch IV consistently demonstrates the highest symptom relief scores by the third trimester across all the patients' groups, whereas patch I yields comparatively lower relief across all periods.

In groups affected by pain but without respiratory challenges (I_P and M_P), symptom relief appears relatively moderate, but more consistent across patches. In particular, patches III and IV are consistently associated with improvement and pain relief, with a beneficial peak occurring for patch III at the beginning of the GRx protocol (Fig. 9, top and bottom left panels). The overall improvement is more evident in groups with respiratory challenges (I_RP and M_RP), as seen by the prominent shift from lower to higher symptom relief scores over time (Fig. 9, top right and bottom right panels). Nevertheless, patch I seems to work effectively in giving relief to respiratory difficulties as soon as the first trimester of GRX, in autumn, but ceases to be reported as beneficial during the 2nd and 3rd trimester, namely winter and spring time.

Also in this case, weather conditions did not appear to influence the physical outcomes; however, lower mean air temperature may have played a role in limiting the perceived relief of chronic pain.

Positive outcomes for participants were further enhanced when they were prompted to consider, beside their own well-being and enjoyment, the well-being of the surrounding living beings, despite certain restrictions being put in place to safeguard the woodland. For example, when participants were asked to remain silent or change their preferred path to avoid disturbing nesting animals, improvements in psychological well-being and physical symptoms were even more pronounced. Moreover, participants exhibited a shift toward greater environmental respect: over time, they demonstrated fewer extractive behaviors (e.g., refraining from picking

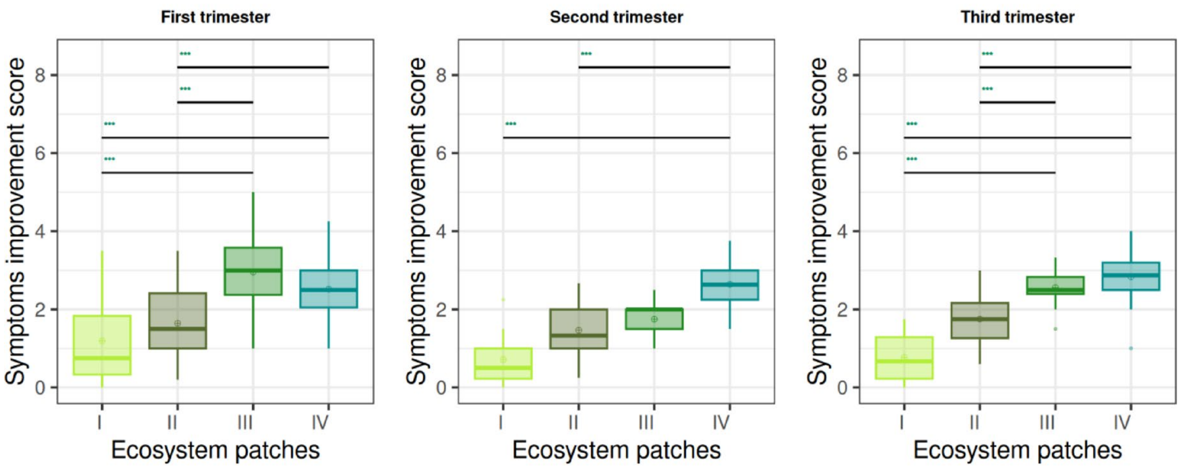

Fig. 8. Symptoms improvement score, as a result of the declared symptoms and their relief assessed with the questionnaire "D" (Tab. SM2, D), in the three trimesters of GRx intervention. The vertical bars represent the standard deviation of the responses; the thick horizontal bar represents the median of the group. Asterisks indicate level of significance at the Tukey post-hoc test with Bonferroni adjustment: * $p < 0.05$, ** $p < 0.01$, ***$p < 0.001$. Statistical tests results and p values are shown in Supplementary Materials III.

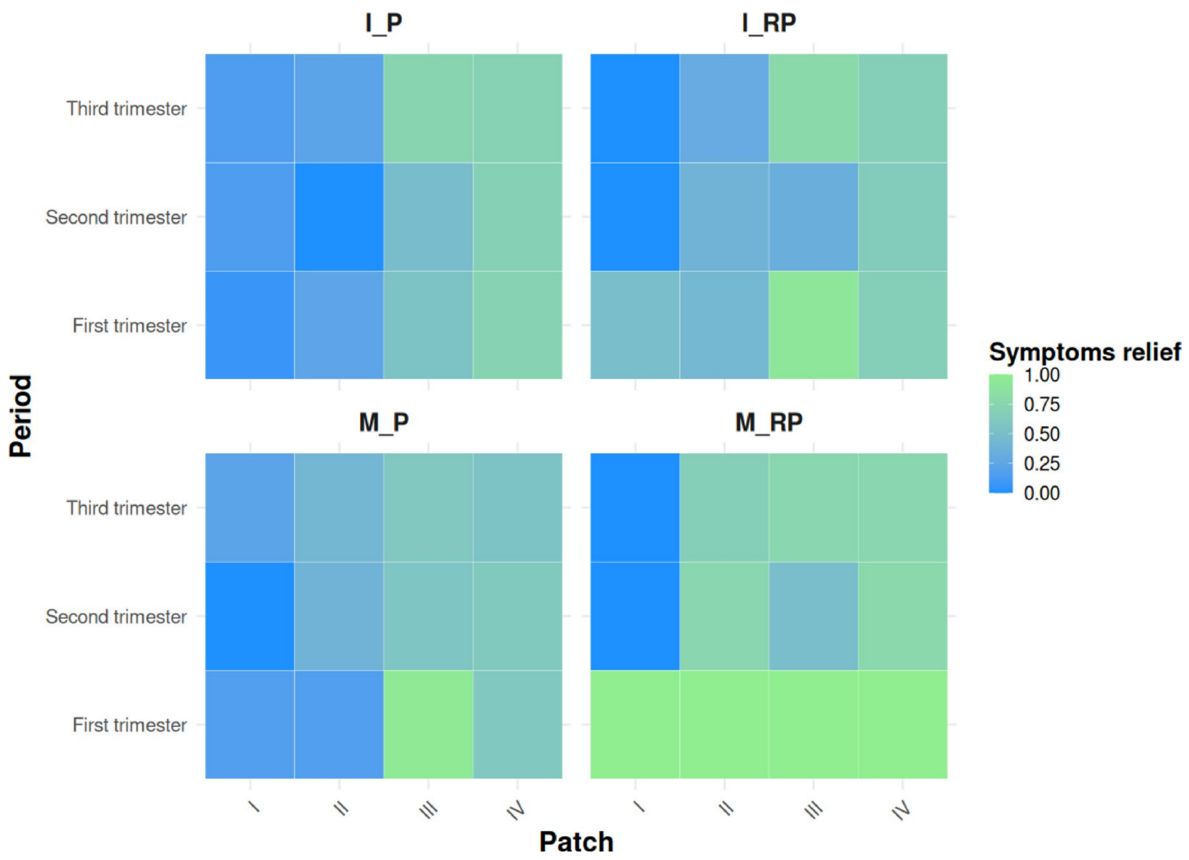

Fig. 9. Symptom relief in different groups of patients, associated to the different patches across the three trimesters of GRx. I_P = Patients with autoimmune conditions and pain; I_RP = Patients with autoimmune conditions, pain, and respiratory difficulties; M_P = Patients with mental health challenges and pain; M_PR: Patients with mental health challenges, pain, and respiratory difficulties. Indicator of symptoms relief has been normalized on a scale 0–1 to improve data visualization.

fruits or flowers) and moved away from expecting immediate results from the GRx protocol, instead embracing the gradual process of health improvement.

In support of these findings, the analysis of the daily medication records highlights the impact of the GRx protocol on medication usage over the course of three trimesters. Initially, patients reported baseline levels of medication usage ranging from 13.0 to 44.0 posology units per week. However, following the intervention, there was a reduction in the required medication across all patients. In the first trimester, the average reduction in medication usage was 4.53 (± 5.33 s.d.) dosage units per week less than the initial situation. This reduction accelerated in the second trimester, with an average decrease of 17.80 (± 15.80 s.d.) dosage units per week and was maintained in the third trimester with 17.73 (± 10.85 s.d.) units per week. Overall, a final average reduction of 85.45% (± 8.00% s.d.) in dosage usage compared to the baseline initial posological units was recorded by the end of the study.

Discussion

Green Prescriptions (GRx) have shown therapeutic efficacy in alleviating symptoms of chronic illnesses. Yet, the link between environmental characteristics of areas devoted to GRx and their potential effects on human health remains underexplored, as does the development of operational criteria for integrating GRx while maintaining ecosystem integrity.

This pilot study is among the first to investigate the potential changes in health outcomes of individuals with complex diseases in relation to different ecological characteristics of patches in a woodland ecosystem. Overall, our results showed that prolonged exposure to a woodland ecosystem yields cumulative health benefits, with outcomes varying significantly according to patch complexity and following a gradient from the least complex patch to the most complex one, as reflected by the ecological indicators provided by the Normalized Structural Combined Index (NSCI), introduced in this study.

Patches with greater structural complexity, such as the mature oak forest (patch IV) and the young transitional oak forest (patch III), were consistently associated with greater psychological well-being and physical symptom relief compared to simpler patches, such as the grassy glade (patch I) and the pinewood (patch II). Notably, no association between the resulting scores and weather conditions or participants' connectedness to Nature was detected, confirming that the observed benefits are independent of individuals' Nature connectedness, as also noted by previous works[67]. These findings underscore the critical role of ecologically intact environments in enhancing GRx effectiveness, as more domesticated or simplified landscapes may lack sufficient therapeutic potential[68].

Temporal trends were also detected during the progression of this study, suggesting that seasonal dynamics and fluctuations in ecological functions influence human responses and health outcomes. For instance, while patch IV—which is dominated by mature oaks with dense and rich understory, including ivy and ferns—consistently supported mental and physical health improvements, patches I and II with less complex structure displayed fluctuating effectiveness across the three trimesters. This further reinforces the hypothesis that the observed outcomes stem primarily from ecosystem properties and functions, encouraging further research to explore the role of ecosystem dynamics when designing GRx interventions.

As a consequence, tailoring GRx protocols requires accounting for patient-specific needs while also considering both the type of ecosystem and, within the same ecosystem, its structural and functional variations over time.

Although existing literature suggests that exposure to specific ecosystems, such as coniferous forests and mountain environments, improve specific symptoms[69], this longitudinal study found that groups with autoimmune and respiratory challenges exhibit high variability across the woodland ecosystem patches and along trimesters, reinforcing the importance of diverse, resilient ecosystems to ensure consistent therapeutic effects that can require different areas, in different seasons.

This study also contributed to shed light on how human perception further influences the effectiveness of GRx in natural environments, as evidenced by participants' preferences, sensory experiences, and their trends in patches with different ecological characteristics and time periods. A possible explanation for the decrease in the variability of preferences and psychological responses over time could be attributed to an increased familiarity with the woodland, which allows individuals to recognize specific landmarks and feel more at ease. This growing familiarity, coupled with an improved affiliation—as shown by other works [67,70]– can help visitors relax and shift their attention to fascinating natural features and resources, rather than on potential threats or dangers.

However, an alternative interpretation may be that richer and healthier ecosystems provide more opportunities for sensory enrichment, which triggers instinctive processes inherited through our evolution to better interpret the environment. For instance, the increased preference for Patch I in spring, when blooming flowers become visible, and the strong appreciation for Patch III in autumn, when mushrooms are present, likely reflect an unconscious perception of resource abundance[71]. This supports previous observations suggesting that some natural features serve as clues and hints for our cognitive system for better interpreting the surrounding environment[72].

The psychological benefits observed in these patches align with a growing body of evidence highlighting the crucial role of unconscious physiological effects triggered during the contact with the natural environment. These effects rely on visual stimuli[73,74], olfactory cues[75], sounds[76], and a variety of other sensory signals, including those coming from the interactions of natural light (e.g., reflection, refraction) with soil and plants, which stimulate the human sensory system and generate a wide range of complex sensations. Despite the challenges in relating these effects to conventional sensory experiences[42,77,78], the improved psychological well-being of participants in this study aligns with prior findings showing that environments with higher naturalness and perceived wilderness promote mental restoration and well-being[3,79], promote mental health[65,80–82], and support stress recovery[83].

Similarly, a series of complex cognitive processes might explain the positive responses observed not only when the human-Nature relationship is leveraged to enhance human health, but also when individuals are explicitly encouraged to respect the ecosystem, thus recognizing the interconnectedness and interdependence between themselves and the environment that contributes to their own health. The GRx implementation method presented here exemplifies how to operationalize GRx in a virtuous manner, fully embracing the Planetary Health approach[84]. Participants in this study not only showed improvements in psychological and physical well-being but also demonstrated greater ecological awareness and respect for the woodland environment. This reciprocal dimension, consistent with previous perspectives on GRx, highlights the mutual advantages of Nature-based interventions and approaches that promote both human and ecosystem health[85,86], fully aligning with the Planetary Health perspective. All of this opens new possibilities for research, particularly those focused on addressing the limitations of this study and closing the existing gaps. First, the retrospective and observational nature of this study does not allow for causal inference, and results should be interpreted as exploratory associations rather than controlled experimental outcomes. Nonetheless, this design provides valuable real-world evidence on how clinical Green Prescription (GRx) protocols are implemented within standard healthcare practice, with further investigation needed to isolate the specific contribution of GRx compared to other concurrent factors. On the one hand, since the small sample size and reliance on mostly self-reported data may constrain the generalizability of findings, we aim and suggest incorporating biomarkers of stress and immune function, as well as objective physiological measurements (e.g., stress hormone levels, heart rate variability) in future research, so as to sharpen the ability to link subjective improvements to measurable biological effects underlying GRx benefits. On the other hand, expanding the study to include other ecosystems, such as other woodlands as well as wetlands and coastal areas, could offer a broader understanding of GRx potential applicability. Therefore, all the methods implemented in this study need to be experimented also in other settings with different ecological attributes, ideally including a more robust assessment in terms of ecological indices and the determination of additional dimensions of biodiversity that could influence the therapeutic potential of natural settings.

Finally, while this study prioritized ecosystem preservation, the impacts of GRx on ecosystems themselves remain unexamined. As an essential component of the Planetary Health framework[87], future research should combine ecological monitoring along with human health assessments to evaluate the long-term sustainability of GRx protocols under a multidisciplinary perspective. This is particularly relevant in areas where GRx participation overlaps with other Nature-based Interventions or recreational activities in Nature, leading to cumulative effects that could trigger harmful feedback loops for both environmental and human health.

In light of our results, preserving biodiversity and maintaining ecosystem complexity appear crucial. On the one hand, overly managed, or monospecific green spaces, risk diminishing their long-term ecological functions and their therapeutic potential due to excessive and uncontrolled use: an approach focused solely on maximizing specific therapeutic benefits through a single habitat type or limited species list of desirable plants[88] and animals, although commendable, could be short-sighted, as it would fail to recognize the potential of other ecosystems or emerging processes that could be vital to human well-being. On the other hand, only resilient and well-functioning ecosystems, where all components are in harmony with the main ecological goal-function and play their crucial roles within the web of life, can we ensure that Nature—whether forests, wetlands, or urban green spaces—truly contributes to human well-being, not just as a temporary "cure" but as part of a true ecological infrastructure for health.

Conclusion

The results of this study, focused on the multifaceted therapeutic efficacy of Green Prescriptions in a woodland ecosystem, support ecosystem structure as the basis for Green Prescriptions by demonstrating the critical role of the properties of ecosystems where therapeutic interventions are implemented. Our findings also highlight that the relationship between ecosystem complexity and health benefits is not linear, calling for integrative approaches that account for the dynamic nature of both ecosystems and human responses.

This study specifically adds to the growing body of knowledge suggesting that GRx protocols, achieved with an ecological-enactive approach, are effective in providing significant alleviation of physical symptoms particularly in patients with respiratory challenges and pain. The progressive reduction in medication usage over the three trimesters, regardless of the group anamnesis, provides compelling evidence for the cost-effectiveness and sustainability of GRx as complementary therapeutic strategies. The lack of a linear and simple relationship between ecosystem characteristics and health outcomes does not detract from the effectiveness of GRx; on the contrary, it highlights the need to view ecosystems as dynamic and complex entities, just as the human body and the individual variability of people. Unlike conventional medicine, which tries to match symptoms to specific drugs, GRx avoid treating natural environments as "pharmacies" where each element of the ecosystem is seen as a remedy for a specific symptom. Instead, it acknowledges that the therapeutic power of Nature lies in the dynamic, multidimensional interaction among ecosystem components and the complex set of information and signals they carry.

This underexplored and challenging complexity should not be seen as an obstacle but as an opportunity to advance Planetary Health: tailoring GRx on patient needs while monitoring and preserving ecosystem structure and functions allows for a flexible and personalized approach, that consider the environmental setting surrounding the place where patients have access to while avoiding harming it. In this way, GRx advances the Planetary Health framework by directly addressing the need for beneficial and respectful interactions between humans and the local environment.

The interdependence between Nature and humans becomes even more important when considering that the perceived well-being and sensation of "being in the right place" that occur in some natural areas are irreplaceable. This supports an intriguing hypothesis suggesting the existence of a still unexplored, complex set of signals that pervade ecosystems, emerging from the complexity of resilient ecosystems but lacking in simpler or degraded ones. These signals may be interpreted by the human central nervous system and other bodily receptors, aiding in processing environmental information and eliciting specific adaptive responses in the human body.

Effectively scaling GRx, however, will therefore require a major cultural shift. The healthcare sector is indeed required to adopt practices that minimize its impact on the Earth's ecosystems and engage in a transdisciplinary dialogue rooted in complexity medicine. At the same time, while it is crucial to preserve ecosystems and the services they provide through their complexity, investments are also needed to create and maintain accessible, safe, and biodiverse green (and blue) spaces, particularly in urban areas where the demand for such interventions is greatest. In fact, monospecific or overly managed green spaces risk losing their long-term ecological functions and therapeutic potential, especially when subjected to frequent and uncontrolled visits.

Future research is needed to expand this framework across different biomes and populations, combining ecological indicators with physiological and perceptual data to better understand how ecosystem structure modulates therapeutic efficacy and might leverage virtuous cycles: through GRx, patients not only experience improved health but also cultivate greater environmental awareness, becoming advocates and stewards of the Nature around them. This fosters a positive feedback loop in which Nature supports humanity, and humanity, in turn, commits to protecting Nature.

To sustain this outcome, policymakers and planners must urgently prioritize biodiversity conservation and the restoration of natural areas, recognizing their established role in promoting and restoring human health, and GRx offer an actionable pathway to reinforce and support this commitment, paving the way for a more sustainable, equitable, and health-oriented future for both humanity and the planet.

Ultimately, the functioning of Earth's ecosystems is inseparably linked to the health of its inhabitants, creating a complex, reciprocal cycle where each is both cause and effect of the other's resilience.

Data availability

The data supporting the findings of this study are not publicly available due to reasons of sensitivity. Anonymized data can be obtained from the corresponding author upon reasonable request.

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Author contributions

A.S. and P.P. are equal contributors to this work and designated as co-first authors. Conceptualization: P.P., G.B., A.S.; Data Curation: A.S., P.P.; Formal Analysis: A.S., P.P., S.P.; Investigation: P.P., G.B., S.P., A.S.; Resources: P.P., F.P.; Software and Visualization: A.S.; Supervision: G.B., F.P. All the authors contributed to the methodological aspects and in writing the original draft as well as reviewing and editing.

Declarations

Competing interests

The authors declare no competing interests.

Ethical statement

This research study was conducted retrospectively on anonymized data, initially gathered as part of clinical practice. The study was conducted in compliance with the ethical principles of the Italian "Codice di Deontologia Medica" (Medical Code of Ethics), as well as with all applicable laws. The study protocol was submitted to Regione Toscana under the public notice D.D. n. 1684/2012 and subsequently approved with D.D. 5015 on 25-10-2012. Fully informed consent was obtained from all patients for participation in activities in natural settings, green prescriptions plan, data collection and treatment. Data was processed in accordance with prevailing ethical standards and data protection laws. Anonymization and encryption were applied to all the data, as well as data protection security protocol, to protect patient identity and privacy.

Additional information

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