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Envisioning future landscapes: A data-based visualization model for ecosystems under alternative management scenarios

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HIGHLIGHTS

- Ecological data were integrated into 3-D visualization of future landscapes.
- Long-term visual impacts of wildfire, grazing and pine colonization were predicted.
- Mediterranean landscapes were reliably represented using only 4% of the flora.
- The visualization was found to be a statistically valid representation of reality.
- The 3-D model is science-based, integrative and accessible to non-experts.

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ABSTRACT

Human-driven landscape changes strongly influence landscape functionality and aesthetics. While landscape planners have access to biophysical data for decision-making, they often do not have the necessary information about social variables, such as aesthetic tastes, feelings, or functions of a place. Visualizing future landscapes under alternative management scenarios could be a valuable tool for aiding land management decisions. Towards these ends, empirical, quantitative ecological data on vegetation composition, pattern, and processes in a Long-Term Ecological Research (LTER) site in Israel were integrated into a computerized, 3-D representation of current and future landscapes.

Our objectives were (1) to visualize landscape-shaping processes, such as wildfire, grazing, and species colonization, that can assist managers, planners, and the public to envision the long-term visual significance of management alternatives and (2) to validate the similarity between the 3-D model and reality. The visual model we developed is based on 30 years of scientific knowledge and ecological data describing vegetation processes in Ramat Hanadiv, a case study of ecological conditions and processes relevant to the Mediterranean and other complex ecosystems worldwide.

Before studying the role of the 3-D model in decision-making, validation was performed by comparing 'current state' model representation with real-world photos from the perspective of the observer. The model was found to be a valid representation of reality.

Looking to the future, we suggest that the ability to create future landscapes using scientific data can assist to improve decision-making processes, balancing ecological and social needs.

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1. Introduction

1.1. Turning data into an applied management tool

Communicating scientific data to non-experts is a major challenge. This challenge is intensified by the scale and scope of the data in question; we see the increasing collection and storage of big data, in which large databases are built, stored, analyzed, and shared and, potentially, could play a significant role as available information for use by decision-makers. However, this data is inaccessible and thus underused. In ecology, for example, the Long-Term Ecological Research (LTER) Network established in 1980 (similar to NEON in the United States) contains platforms encouraging and enabling the creation of quantitative datasets that describe global environmental change and its effects on ecosystems throughout the world (Mirtl et al., 2018). These databases usually include detailed metadata allowing their use in future syntheses and comparisons.

In the face of its increasing ubiquitousness, some authors argue that collecting vast amounts of environmental data not led by questions and hypotheses threatens the principles of evidence-based science that supports management and policy (Lindenmayer & Likens, 2018; Collins & Knapp, 2019). Moreover, GIS layers or raster databases are in most cases inaccessible to non-experts like decision-makers and the public that need a more recognizable landscape language (Nassauer, 1995).

Many landscape ecologists aim to use their discipline to guide a management approach that integrates ecological knowledge and social considerations (Liu & Taylor, 2002). However, alongside a movement towards more applied research in this field, as reflected in the professional literature (Wu, 2017) many studies still focus on the spatial distribution of biological elements or make rather little use of modeling approaches accounting for actual ecological processes (Morán-Ordóñez et al., 2019), both do not suffice as a basis for management and planning.

1.2. Active management of landscapes

Active management is one of the more contemporary approaches to managing open spaces (Perevolotsky & Shkedy, 2013). In contrast to a more traditional "hands-off" approach, active management advocates intervention in ecological processes to facilitate the provision of multiple benefits from the ecosystem. Such an approach is crucial for addressing a major challenge of managing landscapes that have evolved under frequent anthropogenic disturbances – controlling shrub encroachment and regulating woody vegetation cover and biomass (FAO & Plan Bleu report, 2018). Another concept, the adaptive management strategy (Haney & Power, 1996), is one of the pillars of the Long-Term Ecological Research Network (LTER, Mirtl et al., 2018), and is predicated on the idea that good scientific information will reduce uncertainty and inform future practices through a process that links management experimentation, hypothesis testing and observation of ecosystem responses (Bakker et al., 2018). However, this approach has been criticized for its limited actual application and adaptation to different conditions and scales (e.g., Williams, 2011; Tony, 2020).

1.3. Incorporating social considerations into landscape management

Despite the availability of good scientific data and high public trust in science in general (Wellcome report, 2018), most decisions regarding the management of natural landscapes are challenged by additional considerations, including trade-offs, aesthetic values, and cost-benefit analyses subject to individual and group interpretation, often influenced by underlying values and perceptions, e.g., what is the desired landscape and who should decide what is desired? How is the landscape perceived by people from diverse backgrounds and what are its important visual qualities, aesthetics, and functionality vis-à-vis diverse human uses?

By combining empirical scientific data and subjective considerations regarding diverse priorities, desires, and perceptions, landscape management has the task of merging what ecosystem services an area can provide, what people want, and how the area can be designed and managed to achieve what people want (Oliver et al., 2013). To meet the goal of integrating these components, both scholars and practitioners of land management must develop, test, and apply decision-support tools that can merge the public's needs with the area features towards management strategies that are both ecologically sound and socially acceptable (Robinson et al., 2019).

1.4. Ecological and social complexity of forest landscapes

Our knowledge of forest ecosystems and management impacts has expanded significantly in recent years (Schweier et al., 2018; Leal et al., 2019). This expanded understanding is expected to support decision-making according to the sustainable forest management approach (Osem et al., 2008; Machar, 2020). However, forestry is a highly complex field that needs to integrate information from different disciplines and make it comprehensible to people of different backgrounds (Meitner et al., 2005; Kaspar et al., 2018). One underlying problem is that alongside the spatio-temporal and biophysical complexity of forest ecosystems, there is a high degree of social complexity with diverse goals, values, and visions of future forests.

Many studies have examined the impact of landscape management on ecosystem functionality and diversity (e.g., Turner, 1989), but far fewer have addressed the actual impact of such management on aesthetic preferences (although see Gundersen et al., 2017; and a review by Gobster, 1999). Forest and landscape management operations such as clear cutting and thinning or removal of undergrowth have impacts on the aesthetics and the amenity value of the landscape. People have diverse and often strong opinions regarding such management, particularly near urban areas (Depietri & Orenstein, 2020), and land managers need to deal not only with changes in the landscape, but also with changes in the public's perceptions of the landscape (Ryan, 2005; Depietri & Orenstein, 2020) and their implications on the acceptability of different management plans.

These challenges require developing new decision-support tools that can make empirical data and scientific knowledge more accessible and relevant to stakeholder-driven processes and balance the tradeoffs between ecological and social management goals (Kaspar et al., 2018). This can be done, for example, by the illustrative demonstration of the consequences of different decisions in an interactive process between researchers and stakeholders (Haberl et al., 2006; Grêt-Regamey et al., 2013; Bennett et al., 2017).

In this paper we present a visualization tool developed specifically for communicating ecological data and scientific knowledge on complex ecosystems to various audiences.

1.5. Representation of future landscapes using data-based visualization

The need for effective communication in landscape management and planning has resulted in a considerable increase in the use of two and 3D visualizations (Edler, Kühne, & Jenal, 2020; Lewis, Casello, & Groulx, 2012). Many authors have described and reviewed human reliance on visual information to process information and distinguish between different situations (e.g., Bruce, Green, & Georgeson, 1996; Sheppard, 2001). Visualizations are considered a common language that uses our innate abilities to understand visual information.

Computerized, evidence-based visualization models can integrate social, economic, and ecological parameters and enable interdisciplinary analyses. 2D visualizations, although commonly used in fields like forestry (as maps, GIS layers, or spatial modeling outputs), are often too abstract and cannot fully represent landscape complexity and aesthetic qualities. Photographs may provide a valid representation of current landscape conditions, but their inability to represent future or

hypothetical conditions limits their utility in public participation contexts on forestry issues (Lange, 2001; Meitner et al., 2005). To compensate for the shortcomings of other visual data, 3D models can extrapolate upon data from plot-level monitoring with a vast number of information layers and can be used as an empirical basis for constructing visual representations of future scenarios at large scales. Dynamic 3D visualizations have the power and flexibility to present alternative future landscapes side-by-side, within the same setting, and over time, and therefore offer a powerful comparative tool to engage people in environmental issues and problem-solving. Such models have been used, for example, to visually present the possible consequences of climate change, thereby educating stakeholders, raising community awareness, and setting a common ground (i.e., boundary object) between diverse demographic groups. This visual presentation thus catalyzes stakeholder-informed policy formulation (Schroth et al., 2015; Sheppard, 2012).

1.6. Visualization challenges

Advances in computer processing power and graphic software have substantially improved the precision and accuracy of environmental visualizations (Downes & Lange, 2015; Edler et al., 2020). Further, electronic communications and computer networks enable efficient and economical distribution of visualizations to expanding audiences. Consequently, the use of visualization in landscape assessment research and practice is gradually increasing (Lovett et al., 2015). Yet, alongside their benefits, visualizations also pose challenges for both the modelers and the users (Deussen et al., 1998; Sheppard, 2001; Nassauer, 2015).

One basic assumption behind the use of visualizations is that they reflect valid representations based on accurate perceptions and sound judgments made in response to direct experience with the landscape (Daniel & Meitner, 2001; Downes & Lange, 2015). However, the need for abstraction and simplification may conflict with the desire to produce a highly realistic visualization. There is an open and ongoing discussion about what should be considered a valid representation of the landscape and what level of realism is sufficient for engaging the public (Lange, 2001; Appleton & Lovett, 2003; Billger et al., 2016). Some researchers argue in favor of maximizing realism. Highly realistic visualizations of forest landscapes were found to be more valid (Daniel & Meitner, 2001; Lange, 2001; Ribe et al., 2018) and to improve communication, while simplified representations were harder to communicate even to experts without the addition of verbal information (Barrett et al., 2007).

Facing these challenges, our goal was to develop a valid tool based on ecological data and in-depth scientific research which can be used for the communication of complex landscapes to various audiences. The visual products (images, panoramic tools, and short films) will later be tested in stakeholder workshops to assess their efficacy in communicating to decision makers and the public future landscape possibilities and the science and management strategies that may shape those futures.

The Mediterranean landscape provides an excellent opportunity to explore this approach. Lacking a "natural landscape" archetype, Mediterranean landscapes have been described as multi-scale mosaics of different vegetation types and structures, associated with high resilience and rich ecological diversity, co-evolving with social systems through an ongoing history of human intervention (Blondel, 2006). In the face of increasing human pressures on natural ecosystems and their high biodiversity, such complexity is important from a conservation perspective (Myers et al., 2000), and requires the establishment of management strategies at the landscape scale (Scarascia-Mugnozza et al., 2000). We believe that our findings will also be relevant to a wide range of dynamic and highly complex ecosystems such as tropical forests, managed commercial forests, forest-savanna transition zones, and more.

Given the high complexity of these landscapes, our main challenge was to find the optimal balance between abstraction and realism and to identify the minimal set of landscape variables that will provide a valid representation of an extremely diverse plant community in the eyes of the beholder.

A significant portion of the literature reviewing visualization deals with improving communication of environmental data by combining different data sources or translating numbers into symbolic or figurative representation or images (Edler et al., 2020; Metze, 2020) . Visualizations are often used to illustrate the visual impact of adding elements such as wind turbines or solar panels to the landscape (Maehr et al., 2015; Ribe et al., 2018), or to envision possible large-scale impacts of climate change (Schroth, Pond, & Sheppard, 2015; Sheppard, 2012). Yet, very few of these visualizations express the science of dynamic ecosystem processes, such as grazing or fire that have complex effects on ecosystems.

1.7. Objectives

In this study, we present a state-of-the-art 3D computerized landscape model and assess the quality of visualizations produced by the model and their potential relevance for management decision-making. The model is based on long-term quantitative ecological data, expert knowledge, and findings from in-depth scientific research. These sources are integrated to visualize the predicted appearance of future landscapes under alternative management scenarios.

Two questions were posed in this study: (1) how can quantitative scientific data describing vegetation composition, structure, and spatial pattern, be translated into a three-dimensional computerized visual model of current and future landscapes? And (2) is the model a valid representation of reality? i.e., does the visualization reflect the same perceptions and judgments that would have been made in response to direct experience with the landscape?

Our overall objective is to develop and validate our 3-D model, both regarding its degree of perceived visual accuracy (the current study), and its utility in stakeholder-driven management processes (follow-on research).

2. Methodology

2.1. Ramat Hanadiv nature park as a case study

Our research was conducted in Ramat Hanadiv, a privately-owned Nature Park consisting of an open landscape abundant with indigenous Mediterranean fauna and flora. The integration of educational, scientific, and leisure functions makes Ramat Hanadiv a unique site in Israel. The park represents a set of conditions and processes relevant to many landscapes in the Mediterranean region and is one of the most researched and closely managed open spaces in Israel. All data and past research are publicly accessible at http://ramathanadiv.maps.arcgis.com/home/index.html

The varied vegetation formations dominating the nature park reflect the climatic gradient, the topographic and edaphic variability, and the impact of human activity over long historic periods, including grazing and tree cutting. The typical vegetation formation in Ramat Hanadiv is Mediterranean garrigue dominated by low or mid-size shrubs such as *Phillyrea latifolia, Pistacia lentiscus,* and *Calicotome villosa*, and by the dwarf shrub *Sarcopoterium spinosum*. Between the shrub clumps are exposed rock or shallow soil patches covered by herbaceous vegetation. As part of its historical conservation policy, Ramat Hanadiv was fenced in 1950, and grazing was excluded from its area for 40 years, until the early 1990s. Although this policy facilitated the regeneration of woody vegetation, it also led to the encroachment of herbaceous patches, altered the composition of vegetation and animal communities, and increased the frequency and intensity of wildfires (Perevolotsky & Shkedy, 2013). Like other places around the Mediterranean basin, the main management challenges include controlling woody vegetation

cover, minimizing fire intensity and damage, determining, and managing optimum cattle and goat grazing regimes, implementing adaptive management for climate change impacts, and dealing with pine colonization and invasive species.

2.2. Model development

Based on GIS layers, satellite imagery, and quantitative datasets derived from field observations representing over 25 years of research in

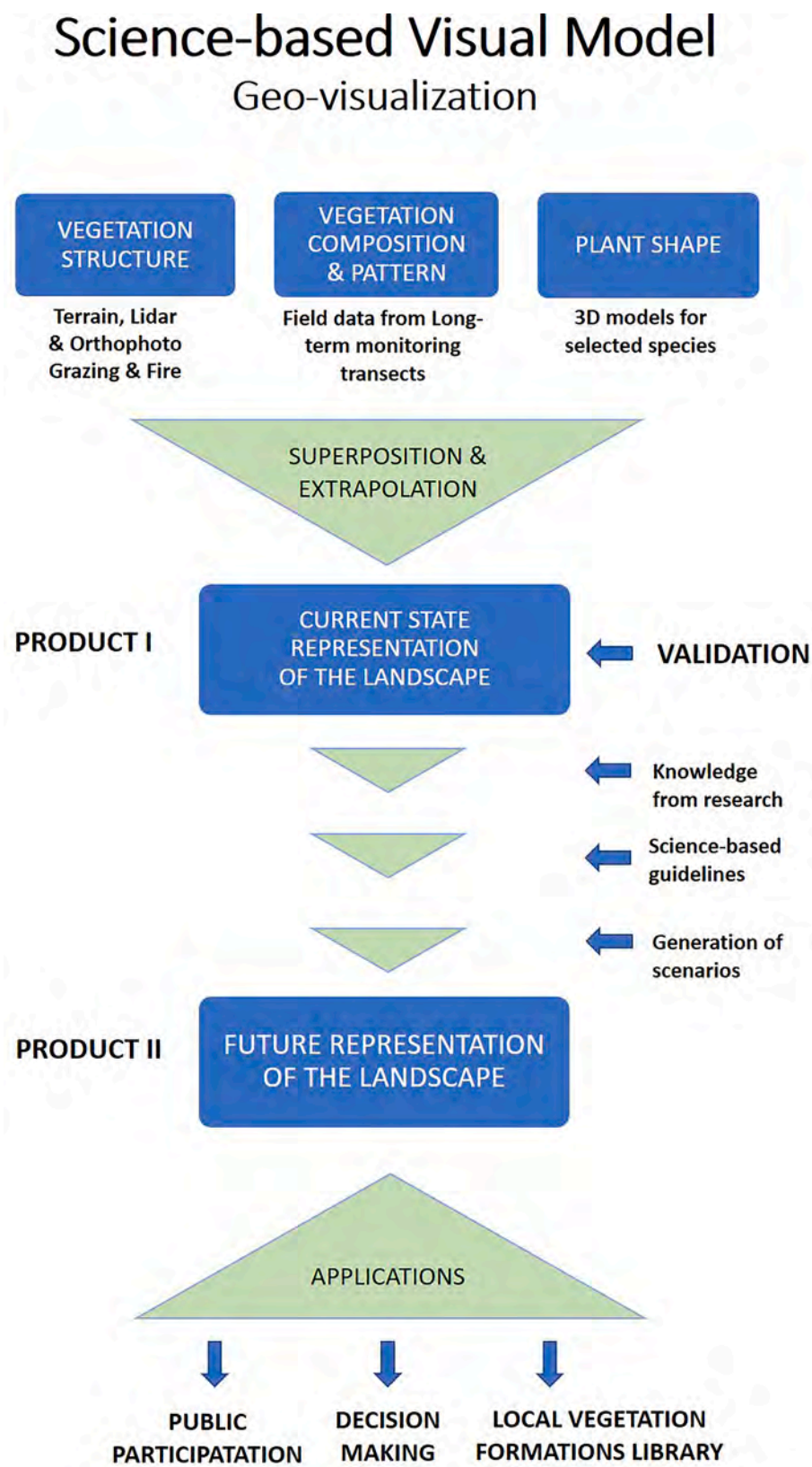

Fig. 1. Stages in developing the visual model.

the park, we have developed a model that visualizes decadal time scales of management alternatives related to different situations of mixed natural garrigue-pine ecosystems.

2.2.1. Approach & technical details

The model was developed in cooperation with Lenné3D GmbH, using the geo-visualization approach. The software used was a visualization system developed by Lenné3D, called Biosphere3D. The process and its various stages are described as a flowchart (Fig. 1).

The model provides real-time 3D landscape visualization of large landscapes (approx. 500 ha) based on detailed scientific knowledge and quantitative data describing species composition, plant sizes and distributions, patch types and spatial patterns. A set of realistic and botanically coherent plant models was created for each of the 27-plant species chosen for the model (Table ii-a-b).

2.2.2. Phase I: Creating the current state model

I. **Data sources:**

Several data sources were used to create the current state model, which, at the second phase, served as the basis for all future scenarios.

a) **Terrain:** Within Ramat Hanadiv Nature Park, the data source was a Lidar image from 2012 (res. 1×1m). Outside the park, the free SRTM global terrain was used (res. 90×90m).

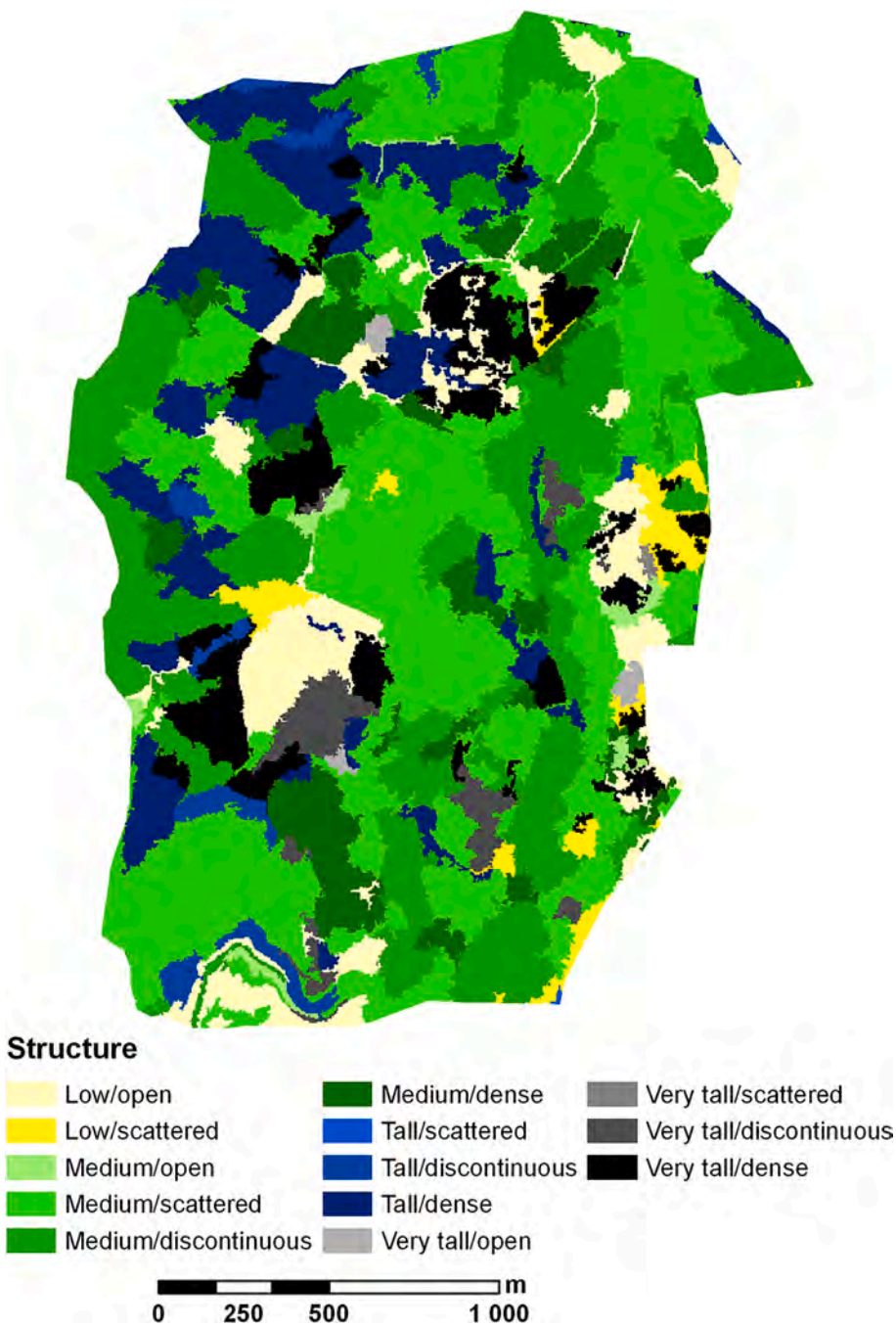

Fig. 2. Vegetation structural units, created by automated segmentation of Lidar and Orthophoto layers (Bar Massada et al., 2012).

b) **Imagery:** Within Ramat Hanadiv an orthophoto from 2011 was used (res. 0.25×0.25 m). Outside the park, BING Map was used (via ESRI, res. 1×1m).

c) **Texturing:** Draped textures within the park were based on Ramat Hanadiv's soil layer (Kaplan, 1989), with some spatial details added to it. A layer of roads and trails was drawn based on the imagery.

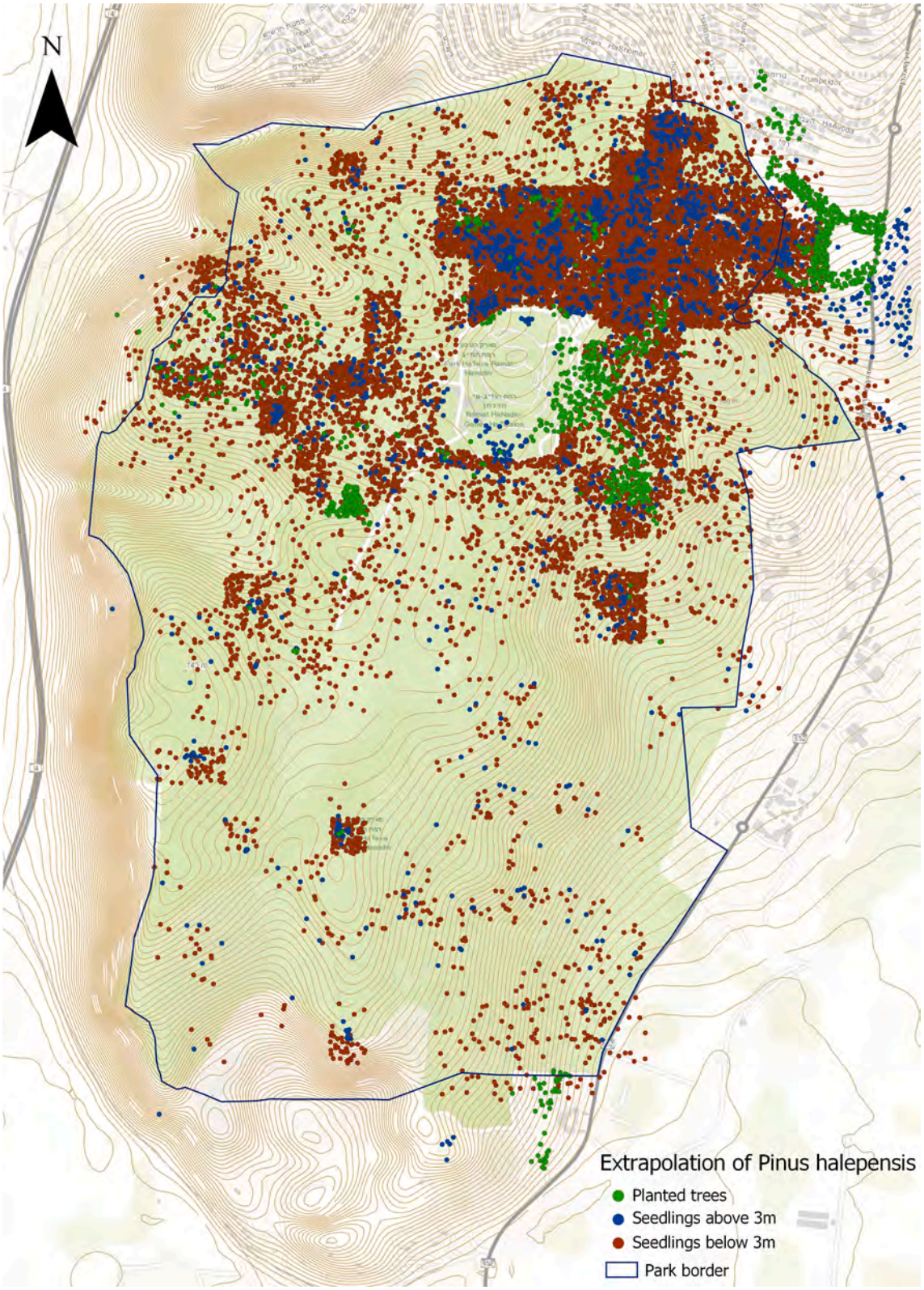

Fig. 3. Aleppo pine extrapolation map (based on the findings by Osem et al., 2011). Map is based on a 100x100m grid, drawn for the area of the highest density, North of the park and used to extrapolate the number of seedlings to the park's scale. In each cell, seedlings above 3 m were counted, multiplied by 12 to get the number of "below 3 m seedlings" and randomly distributed, with random tree heights between 0.6 and 2.5 m.

d) **Management:** We used GIS layers representing the prominent grazing management categories in the park (cattle and/or goat grazing areas, ungrazed areas), and a layer separating areas that were previously burnt (in 1980) and those not.

e) **Vegetation type:** The visualization was based primarily on a vegetation structural types map of Ramat Hanadiv produced from aerial photography and Lidar datasets (Bar Massada et al., 2012, Fig. 2), in which different categories (e.g., tall dense maquis, medium sparse garrigue, sparse cypress grove, etc.) represent vegetation height, density and dominant woody composition. A detailed description of categories and adjustments made are detailed in appendix A (Table i).

f) **Aleppo pines** *(Pinus halepensis)*: It is the most widespread pine species and the most extensively used for afforestation in Israel. Its expansion into natural habitats is becoming frequent and an environmental issue (Osem et al., 2011). The distribution of planted pines was taken from a detailed field survey (Osem et al., 2011). Tree height attributes were taken from Lidar (DSM-DTM). All pines were divided into three size categories: large, planted trees; seedlings above 3 m; and seedlings below 3 m (extrapolated from field survey using a 100x100m grid, Fig. 3).

II. Creating 3D models for selected species

In this stage, 15 woody plant species that are considered prominent in the ecological and aesthetic landscape ("key players") were identified and represented in their current condition and under every future scenario. Models were assigned for specific vegetation strata and distributed according to spatial pattern data for each structural type, e.g., patch size, the distance between patches, distribution mode (random, aggregated, structured). The data required for each model was derived from prior ecological knowledge and high-resolution photos (Fig. i). It included the plant's species, developmental stage, age, height, growth habit (in a forest or stand-alone), condition (green/dry/green crown ratio), season, number of trunks, canopy & trunk diameter, colors, and textures (Table ii-a).

III. Vegetation modeling of structural types

The cover and distribution of different structural types in the park were derived from the layer described above (Bar Massada et al., 2012, Fig. 2). Vegetation modeling was conducted as follows: average vegetation gaps, as well as the relative cover and height distribution for each species were derived from transect measurements. Since the number of species in the vegetative community exceeds the number of species reproduced by the 3D models, coverage was extrapolated to only the species represented by 3D models. Distribution patterns for each species were estimated from species sequence and grouping within the transects. Health conditions (percentage of dead and dehydrated trees in each structural type) were also incorporated into the model. The output of this stage is presented in Fig. 4a-d.

The typical composition of common herbaceous patch types is also represented in the model, as detailed in section IV below.

IV. Vegetation modeling of herbaceous patches

The herbaceous plant community of the nature park is composed of more than 500 species that could not all be represented by models of individual species. Therefore, the vegetation in the different herbaceous patches was represented by 5–6 dominant species characterizing each patch (through size, life-form, appearance). Herbaceous patch types were based on quantitative field data from vegetation sampling of transects (Table ii-b). Distribution patterns were derived from relative frequency data of the represented species. All these models were assigned for the herbaceous layer. **Four typical patch types were represented (Fig. ii -a-d)**: (a) Un-grazed patch (full potential green); (b) Grazed patch; (c) Anemone patch (which develops under heavy cattle grazing conditions); (d) Cyclamen patch (common in dense pine understory).

2.2.3. *Phase II: Creating future scenarios*

The first stage of the process was to develop a valid representation of the current landscape state to serve as a baseline for any future scenario.

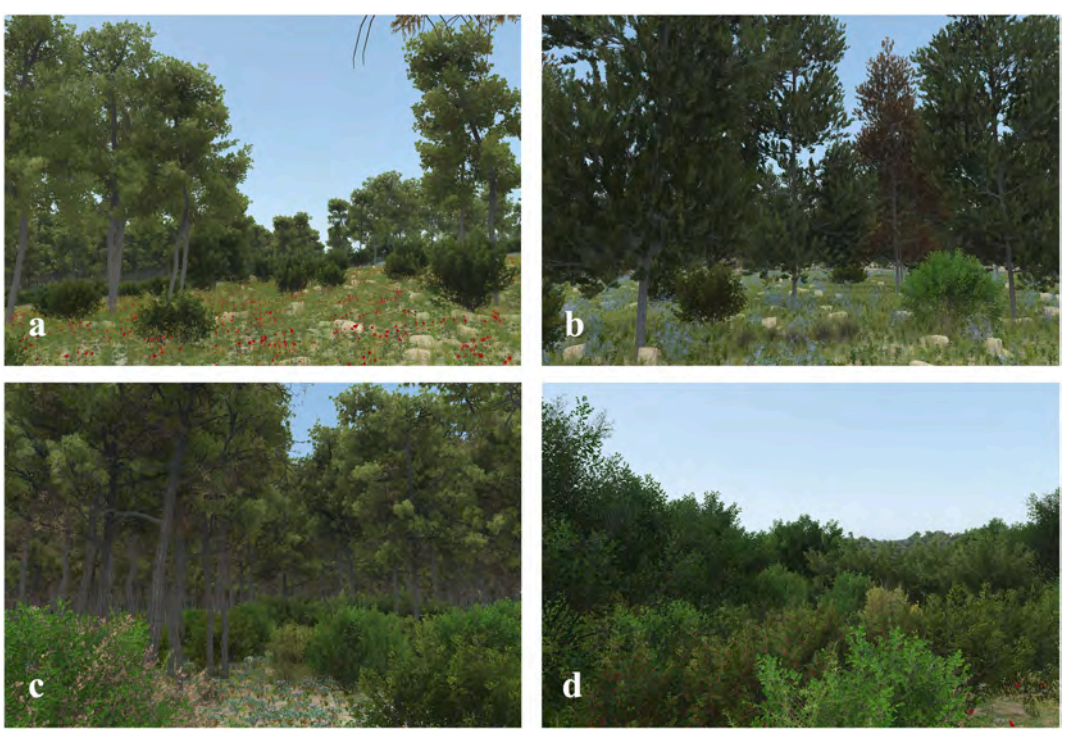

Fig. 4. d: Examples of current state representation of structural types demonstrating interaction between vegetation types and management regimes.a. Sparse pines (cattle grazing, anemone patch); b. Dense cypress (cattle grazing); c. Dense pine grove with Cyclamen patch; d. Tall dense maquis (ungrazed).

This was done through a bi-directional dynamic process that involved calibration and refining of the products by five different experts, all with close familiarity with the research site and the model development process. The experts mainly addressed the level of realism of the elements in the image (soil color, trunk texture, the appearance of a certain species, the flowering intensity of herbaceous patches or shrubs, etc.). This stage of "expert validation" was considered important for reaching the best representation possible of current reality.

After this stage was completed, was the model used to develop future scenarios according to the parameters, assumptions, and guidelines determined by the research team.

Seven management scenarios were developed, all based on 1-hectare cell size, representing an average management unit. The scenarios reflect existing scientific knowledge and were based on a matrix filled by a team of researchers who assessed, based on their research and expertise, the expected dynamics (e.g., growth, expansion, and mortality) and condition (e.g., appearance) of key vegetation elements (i.e., dominant plant species or species groups) in each scenario. The scenarios depict the appearance of future landscapes under alternative management decisions. In choosing the scenarios, we focused on land management challenges common to many areas, e.g., what would be the visual significance of post-fire treatments, selective or complete pine removal, cessation of grazing, or "letting nature take its course" - allowing for vegetative succession with no active or direct human intervention (Table 1).

The output of this stage is a computerized dynamic 3-D model of the whole park, from which different images and short films that represent the current state and the future landscapes of Ramat Hanadiv were created. Fig. 5, for example, represents one specific location (garrigue with sparse pines), in the current state (5a) and in seven different future scenarios.

2.3. Model validation

While developing the model, we aimed to achieve the necessary abstraction without compromising on visual realism. Since visualizations have persuasive power and are highly dependent on the process and technology (Sheppard, 2001; Nassauer, 2015), we had to prove a good enough similarity of the model to reality before applying it to decision-making processes.

As our research deals with people's visual perceptions of landscapes, the most important indicator for the validity of the visualizations is whether they represent actual landscapes from the perspective of the observers.

The "response equivalence" of judgements made when viewing the real setting or its representation has been previously described as a fundamental requirement for many landscape assessments (Lovett, Appleton, Warren-Kretzschmar, & Von Haaren, 2015; Palmer & Hoffman, 2001) and has been experimentally tested as a measure of validity (e.g., Bishop & Rohrmann, 2003; Wergles & Muhar, 2009). In accordance with this idea, we developed and conducted a validation procedure that was based on the way people perceive the landscape. Our assumption was that perceived similarity between the model and the field photographs would be sufficient to assume that people would trust the model and refer to it as a valid representation of reality.

The validation experiment was conducted by presenting the current state model representations vs. real world photos (taken in the field at the very same locations as were reproduced from the model) and asking the observer to select and rank three photos (out of eight) most similar to the model.

The "current state" model representation of 12 iterations (selected locations in the park, Fig. iii-b) were compared, separately for each case, to a set of 8 "real world" photos taken in various locations in the field. In each set, only one photo represents the same location and observation angle as the model (this will be referred to as the "model photo," Fig. iii-a) and seven were randomly picked from a "photo pool" taken at other locations (to avoid auto-correlation), see example in Fig. 6. All the field photos in the photo pool were taken by a professional photographer, from the same coordinates, height, aperture, zoom, light conditions, and season (late winter) as represented in the model, but from different

Table 1
Science-based guidelines for the creation of future scenarios.

Scenario	Definition	Projection Horizon	Details	Guidelines
1	**BUSINESS AS USUAL** (BAU; no change in management)	30 years	Cattle & goat grazing continues; Aleppo pines left as they are (no treatment)	• Planted pines stay as they are • Seedlings > 3m will grow to 9m or 12m (randomly) + 10% random death • Smaller pines will be added according to the key 1:12 (300m from a dispersing tree); or 1:4 (greater distance). They will be randomly distributed between height categories 2,4 and 9 m. +10% random death (all sizes) • Understorey changes will not be modelled
2	**COMPLETE PINE REMOVAL**	30 years	Removal of all Aleppo pines of all sizes	• Understorey changes will not be modelled
3	**MODERATE INTERVENTION**	30 years	Complete removal of Aleppo pines below 3m every 5 years	• Planted pines stay as they are • Seedlings > 3m will grow to 9m or 12m (randomly) + 10% random death (to mature trees) • All Aleppo pines < 3m will be removed
4	**POST FIRE** 10-year projection.	10 years after fire	Wildfire burns the entire area. Scenario will present a ground cover of seedlings of the same age (cohort), 4m tall	• Seedlings will be distributed as follows: 4-6 seedlings in a radius of 10m around every pine that was present before the fire • 30% removal of the woody garrigue cover • Tall Phillyrea shrubs will be removed, only ≤ 1.5m shrubs will be left • Tall Pistacia shrubs will be removed – only shrubs ≤ 0.6m will be left
4a	**POST FIRE** 30-year projection.	30 years after fire	Wildfire burns the entire area. Scenario will present a mature, tall, and dense pine forest with an upper layer of same age and a suppressed understorey with pine seedlings	• Seedlings will be distributed as follows: 4-6 seedlings in a radius of 10m around every mature pine that was present before the fire. Above density of 150 trees/hectare, pine digital model changes from solitary to grove growth form. • All seedlings will be 12m tall (a cohort) • 20% random mortality (25% mortality in patches with tree density above 150 trees/hectare) • Tall Phillyrea shrubs will be removed, only 1.5m shrubs will remain • Removal of the woody garrigue cover 30% more that in scenario 4 (due to pine shade) • Within a 10m perimeter around every mature tree, 4-6 seedlings (2m tall) will be distributed • Tall Phillyrea and Pistacia shrubs will be removed from the model • Relative cover of Pistacia will increase by 20% (as it is more shade tolerant than other shrub species)
5	**POST-FIRE PATCH MANAGEMENT**	30 years after fire	Pine management - applying different treatments to different patches to create a heterogeneous landscape pattern	• The north part of the park ("invasion front"), where patch management will be applied, and the south part of the park, where all pines will be removed, ("Pine Free Zone", PFZ), will be separated • In the northern part, management will be as follows: – Management units will consist of one-hectare patches – Patches (one-hectare grid cells) will be randomly distributed in the area, and each will be subjected to one of three treatments: – Complete removal of all pines (60% of the northern area) – Mixed forest 50-100 trees/hectare (30% of the northern area) – Coniferous forest 200-300 trees/hectare (10% of the northern area)
6	CESSATION OF GRAZING	30 years	Cease all cattle and goat grazing in the entire park area	**After 30 years, our assumption is that each formation experiences succession as follows:** • Tall dense maquis patches stay as they are (dominated by oaks) • Medium dense garrigue patches consisting of tall, dense maquis, stay as they are (dominated by mature Phillyrea and Pistacia) • Medium sparse garrigue transforms to medium dense garrigue • Low open areas transform to medium sparse garrigue • Coniferous grove understory experiences a 30% increase in height and cover • Aleppo pines experience a 40% decrease in density

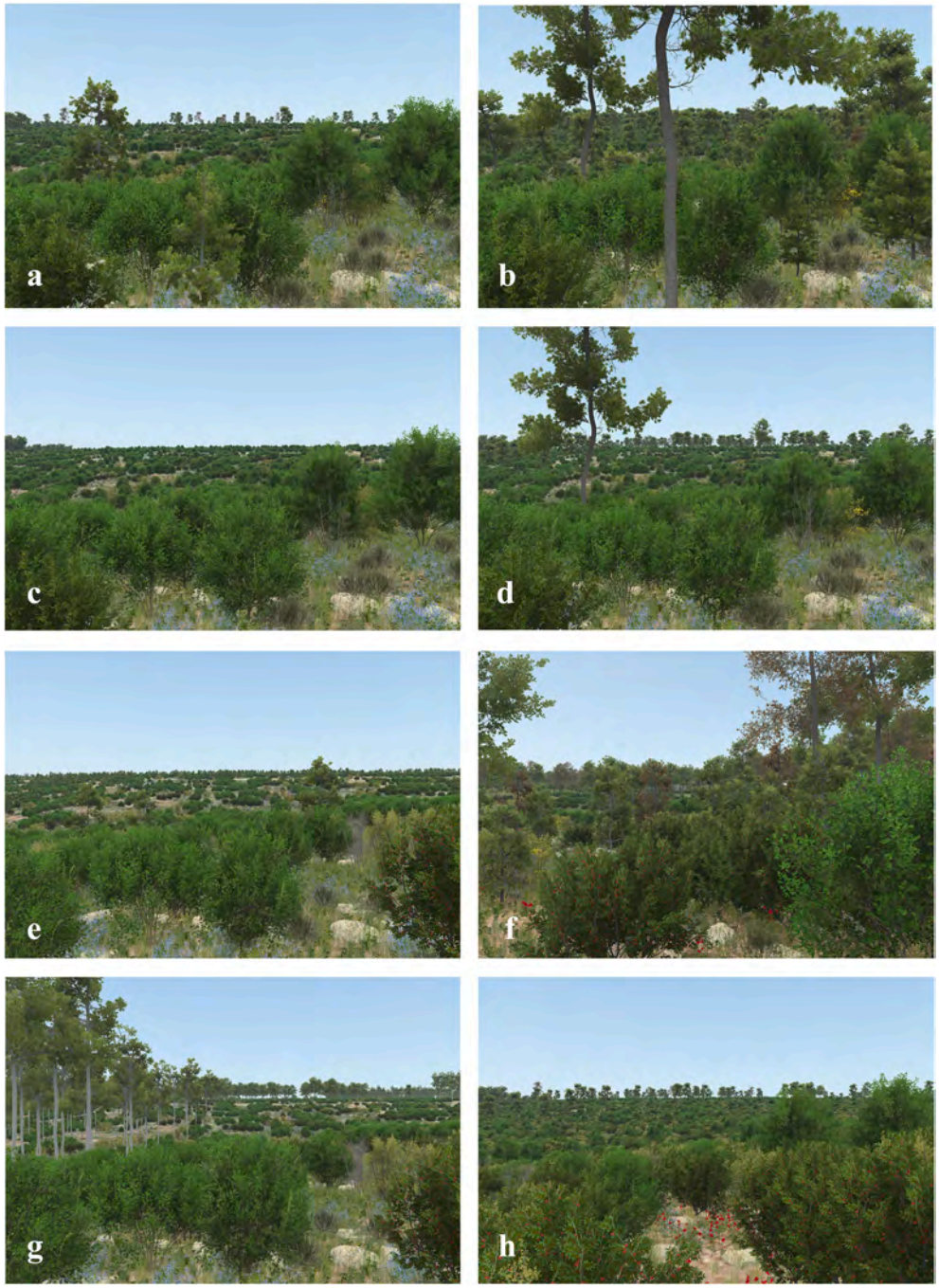

Fig. 5. h: Representation of current and future scenarios of a garrigue with sparse pinesa. Current state, sparse pines; b. Scenario I – 30 years; BAU; c. Scenario II – 30 years; complete pine removal; d. Scenario III – 30 years; moderate intervention; e. Scenario IV – 10 years; post-fire; no intervention; f. Scenario IVa – 30 years; post-fire; no intervention; g. Scenario V – 30 years; post-fire; patch management; h. Scenario VI – 30 years; cease of cattle grazing.

angles (taken at exact angles with a compass, to avoid bias, Fig. iii-a). This stage was completed in Mid-February 2016.

The next stage was querying a sample of 40 professional respondents (ecologists, landscape architects, foresters, and local land managers) regarding the similarities between the model and the field photos. These audiences will later be queried about the extent to which the model assists them in making decisions.

It should be emphasized that in complex forest landscapes characterized by small-scale spatial heterogeneity, as in the study area (Fig. 2), the ability to distinguish between different vegetation structures is limited, especially since the visualizations are average representations of vegetation structure. As a result, picture similarity from closer locations near the point is not always higher than picture similarity from farther away locations. Hence, these pictures could be considered random locations and success in choosing the right photo attests to the success of visualization to capture and represent the landscape in the field.

All the respondents' choices were encoded into a general binary matrix and analyzed using Repeated G-tests of Goodness-of-fit (McDonald, 2014) to check whether there was an overall deviation from the expected distribution and whether there was a significant variation among the different locations. This method suits nominal variables with p values adjusted for multiple comparisons.

Fig. 6. Example of an experimental panel to test the perceived fit between the model (right) and field photos. Location 117b, matching photo is number 3.

2.3.1. *Validation results*

Participants selected the "correct photo" (the photo that represented the landscape model) in their first guess significantly more than expected by chance, in 10 of the 12 sites. Moreover, the correct photo was one of the three selected photos in 393 of 474 cases. This yields an average success rate of 82.9%, much higher than the 37.5% expected by chance, highly significant in 11 of 12 sites (Table 2). Overall, the current state model was determined to be a valid representation of reality (G-test; $P < 0.00001$). No relationship was found between the vegetation formation and success in identifying the corresponding photo. In two specific cases, the respondents were unable to identify the correct picture in the first attempt due to the (random) presence of a very similar picture in the experimental set (case 118, corrected in the second choice), or due to an "element bias" (case 1E), resulting from the fact that the model is an average representation of vegetation structure and dominant elements (e.g., a tall tree on the right, a group of shrubs to the

Table 2
Validation experiment data and results.

FORMATION	LOCATION	N	Match 1st. picture						Match 1 of 3 pictures					
			No. Match	% Match	% Expected	Df	G-VALUE	*P-VALUE*	No. Match	% Match	% Expected	Df	G-VALUE	P-VALUE
NATURAL GARRIGUE	115	40	14	0.350	0.125	1	13.372	0.0002554	38	0.950	0.375	1	60.542	< 0.00001
PLANTED GROVES	122	40	20	0.500	0.125	1	33.067	< 0.00001	30	0.750	0.375	1	23.263	< 0.00001
NATURAL GARRIGUE	114B	37	20	0.541	0.125	1	36.668	< 0.00001	28	0.757	0.375	1	22.332	< 0.00001
DENSE MAQUIS	117B	40	17	0.425	0.125	1	22.295	< 0.00001	32	0.800	0.375	1	30.261	< 0.00001
NATURAL GARRIGUE	2N	39	15	0.385	0.125	1	16.823	0.0000410	33	0.846	0.375	1	36.888	< 0.00001
NATURAL GARRIGUE	113	39	31	0.795	0.125	1	91.482	< 0.00001	35	0.897	0.375	1	46.625	< 0.00001
PLANTED GROVES	110	40	36	0.900	0.125	1	124.781	< 0.00001	38	0.950	0.375	1	60.542	< 0.00001
DENSE MAQUIS	118	40	4	0.100	0.125	1	0.243	0.6219368	31	0.775	0.375	1	26.618	< 0.00001
NATURAL GARRIGUE	4W	40	19	0.475	0.125	1	29.275	< 0.00001	34	0.850	0.375	1	38.520	< 0.00001
LOW OPEN	111	40	17	0.425	0.125	1	22.295	< 0.00001	37	0.925	0.375	1	54.091	< 0.00001
NATURAL GARRIGUE	3N	40	30	0.750	0.125	1	82.450	< 0.00001	39	0.975	0.375	1	68.092	< 0.00001
NATURAL GARRIGUE	1E	39	4	0.103	0.125	1	0.190	0.6632159	18	0.462	0.375	1	1.216	0.2702411
Average match (%)							47.89660						82.80737	
Expected							12.50000						37.50000	
Total G-VALUE							472.94318						468.98860	
Degrees of freedom							12						12	
P-VALUE for total G							< 0.00001						< 0.00001	

left, and open area in the middle) may influence the decision even if the frequencies were completely different (Table 2).

These results indicate that the model successfully represents the landscape it is based upon. Given that the model is derived from specific quantitative parameters, and that similar parameters can be constructed for future scenarios, we assumed that the model is likely to coherently visualize future scenarios. The effects of the model on people's preferences regarding future landscapes, and its unique contribution to decision-making, are studied in follow-on research (in preparation).

3. Discussion

From Covid 19, to climate change, to forest management, communicating scientific data to non-experts has become a necessity and a major challenge in an age of information overload, lack of transparency, and a lack of tools to support decision-making and public participation processes.

The visualization developed in this study offers an integrative approach to describing vegetation structure by merging data at various ecological scales and expressing a wealth of knowledge about species, associations, and structures into one product that can contribute to decision making. Its uniqueness lies in its scientific foundation based on data from a continuous long-term monitoring program and in its capacity to provide visualizations of future landscapes based on the interaction between long-term, dynamic ecological processes and hypothetical management decisions.

Another important contribution of the visualization model lies in the fact that it has been tailored specifically to landscapes characterized by small scale landscape heterogeneity, multi-layered vegetation, and high complexity that are not easily described by simple measures such as density, height, and stem diameter, as is the case of Mediterranean ecosystems (Perevolotsky & Sheffer, 2011; Filotas et al., 2014). This has been achieved in our visualization by modeling only 4% of the species. Furthermore, in many areas, the core interventions represented by our models, like post-fire management and pine expansion from plantations into natural sites, are a major source of debate among nature conservationists, foresters, and other landscape managers.

Our results indicate a significant similarity between the modeled landscapes and the real world, as perceived by a sample of practitioners and decision-makers with close familiarity with Mediterranean landscapes. Their choices reflect landscape attributes present in the pictures such as geology, botany, light, composition, dimensions, form and complexity, and their own experience, knowledge, and expectations.

One of the key factors contributing to the validity, and hence the viability, of the product, is the fact that the model was based on detailed biophysical data from the park only. Also, the guidelines for the visualization modelers (Table 1) and any assumptions made in this context were linked to scientific results from previous studies conducted in the park (e.g., Bar Massada et al., 2012; Hadar, Jobse, & Ungar, 2013; Osem, Lavi, & Rosenfeld, 2011).

The challenge of distributing thousands of plant models to create a realistic landscape scene has been previously dealt with through rule-based procedural plant modeling (e.g., Deussen et al., 1998; Grêt-Regamey et al., 2013). In order to achieve this, we took advantage of existing detailed quantitative information on the composition, abundance, and spatial distribution patterns of the species inhabiting the landscape. Using this approach allowed us to visually examine different future scenarios created based on quantitative data.

In developing the model, we faced difficulties and limitations when making decisions about which and how many species should be represented. Of the 660 species growing in the park, only 27 species, (4% of the flora), and only 4 herbaceous patch types were presented in the model, mainly due to time and budget constraints. Moreover, the model was based on relatively simple information about vegetation structure in complex forest landscapes, characterized by fine-scale heterogeneity and low visual distinction, as are many landscapes on the planet. Extrapolation was needed to compensate for missing information about the entire area.

In addition, the visualization expresses an average vegetation structure so that the different elements in the visualization are not necessarily located in the same place as in the image. These conditions have made the choice of the correct photo a difficult task even for professionals who are experienced in subtle distinction between vegetation formations. Nevertheless, despite these limitations, we succeeded in reflecting the landscape in a way that was perceived by people as highly realistic.

The explanation for this success lies in the relationship between structure and species dominance. In the woody layer (trees and shrubs), a small number of dominant species are responsible for the bulk of total vegetation cover. *Pinus halepensis*, *Pistacia lentiscus, Phillyrea latifolia* and *Calicotome villosa* alone account for around 90% of the total cover (data from LTER plots). Each one of these species was represented by a set of models describing its appearance in different sizes and situations, e.g., 14 different models were built for *Pinus halepensis* alone (Table ii-a). The herbaceous layer, in contrast, is perceived more at the patch level, as a brown or green background represented by density and texture. We conclude that a visualization focusing on different variations of dominant woody species allows for the representation of the real structural complexity of the landscape, while the addition of less dominant species will not fundamentally change the way these landscapes are perceived and assessed. These results coincide with those of Appleton and Lovett (2003) that emphasized the importance of detailed foreground vegetation on the viewers' perceptions and ratings.

An additional advantage of our visualization model is its capacity to portray dynamic processes. Much of the professional literature on visualization relates to the constructed environment (e.g., Wergles & Muhar, 2009 (or the addition of static elements to an existing landscape, and visual effects of those additions (e.g., Maehr et al., 2015). Natural landscapes are dynamic by nature and land managers need to manage processes rather than states. The model developed in our study is a tool that reflects landscape dynamics, making it a suitable tool for examining long-term visual impacts of management operations on natural ecosystems.

Furthermore, the data and metrics feeding the model are directly adapted for visualization. As such, the model has the potential for continuous improvement through the development of quantitative visual indices (e.g., tree crown density, leaf area indices, or the proportion of dry vs. green foliage). The integration of such data into the model can improve the level of realism and accordingly the trust among stakeholders using the visualization, given that full transparency has been maintained throughout the process.

In this work we managed to develop and validate a visualization tool for challenging landscapes with a limited set of species and variables. How many elements and variables can be reduced without compromising the perceived realism and the added value of including more elements, remain open questions for future research.

3.1. *A sustainable approach for decision-making in landscape management*

Referring to the definition by Perkins (1992, pp. 266), a "good enough visualization" is one with "a high degree of perceived realism (which) conveys maximum quality, contains enough data, yet is efficient in terms of equipment costs, storage & management" we argue that our visualization tool meets these objectives. This was achieved by integrating high-quality data layers, long term monitoring data, and expert knowledge (including close familiarity and a good understanding of inter-species relationships in the community) into one comprehensible product.

A visualization tool such as the one as presented here can serve as a "boundary object," bringing together scientists, with their in-depth understanding of natural systems, and a diverse array of additional

stakeholders with opinions, desires, and knowledge about natural landscapes for collaborative discussion regarding their shared future. This represents the integration and translation of different knowledge sources in a way that can bridge the gap between landscape ecology research and its applied value for management and planning.

Finally, visualization is sometimes described as "time travel," showing historical or future conditions and bringing the future to life (e.g., Schroth et al., 2015). At a time when talking about sustainability and the world we leave for future generations is so ubiquitous, landscape visualizations that allow us to glimpse this world while maintaining full transparency regarding preparation and assumptions underlying the construction of the tool can add aesthetic/visual considerations into the societal discourse about human-nature relationships from a sustainability viewpoint. These aspects will be examined in the next stage of our research.

CRediT authorship contribution statement

L. Hadar: Conceptualization, Methodology, Data curation, Resources, Funding acquisition, Formal analysis, Writing – original draft. **D.E Orenstein:** Supervision, Conceptualization, Writing – review & editing. **Y. Carmel:** Supervision, Methodology, Writing – review & editing. **J. Mulder:** Software, Visualization. **A. Kirchhoff:** Software, Visualization. **A. Perevolotsky:** Conceptualization, Validation. **Y. Osem:** Supervision, Conceptualization, Methodology, Validation, Writing – review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104214.

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