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Climate change disproportionately affects visual quality of cultural ecosystem services in a mountain region

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ABSTRACT

Expansive vistas in mountain systems make scenic viewscapes – the visible portions of a landscape with which people form a connection – essential providers of cultural ecosystem services (CES). Like the dynamic systems they encapsulate, mountain viewscapes are subject to change, but the CES they provide are rarely considered from future or dynamic perspectives. Here we forecasted change in CES, using climatic shifts of a culturally valuable tree species, quaking aspen (*Populus tremuloides*), along scenic byways as an example of how viewscapes change through time. We simulated future aspen distributions in the Colorado Rocky Mountains through 2120 under three climate change scenarios and computed change in aspen visibility in 32,949 viewscapes. Across each scenario, the total area of aspen and its visibility from byways declined, but visible declines were 1.5–3.1 fold greater than declines in the study area overall. Differences between visible and total aspen peaked in mid-elevations (2000–3000 m) where aspen is most abundant. In contrast, aspen is forecasted to increase and become disproportionately more visible from scenic byways at lower elevations. Mismatch between total and visible declines in aspen highlights opportunities for tighter connections between landscape planning and ecological research for more comprehensive understanding of future changes in CES.

1. Introduction

The scenic vistas, rugged topography and biodiversity that shape mountain landscapes provide numerous nonmaterial benefits. Cultural identity (Knez & Eliasson, 2017), symbolism (Schirpke et al., 2018), tourist appeal (Beedie & Hudson, 2003) and recreation opportunities (Tenerelli et al., 2016) are all critical dimensions of the ecosystem services of mountain systems. The cultural ecosystem services (CES) of mountain landscapes are particularly vulnerable to the effects of climate and land use change, because of the constraints of high altitude and the unlikeliness of replacement (MEA, 2005; Palomo, 2017). As landscapes change over time, impacts to CES may differ from impacts to provisioning and regulating ecosystem services (Rodríguez et al., 2006; Schirpke et al., 2013; Vukomanovic & Steelman, 2019), and can vary with cultural perspective, preferences and needs (MEA, 2005). Considering their vulnerability and distinct responses to change, examination of the multiple, interacting dimensions of CES are needed to garner insight into the dynamics of mountain social-ecological systems (Carpenter et al., 2009; Palomo, 2017).

Viewscapes – the visible portions of a landscape with which people form a connection – are an essential component of CES in mountain systems (MEA, 2005; Vukomanovic et al., 2018). Viewscape analysis offers insight into values of cultural and economic importance by identifying what is visible from a human vantage point. Viewscape analyses have been applied across a range of research topics, from studying the cultural values of past societies (Garcia-Moreno, 2013; Wernke et al., 2017), to measuring the aesthetic value of natural landscapes (Poudyal et al., 2010; Hamilton & Morgan, 2010), to siting energy development (Möller, 2006; Wróżyński et al,., 2016) and exurban housing (Vukomanovic et al., 2019). Viewscapes studies have also characterized the value of scenic drive corridors (Chamberlain & Meitner, 2013; Anderson & Rex, 2019) and have been used in landscape planning for parks and protected areas (Chamberlain et al., 2015; Tabrizian et al., 2020).

Computational advances are helping researchers study viewscapes over larger regions in more detail (Tabik et al., 2013; Vukomanovic et al., 2018). However, previous viewscape studies of aesthetic preferences and experiences generally consider only snapshots in time, disregarding the dynamic nature of landscapes or new conditions that arise in the future following environmental change. For example, Van Berkel et al. (2018) quantified viewscapes across a portion of the South Atlantic Coastal Plain, USA, to assess the visual-sensory experiences of

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Fig. 1. The autumn color change of quaking aspen trees is a visually striking component of Colorado mountain landscapes. (Photo courtesy of Kyle Hammons).

outdoor recreationalists, but they did not consider how those environments change through time. As land use and climate change re-shape landscapes, place-specific aesthetic values may change as well. On the other hand, many studies have used dynamic models to forecast environmental change, such as LANDIS-II (LANdscape DISturbance and succession; Scheller et al., 2007) or RhESSys (Regional Hydro-Ecological Simulation System; Tague & Band, 2004), but model applications generally don't consider how those environmental changes affect CES from a human perspective. For example, Cassell et al. (2019) found that climate-driven increases in fire activity and severity will make high-elevation landscapes more homogeneous, but the extent to which those changes would be visible to people or affect their perceptions of the landscape was not considered. No studies to date have combined viewscapes models with spatially-explicit forecasts of environmental change to characterize future dynamics of cultural ecosystem services.

The scenic beauty of quaking aspen (*Populus tremuloides*) groves exemplifies the dynamic role that mountain viewscapes play in shaping CES in western North America. The visually striking form and color of large aspen groves are distinct features of many western mountain landscapes (Fig. 1) and contribute to CES through tourism (NPR, 2009; CTO, 2018), recreation (Harniss, 1981; DeByle & Winokur, 1985; Shepperd et al., 2006), aesthetics (DeByle & Winokur, 1985; McCool, 2001) and symbolic value (McCool, 2001). Where viewscapes coincide with aspen groves they supply aesthetic qualities such as visual complexity, visual scale, sense-of-place and connection to ephemera (Tveit et al., 2006). For example, aspen's dual-toned leaves produce distinct visual and auditory experiences when fluttering in the wind (McCool, 2001). Autumn color change in aspens turns large swaths of the landscape bright gold, contributing to the extension of the summer tourism season into autumn and associated economic gains from tourism to mountain communities (NPR, 2009; RRC, 2018). Aspen play important roles in Ute history (Simmons, 2001; Kaelin, 2003), medicinal practices (Willard & McCormick, 1992; Anderton et al., 2012) and religion (Willard & McCormick, 1992; Brown, 2001). Their dense stands and striking color change inspires intangible, emotional experiences and spiritual connection, such as feelings of familial belonging and symbolism of both resilience and change (McCool, 2001).

Aspen is a keystone species that provides vital ecological functions such as supporting wildlife habitat (Shepperd et al., 2006), providing protection for soil and water (Shepperd et al., 2006) and contributing resources for grazing and foraging (Campbell & Bartos, 2001). Aspen are medium-sized (6–18 m tall, 8–46 cm diameter) clonal deciduous trees whose stands occur between 1,500 m and 3,650 m in elevation (DeByle & Winokur, 1985). Although generally resilient to disturbance and often the first tree to recolonize post-fire (Perala, 1990), aspen's shallow, rhizomatic root structure makes them vulnerable to drought conditions (Anderegg et al., 2013). Environmental changes associated with increases in temperature and decreased precipitation have caused declines in aspen populations over the late 20th century (Rehfeldt et al., 2009; Hanna & Kulakowski, 2012; Worrall et al., 2015). And this trend may continue under climate warming, as aspen distributions shift northward and upward in elevation, with extirpation in arid and hilltop portions of their range (Zegler et al., 2012; Yang et al., 2015).

Though mountain viewscapes are subject to change in response to the dynamic systems they encapsulate, the cultural ecosystem services they provide are rarely considered from future or dynamic perspectives. Here, we forecast 100 years of future changes in the total area of quaking aspen and in the aspen visible from scenic byways in the Rocky Mountains of Colorado, U.S.A. We examine the future of aspen viewscapes by asking three questions: 1) will aspen populations expand or decline over the next century? 2) will the visibility of aspen from byways change in proportion to the total area of aspen? And 3) how do forecasts vary across different scenarios of climate change? By identifying mismatches between total and visible declines in aspen, our study demonstrates the need for integrating ecosystem services research and landscape planning, and for gaining more comprehensive understanding of future changes in cultural ecosystem services through forecasting.

2. Methods

2.1. Study area

Aspen trees dominate many of the mountain landscapes most visited by tourists on Colorado's Front Range (Fig. 1), underscoring their value to the state's nearly $20-billion tourism economy (CTO, 2018) and their contribution to the scenic quality of the region's natural landscapes and the recreation opportunities they afford (OIA Southwick Associates, 2017). Our study focuses on aspen tree distributions in Boulder and Larimer counties, Colorado, USA, which form the tourist gateway to Rocky Mountain National Park. In 2017, 20 percent of the state's 34 million visitors spent time on state Scenic and Historic Byways (CTO, 2018). We modeled viewscapes along 331 km of three Colorado Scenic Byways: Cache la Poudre, Trail Ridge Road and Peak-to-Peak Highway (Fig. 2). Cache la Poudre is a narrow canyon that stretches west from the city of Fort Collins for 93 km, rising from 1,592 m to 3,129 m in elevation. Trail Ridge Road, the highest continuous highway in North America, starts at 2,292 m in Estes Park and travels through Rocky Mountain National Park (RMNP) over the Continental Divide to a maximum elevation of 3,713 m. RMNP hosts more than 4 million visitors annually (NPS, 2019). To fully characterize Trail Ridge Road, we also included the segment of Colorado Highway 34 that joins Loveland to Estes Park, for a total road length of 107 km. The Peak-to-Peak Highway runs north to south along the Front Range mountains from Estes Park to Nederland between 2,294 and 2,847 m in elevation. We included state highways 119 and 7, which connect the Peak-to-Peak Highway to the population centers of Boulder and Lyons, for a total length of 131 km. Designated viewpoints/overlooks and culturally significant vistas also occur along these connector routes.

The region is 56 percent federal public lands, including 4,209 km^2 of Arapaho and Roosevelt National Forests and 687 km^2 of Rocky Mountain National Park. Elevation ranges from 1,454 m to 4,347 m and treeline occurs around 3,500 m where alpine tundra begins (Peet, 1981). Lower elevations support grasslands, woody shrubs and sagebrush (*Artemisia tridentata*) (Peet, 1981; Decker, 2007). These shrublands give way to montane forests of ponderosa pine (*Pinus ponderosa*), Douglas fir (*Pseudotsuga menziesii*) and quaking aspen at middle elevations (Peet, 2000). Higher elevations support subalpine forests of subalpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*) and quaking aspen (Veblen et al., 2000). The total population for both counties is approximately 670,000 (DOLA, 2018). The region has experienced marked population growth in recent

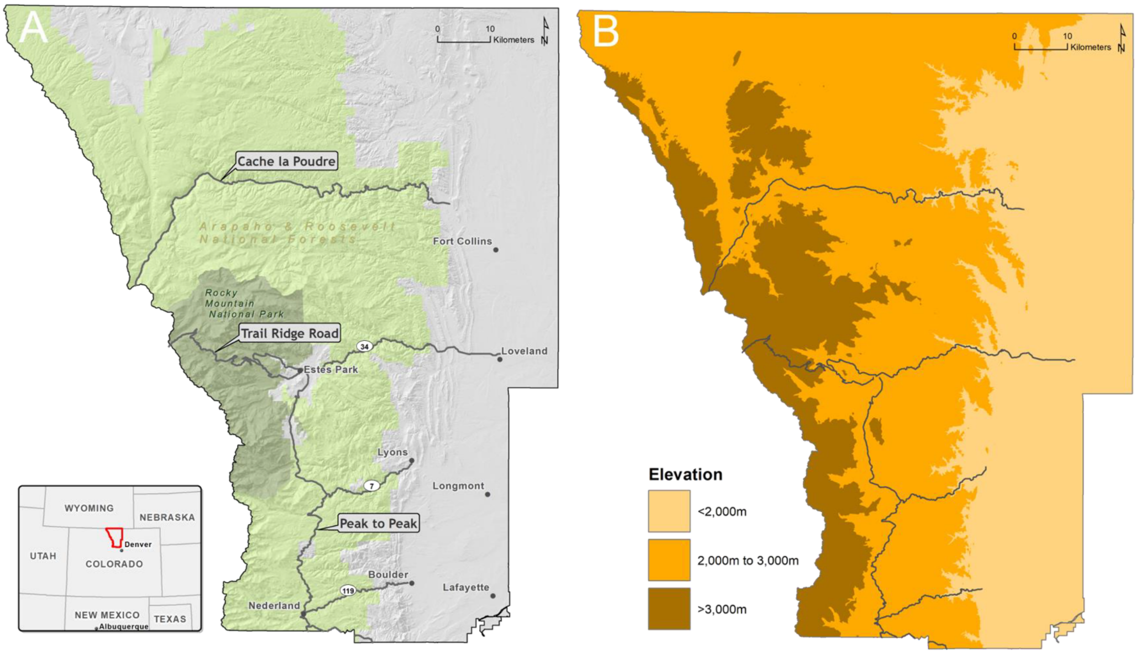

Fig. 2. The study area (A) comprises Boulder and Larimer counties in Colorado, USA. We classified the elevation range (B) into three strata: < 2,000 m, 2,000 to 3,000 m and > 3,000 m.

decades, with Boulder county growing 31% and Larimer county growing 70% between 1990 and 2010 (DOLA, 2018).

2.2. Forecasting aspen distribution

LANDIS-II (Landscape Disturbance and Succession model) is a process-based, spatially explicit landscape model of forest succession (Scheller et al., 2007) that is widely used in the study of ecological change – from simulating disturbance regimes (Syphard et al., 2011), to modeling carbon storage (Liang et al., 2018), to exploring potential impacts of harvest policy (Wang et al., 2014). The model simulates multiple stochastic processes, including disturbances such as wildfire and invasive pests, and uses variable time steps, e.g. from monthly weather conditions to annual tree growth, to differentiate scales of ecological process (Scheller et al., 2007). We mapped all data and ran all simulations at a 50-m grid cell resolution.

We considered three climate scenarios 100 years into the future: 1) no climate change, where future temperature and precipitation patterns mirror those observed from 1980-2010; 2) 4 °C temperature increase with 15% less precipitation (warmer/drier); and 3) 4 °C increase with 15% more precipitation (warmer/wetter). We used a mountain microclimate simulation model (MTCLIM; Hungerford, 1989; Bohn et al., 2013) to provide spatially-explicit estimates (200 m) of monthly temperature and precipitation based on data measured at National Weather Service stations (NOAA NCEI). In scenarios 2 and 3, temperature and precipitation increased or decreased linearly at decadal timesteps. This rate of temperature increase represents moderate regional future climate projections for the western United States (IPCC, 2013) and are comparable to RCF 4.5 (Joyce et al. 2018). There is tremendous uncertainty about precipitation projections for the Rocky Mountains and the Colorado Front Range could either change with the Northwest (more precipitation) or with the Southwest (less precipitation) (Mote et al., 2014; Garfin et al., 2014). The forecasted precipitation changes in scenarios 2 and 3 brackets this variability (van Oldenborgh et al., 2013).

We used the Century Succession extension (Scheller et al., 2011) to simulate future changes in the spatial distribution of quaking aspen (*Populus tremuloides*) and eight other commonly occurring species: *Abies lasiocarpa, Picea engelmannii, Pinus contorta, Pinus ponderosa, Pseudotsuga menziesii, Pinus flexilis*, evergreen shrubs and deciduous shrubs. This extension integrates aboveground successional dynamics with carbon and nitrogen cycling, and all ecological processes are influenced by temperature and precipitation at monthly timesteps. Life history traits for each species (Table 1) were derived from the USDA's North American Silvics Manual and existing LANDIS-II models parameterized for similar regions (Perala, 1990; Syphard et al., 2011; Loudermilk et al., 2014). Aspen life history traits (Table 1) reflect the species' primarily vegetative reproductive strategy, as well as infrequent but possible long-range seed dispersal. Aspen have low shade and fire tolerance, but are some of the first to recolonize post-fire due to their vegetative regeneration via roots suckers that often survive fires. (Perala, 1990). Vegetative reproduction productivity may be somewhat inhibited by ungulate and livestock grazing, and therefore was set at 0.9 (Perala, 1990; Yang et al., 2015).

Succession in LANDIS-II considers spatial interactions among sets of species-age cohort rasters within climatically similar ecoregions. The initial spatial distribution of each species was derived from LANDFIRE data (2013). We determined initial species age-cohorts in each grid cell from field measurements of the Forest Inventory and Analysis (FIA) Program of the U.S. Forest Service (USFS, 2013). The model simulates succession based on species life history, responses to disturbance, dispersal and establishment probabilities, and biomass growth.

Stochastic wildfire, insect biological disturbance agents, and wind events shape the establishment, growth, dispersal and longevity of populations. We used the Dynamic Fire and Fuels System (2.0.5) extension to simulate stochastic fire events and spread. The Dynamic Fire extension uses historical fire occurrence and fuel characteristics to simulate fire behavior and fire effects (Yang et al., 2007; Sturtevant et al., 2009; Syphard et al., 2011; Loudermilk et al., 2013, 2014). We used LANDFIRE Fire Regime products (2012) to stratify the study region into four fire regime units (FRUs) that share similar fire risk parameters, such as number of fires (ignition probability) and mean fire size, and climatic conditions (Sturtevant et al., 2009) Fire severity varies as a function of time since last fire and available fuels and depends on the tree species present and their relative susceptibility to fire. Species survive and succumb to fire based on their fire tolerance and the mortality susceptibility of their age cohort (Sturtevant et al., 2009)

We used the Base Wind (2.1.2) extension, parameterized for wind

Table 1
Life history traits used to parameterize LANDIS-II forest succession model. Shade and fire tolerance are measured on a scale of 1 (least tolerant) to 5 (most tolerant).

Species	Longevity (years)	Years to sexual maturity	Shade tolerance (1–5)	Fire tolerance (1–5)	Effective seed dispersal dist. (m)	Max. seed dispersal dist. (m)	Vegetative reproduction probability	Vegetative reproductive min. age	Vegetative reproductive max. age	Post-fire resprouting
Abies lasiocarpa	300	20	5	1	30	60	0	0	0	N
Picea engelmannii	600	40	4	2	30	180	0	0	0	N
Pinus contorta	350	7	1	2	30	100	0	0	0	N
Pinus ponderosa	700	20	2	5	35	150	0	0	0	N
Pseudotsuga menziesii	350	15	2	4	100	1000	0	0	0	N
Populus tremuloides	200	15	1	2	30	7500	0.9	1	175	Y
Pinus flexilis	1000	20	1	3	30	5000	0	0	0	N
Evergreen shrub	80	5	1	1	30	1000	0	0	0	N
Deciduous shrub	80	5	1	1	30	500	0.8	1	70	Y

event size and severity from regional field measurements (Veblen, 2000; Lindemann and Baker, 2001; Kulakowski and Veblen, 2002). The probability of mortality varied by severity of wind event and cohort age. We used the Base Biological Disturbance Agent (3.0) extension to model impacts of spruce beetle, pine beetle and spruce budworm on tree species. The BDA extension was parameterized for insect life histories and dispersal abilities based on existing LANDIS-II models in similar regions and relevant literature on dispersal rates (Sturtevant et al., 2004; Jackson et al., 2008; Safranyik et al., 2010) and host species susceptibility (Veblen, 2000; Negrón & Popp, 2004; Hicke & Jenkins, 2008; Raffa et al., 2013).

We conducted a sensitivity analysis on 14 model parameters including life history (shade and fire tolerance), input biomass and Annual Net Primary Productivity (ANPP), as well as susceptibility and mortality parameters for fire, wind and biological disturbance agents (Appendix S1; Table 1). We altered continuous parameters by ± 10%, and categorical parameters by ± 1 unit to test the sensitivity of above ground biomass (AGB) at model years 10 and 50 to changes in individual parameters.

For each climate scenario, we ran five stochastic iterations of LANDIS-II from 2010-2120. Each model run took approximately three days on a dedicated machine and outputs were generated at 10-year intervals. The initial timestep is a spin-up of the model, so model outputs covered 2020–2120.

Output rasters were age-cohort distributions of quaking aspen and we used R 3.3 for data preparation and analysis (R Core Team, 2016). For each of the three climate scenarios, we combined the five model runs into one presence-absence raster surface per timestep. We mapped aspen as present in a cell where a majority (3 +) of the five model runs indicated aspen presence.

2.3. Viewscape analyses

We calculated 32,949 viewscapes on a 10-m DEM (USGS, 2017) from observer points at 10-meter intervals along the scenic byway roads (Fig. 2). Fine-grain (10 m) DEM and observer point intervals were chosen to minimize overestimation of bare-earth viewscapes (Vukomanovic et al., 2018). The observer points were located at elevations ranging from 1,526 m to 3,713 m, with a mean elevation of 2,357 m. We used an observer elevation offset of 1.07 meters to match the standard eye height of drivers used in transportation safety requirements (AASHTO, 2001). We set the maximum visibility distance to 10 km in all directions from each observation point (Marsh and Schreiber, 2015). For each point, we used the r.viewshed module, a computationally efficient line-sweeping algorithm in GRASS GIS 7.4.4 to calculate visible grid cells on the DEM (Haverkort et al., 2009; Vukomanovic et al., 2018).

For each viewscape, we calculated a) the total visible area (viewscape size), and b) the area of aspen within each viewscape based on the LANDIS-II outputs of future aspen distribution. To match our LANDIS-II and viewscape modeling, we resampled the 50 m resolution output of aspen distribution to 10 m using the nearest neighbor method. We also computed a composite viewscape by combining the spatial footprint of all viewscapes and calculated the number of times each grid cell is visible as an observer moves along the scenic byway.

3. Result

3.1. Forecasts of aspen distribution

At initial conditions of the LANDIS-II model (year 2020), aspen occurred between elevations of 1,542 m and 3,872 m and occupied over 1,000 km^2 of land area (Fig. 3; Table 2).

Across the study area, aspen are forecast to decline over the next 100 years in all climate scenarios (Table 2). Climate change exacerbated aspen loss 2.1 fold (warmer/drier climate) to 2.3-fold

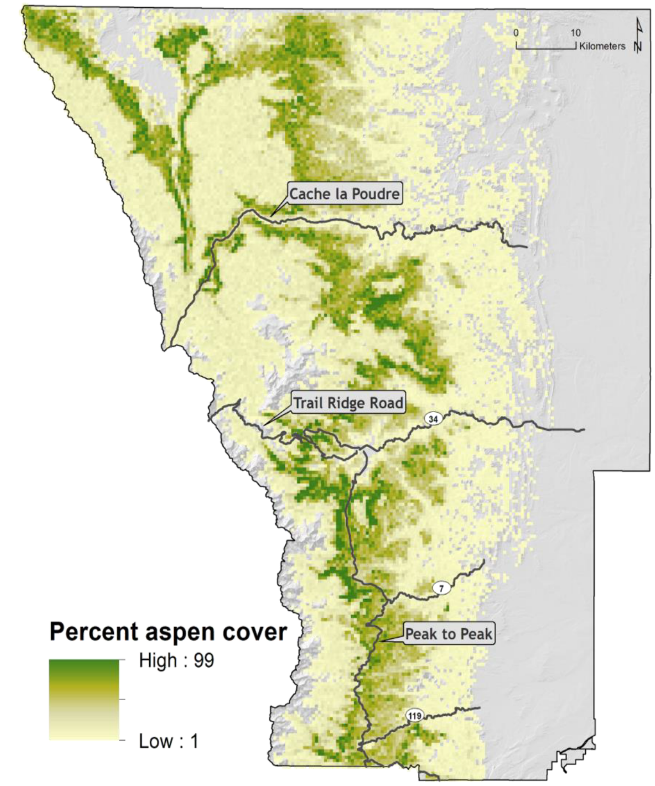

Fig. 3. Aspen distribution at initial conditions of the LANDIS-II forest succession model. Displayed at 500 m resolution for visualization – each 500 m cell represents the proportion of 50 m cells with aspen presence.

(warmer/wetter climate). Stratified by elevation, aspen increased at lower (< 2,000 m) elevations and declined at middle (2,000–3,000 m) and higher (> 3,000 m) elevations (Table 2). With climate warming, aspen increase at lower elevations was 20 times smaller than the projected increase under a no climate change scenario. At middle elevations, where most aspens currently occur, climate change exacerbated aspen loss 3.3 to 3.5-fold. At higher elevations, aspens populations declined, but area lost under climate change scenarios was half of that with no climate change (Table 2).

There was agreement among the climate scenarios that aspen are most likely to persist at middle elevations (Fig. 4a). There was 75% less certainty that aspens would persist at higher elevations and lower elevations had the least certainty of aspen persistence (Fig. 4b).

The LANDIS-II model was not overly sensitive to any of the individual parameters tested in the sensitivity analysis (Appendix S1; Table 1). Aboveground biomass (AGB) changed < 10% for any given input parameter changed by ± 10% or 1 unit. AGB was most sensitive to the maximum biomass parameter, which caused a 7.19–8.89% change at year 10, and a 5.91–9% change by year 50. AGB changed by less than six percent with adjustments to all other parameters.

3.2. Viewscape characteristics

Viewscape area ranged from 0.009 km^2 in the narrow canyons of the Cache la Poudre to 53.78 km^2 above the treeline along Trail Ridge Road (mean = 6.31, SD = 7.37; Fig. 5). Viewscapes seen from above 3,000 m averaged 12.91 km^2 (SD = 6.76), while those seen from below 2,000 m averaged 7.60 km^2 (SD = 7.55). Middle elevation viewscapes averaged 6.76 km^2 (SD = 7.32).

The composite viewscape (spatial footprint of all viewscapes) totaled 951 km^2 (10.9% of the two county study area) (Fig. 6). Repeat views were highest along upper elevation plateaus along Trail Ridge Road and Peak-to-Peak Highway, as well as some areas of the valley that can be seen from the foothills above (Fig. 6). The composite viewscape was constricted at mid-elevations, with a smaller number of repeat views in canyons like Cache la Poudre where an observer may see a portion of the landscape only once or twice as they travel along the route.

3.3. Aspen visibility

Over 100 years, aspen within scenic byway viewscapes declined in all three climate scenarios. The mean aspen area within individual viewscapes decreased from 1.33 km^2 to 0.984 km^2 (no climate change), 1.008 km^2 (warmer/drier) and 1.014 km^2 (warmer/wetter). Aspen declined within viewscapes above 3,000 m, but the decline was smaller under climate warming conditions (Table 1). Viewscapes at lower (< 2,000 m) elevations gained aspens, but the increase was smaller under climate warming (Table 1). At mid-elevations, where most aspen are found, the decrease in aspen visible from scenic byways was similar across all three climate scenarios (18.8–22%).

Aspen loss was not uniform and in aggregate scenic byway viewscapes lost 1.5 to 3.1 times more aspen than the study area overall (Table 1). At elevations below 2,000 m, viewscapes gained 1.25 to 5 times more aspen than the study area overall (Table 1), with a more pronounced gain in climate warming scenarios. At middle elevations (2,000–3,000 m), aspen within viewscapes declined 1.6 to 4.6 times more than the landscape overall. The differences between viewscape and study area aspen loss at elevations above 3,000 m differed with climate scenario: loss was exacerbated in the no climate change scenario and lessened in climate warming scenarios (Table 1).

Repeated views are a measure of the visual experience of moving through the landscape (Fig. 6). Areas that were repeatedly seen

Table 2
Modeled change in aspen area (km^2) over 100 years (2020–2120) across the study area ("Total aspen") and within the viewscapes of scenic byways ("Visible aspen"). The "Repeat aspen views" characterizes the scenic drive experience by counting aspen cells each time they are visible from a point along the road. Aspen area is reported for the entire study area in the top row and then stratified by elevation.

		Initial conditions	No climate change		Warmer/drier climate		Warmer/wetter climate	
	Visible aspen (km^2)	284	227	−20.07%	222	−21.83%	221	−22.18
	Total aspen (km^2)	1,083	1,013	−6.46%	934	−13.76%	924	−14.68%
	Repeat aspen views (km^2)	54,177	39,851	−26.44%	41,230	−23.90%	41,140	−24.06%
< 2,000 m	Total aspen	10	30	200.00%	11	10.00%	12	20.00%
	Visible aspen	2	7	250.00%	3	50.00%	3	50%
	Repeat aspen views	197	555	181.00%	220	11.56%	227	14.87%
2,000 to 3,000 m	Total aspen	977	937	−4.09%	847	−13.31%	839	−14.12%
	Visible aspen	250	203	−18.80%	196	−21.60%	195	−22%
	Repeat aspen views	43,880	33,513	−23.63%	33,520	−23.61%	33,524	−23.60%
> 3,000 m	Total aspen	97	46	−52.58%	75	−22.68%	73	−24.74%
	Visible aspen	32	16	−50.00%	23	−28.13%	23	−28.13%
	Repeat aspen views	10,100	5,783	−42.74%	7,490	−25.84%	7,389	−26.84%

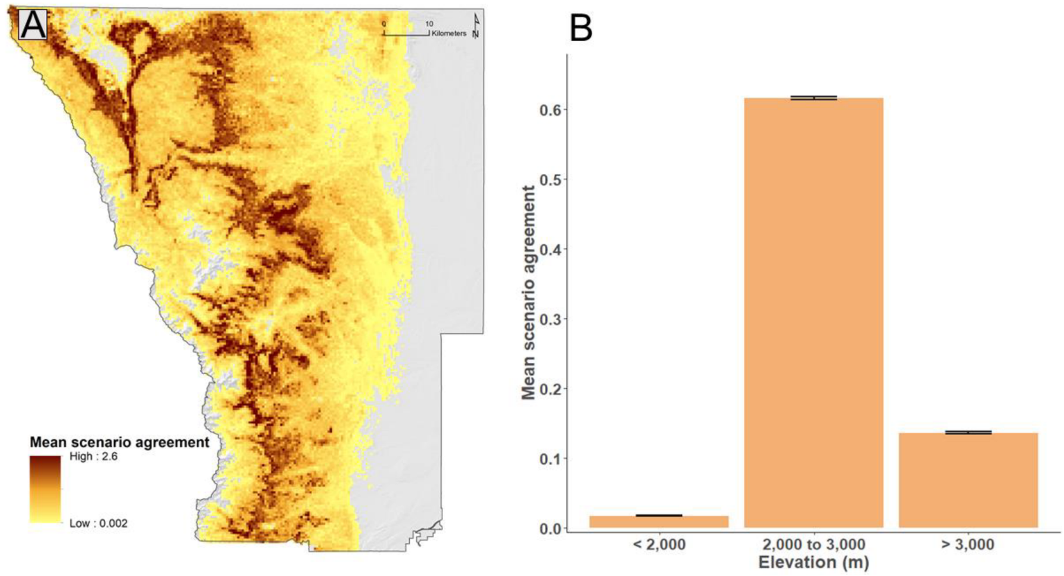

Fig. 4. A) Mean spatial agreement of aspen occurrence among the three climate scenarios: no change, warmer/drier and warmer/wetter. Agreement ranges from 0 – 3. The 50 m resolution outputs were coarsened to 500 m for visualization. B) Mean scenario agreement by elevation strata. Bars represent 95% confidence intervals.

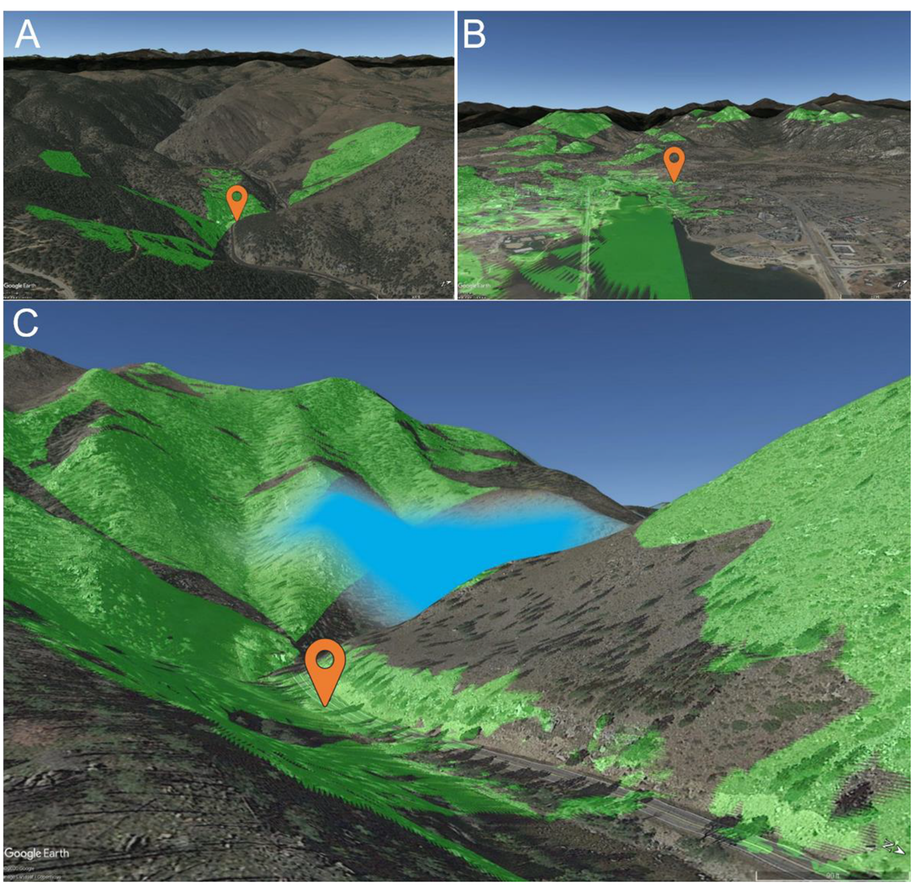

Fig. 5. Examples of viewscapes (green) calculated at points (red circles) along designated scenic drives. In narrow canyons, viewscapes were constricted by topography (A), while in larger valleys like near Estes Park (B), viewscapes included sweeping views of mountain peaks above. We overlaid modeled aspen distribution (blue) to compute the area of visible aspen in each viewscape (C).

throughout the scenic drive lost more aspen at low and middle elevations than viewscapes overall. At high elevations, the areas seen most frequently along scenic drives lost less aspen than the viewscape overall.

4. Discussion

A growing body of literature shows that mountain viewscapes provide essential cultural ecosystem services ranging from recreational opportunities (Tenerelli et al., 2016) to cultural identity (Knez & Eliasson, 2017). Mountain regions are expected to be hit hard by climate change (Pepin et al., 2015), with the potential to irrevocably change mountain viewscapes. But the extent to which viewscapes and their CES change through time has received little attention. To our knowledge, no studies to date have combined spatially explicit, process-based ecological models with viewscape models to understand visible

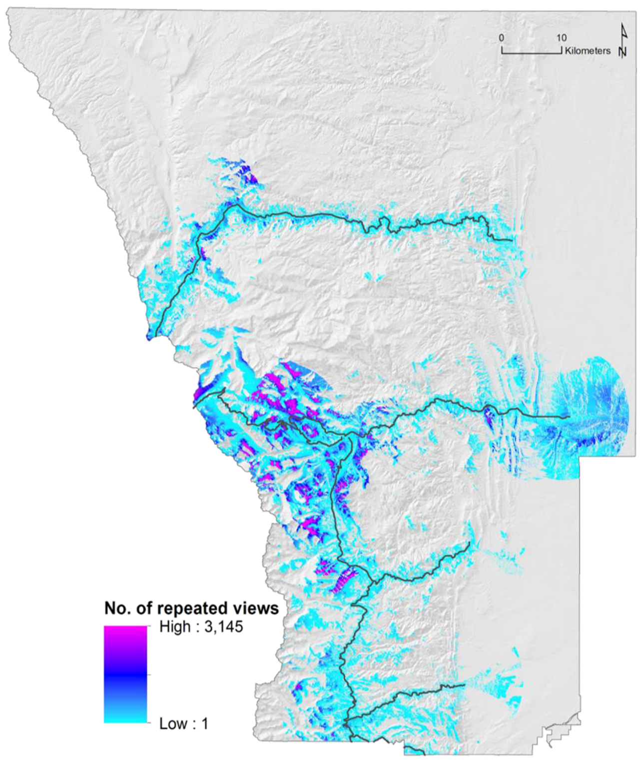

Fig. 6. The composite viewscape of 32,949 observer points along scenic drives in Boulder and Larimer counties, Colorado, USA. Repeat views are the number of times each grid cell is visible as an observer moves along the scenic byway – pink areas had the largest number of repeat views, while areas in light blue were seen only one to two times.

changes to future landscapes. Using climatic shifts in the visibility of quaking aspen along scenic byways, we show how forecasting can be used to assess future changes in CES. Our findings predict disproportionate declines of a CES in viewscapes and demonstrate the need for integrating viewscape studies with ecosystem process models and scenario planning to understand future changes in cultural ecosystem services.

4.1. Projected and visible aspen decline

Our forecasts that aspen will decline in the Colorado Rockies are consistent with projections for Utah reported by Yang et al. (2015), as well as continental-scale species composition models (Rehfeldt et al., 2009; Worrall et al., 2015). Our ensemble of all three climate scenarios indicates that aspen will most likely persist at mid elevations (2,000 to 3,000 m; Fig. 4), where the current population is largest and appears to be most stable (Table 1). Yang et al. (2015) and Strand et al. (2009) report similar findings and noted these areas' low suitability for aspen's shade-tolerant competitors, and pockets of high-moisture well suited for aspen persistence. While lower elevations ($<$ 2,000 m) were forecasted to gain aspen in all climate scenarios, and high elevations ($>$ 3,000 m) projected to lose aspen, the magnitudes of those gains and losses were substantially less in climate warming scenarios compared to the scenario of no climate change, indicating both total and visible aspen moving upward in elevation with warming temperatures. Small gains in aspen at lower elevations are likely occurring through opportunistic post-fire recolonization and encroachment into lower montane grasslands and shrublands. Fire regimes in mountain regions are particularly sensitive to climate change (Pepin et al., 2015; Vukomanovic & Steelman, 2019), which, coupled with decades of wildfire suppression, creates conditions for potentially large wildfires to modulate future aspen distribution (Yang et al., 2015). Future research should explore where and how stochastic fire events affect aesthetic cultural ecosystem services.

When the distribution of aspen groves and scenic byway viewscapes are considered jointly, we gain insight into when and where aspen decline may affect the provisioning of aspen's aesthetic CES. For example, our finding that aspen decline disproportionately affects viewscapes means that scenic byway travelers will experience more decline than is occurring on the landscape as a whole. Though fewer aspen groves occur in the higher and lower elevations (Table 1), these elevation zones offer some of the most expansive, scenic vistas (Fig. 6). For example, the largest viewscapes are located as byway travelers first enter the foothills of the Rocky Mountains, where the topography creates sweeping views of urban centers, grasslands and agriculture of the valley below, as well as views of surrounding foothills and distant peaks (Fig. 2). Large viewscapes also occur at high elevations, where prominent peaks are visible above the scenic byways. Because these landscapes make up the majority of the scenic drive experience (Fig. 6), these large, conspicuous areas may contribute relatively more to the region's cultural ecosystem services than the smaller, more constricted mid-elevation viewscapes that often occur in narrow canyons such as Boulder and Cache la Poudre (Fig. 6). Aspen is less visible from scenic byways at mid elevation, potentially hiding substantial declines in aspen in the future even though aspen is most abundant here.

We found repeated views to add a nuanced perspective to how aspen viewscapes are experienced by measuring the proportion of time an area is visible throughout the scenic drive. The smaller viewscapes at mid elevations, with fewer repeated views and large aspen decline, may be especially vulnerable to visible aspen loss. A different pattern occurs for high elevation viewscapes; here the visibility of aspen declines may be less dramatic in areas with more repeat views compared to locations with only a few repeat views (Fig. 6). At high elevation, aspen is visible from more locations along scenic byways and proportional to total decline. At these elevations, less visible aspen decline intersects with large, sweeping viewscapes, often associated with higher aesthetic value (Tveit et al., 2006). Therefore, higher elevations may support important future refugia for people to see aspen.

4.2. Impacts to cultural ecosystem services

Visible loss of aspen trees is detrimental to landscape aesthetic CES. Specifically, declines in aspen may affect the fundamental visual identity of the landscape due to the tree's contribution to visual complexity, sense-of-place and ephemera (Tveit et al., 2006). Aspen are the primary deciduous tree in the region, have distinct white bark and two-toned leaves, and produce a recognizable "quaking" or "crackling" noise when the wind blows, distinguishing them from the coniferous trees that dominate the landscape. Fewer visible aspen may mean less complexity of visual form, color and texture on the landscape. Aspen also contributes to the imageability or sense-of-place of Colorado's mountain viewscapes, exemplified by the way aspen imagery is used to position Colorado's tourism and recreation experiences in unique, picturesque landscapes. For example, on the Colorado Tourism Office website, pictures of aspen account for 25% of featured photographs (CTO, 2020). Understanding where aspen may decline is vital information for planning and policy in tourism-dependent communities. Aspen's color changes are the primary visual marker of the change of seasons, both in its striking gold leaves in autumn and its bright green buds in spring, contributing to ephemeral visual quality (Fig. 1). Aspen are also markers of short-term weather-related ephemera because of the distinct visual and auditory experiences their leaves produce during wind events. Loss of these visual qualities could diminish spiritual and community values, as well as emotional and personal experiences (McCool, 2001). We note that there is significant opportunity and need for further research on the unique contributions of aspen to visual quality and sense-of-place experiences.

Use of bare-earth DEMs can lead to overestimation of viewscape area, as they do not account for trees and above-ground structures that may obstruct landscape visibility. LiDAR data is not currently available for the study region, so we used 10-m resolution DEMs to minimize overestimation (Vukomanovic et al., 2018), with consistent methods across climate scenarios. Andersen & Rex (2019) found that the difference between using a DEM and LiDAR-based DSM along a mountainous scenic drive corridor was negligible when considering binary (visible/not visible) viewscapes. They found significant differences between the two methods only when considering the number of times each pixel was visible, which may mean that our DEM results overestimate the number of repeat views. Assuming this possible overestimation is consistent across scenarios, our results indicate that loss of repeatedly-visible aspen could be less pronounced in climate warming scenarios, especially at higher elevations.

4.3. Future research

Increased residential development, restructuring of rural land use, and urban sprawl have the potential to change how nearby forests are managed for timber harvest and fire suppression. Due to aspen's opportunistic colonization of recently burned areas (Perala, 1990), aspen distribution is particularly sensitive to changes in fire regime (Yang et al., 2015). Our ecological modeling projections do not account for increase in impervious surface or population growth and accompanying changes to fire management policy. Future studies may undertake the exploration of stakeholder-driven land use change and fire management scenarios to study their effects on the visibility of scenic aspen stands. For example, scenarios of future development can be used to understand how increased wildfire suppression near residential areas may affect forest succession and composition, leading to changes in visible aspen cover. However, it will be important to consider the propagation of model uncertainties when linking multiple forecasting modalities (Ascough et al., 2008).

Emerging research on forecasting vegetation structure could complement future research that relies on simulating DSMs to forecast changes to viewscape conditions. Forecasting vegetation structure along roadways could allow for more representative future viewscape models at resolutions akin to present-day LiDAR-derived DSM viewscapes. The approach introduced here could be expanded beyond quaking aspen to explore how the complete species composition of the landscape will change on century scales and provide a more comprehensive picture of the aesthetic, symbolic, tourism and recreation ES supplied by Rocky Mountain viewscapes. We encourage further study of viewscape preferences through approaches complementary to the methods described here. Immersive visual environments provide promising platforms for exploring preferences for simulated future landscapes (Huang et al., 2019). Hedonic modeling may also reveal the connections between ecological shifts and cultural ecosystem service provision. We also believe future attention to the CES of mountain viewscapes can benefit from more detailed geospatial representation of how people experience a landscape as they move through space (Chamberlain & Meitner, 2013)."

5. Conclusion

There is increasing recognition that spatially explicit models of environmental change are required to illuminate connections between landscape characteristics and ecosystem services (De Groot et al., 2010). The mismatch between aspen's total and visible population decline highlights the need for tighter connections between ecological research and regional planning. A process-based spatially-explicit model of forest succession allowed us to forecast and examine future distributions of a valued ecosystem service under multiple scenarios of climate change. We found the combination of ecosystem process modeling and viewscape approaches useful for characterizing the disproportionate decline in the aspen trees that people actually see relative to total population declines, and therefore in pinpointing when and where this CES will be most vulnerable or resilient in the future. Viewscape approaches also offer a window into the visual experience of those moving through the landscape (e.g. Anderson & Rex, 2019). Both these insights are critical to understanding changes to CES and informing landscape planning efforts. The ramifications of visible aspen decline to landscape perception and local tourism economies could be significant, given that Colorado's 37.9 million visitors cited scenic mountain landscapes as a top reason for visiting (CTO, 2018).

The viewscapes approach allows us to map and quantify change, which has been a challenge for cultural ecosystem services (Milcu et al., 2013). More explicit "accounting" of CES facilitates their inclusion in ecosystem service assessments, contributing to a more comprehensive understanding of how, when and where ecosystem services are changing (Maes et al., 2012; Liu & Opdam, 2014). Our results illustrate how environmental change in aggregate may not reflect changes to important dimensions of CES, such as the experience of travelers on scenic byways, which are difficult to measure in dynamic and future contexts with traditional methods such as field surveys, revealed preference studies, and photography techniques. By leveraging projections of future species distribution, we highlight areas that may be prioritized in future landscape planning, such as designation of protected visual resources, optimizing scenic overlooks, forest and fire management plans and integration into qualitative research on landscape preferences and cultural values. In places where sensitive mountain ecosystems intersect with tourism-dependent communities, our study highlights how viewscapes can shape CES in the future.

Declaration of Competing Interest

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

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