earth

Review

A Multi-Scale Blueprint for Building the Decision Context to Implement Climate Change Adaptation on National Wildlife Refuges in the United States

Dawn Robin Magness [1,*], Ella Wagener [2], Emily Yurcich [2], Ryan Mollnow [2], Diane Granfors [2] and Jennifer L. Wilkening [3]

[1] U.S. Fish & Wildlife Service, Kenai National Wildlife Refuge, 1 Ski Hill Road, Soldotna, AK 99669, USA
[2] U.S. Fish & Wildlife Service Alaska Region, National Wildlife Refuge System, 1011 East Tudor Road, Anchorage, AK 99503, USA; ella_wagener@fws.gov (E.W.); emily_yurcich@fws.gov (E.Y.); ryan_mollnow@fws.gov (R.M.); diane_granfors@fws.gov (D.G.)
[3] U.S. Fish and Wildlife Service, National Wildlife Refuge System, Natural Resource Program Center, Fort Collins, CO 80525, USA; jennifer_wilkening@fws.gov
* Correspondence: Dawn_Magness@fws.gov; Tel.: +1-907-741-9422

Abstract: Climate change and ecological transformation are causing natural resource management to be applied to nonstationary systems. Managers can respond to dynamic ecosystems by resisting, accepting, or directing ecological change. Management response is constrained by a decision context, defined as an interconnected social system of values, rules, and knowledge that affects how problems can be addressed. We provide a multi-scale blueprint for creating a decision context that increases capacity for implementing climate adaptation, including novel approaches in the National Wildlife Refuge System, a continental conservation network administered by the U.S. Fish and Wildlife Service. We use the Tetlin National Wildlife Refuge in Alaska as case study to illustrate blueprint concepts and to provide "proof-of-concept" for application. The blueprint builds on ideas and practices from scenario planning, adaptive management, and adaptive pathway planning, which are approaches that promote action in the face of uncertainty. Management considerations focus on stewarding biodiversity in a changing climate by addressing what futures are possible, what interventions can be used to shape future conditions, and how to coordinate a regional conservation strategy. The blueprint focus on decision context promotes a longer-term social process of engagement that is complementary to, but larger than, any one decision process.

Keywords: climate change adaptation; wildlife management; resist-accept-direct (RAD) framework; nonstationary systems; National Wildlife Refuge System; natural resource management; decision context; social-ecological system; scenario planning; adaptive management; adaptive pathway planning

check for updates

Citation: Magness, D.R.; Wagener, E.; Yurcich, E.; Mollnow, R.; Granfors, D.; Wilkening, J.L. A Multi-Scale Blueprint for Building the Decision Context to Implement Climate Change Adaptation on National Wildlife Refuges in the United States. *Earth* **2022**, *3*, 136–156. https://doi.org/10.3390/earth3010011

Academic Editors: Timothy Kittel and Terri Schulz

Received: 5 October 2021
Accepted: 29 January 2022
Published: 3 February 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Building a connected network of conservation lands is the most widely recommended climate adaptation strategy to protect species by allowing them to naturally re-sort across changing landscapes [1–3]. Land management agencies may also need to adjust current management objectives and practices given the potential for profound change [4]. Agencies in the United States have used historical conditions to define management targets and often assume that past management outcomes can predict future success. In the past, management targets were easier to communicate because current or historical conditions were known and observable [5]. In a rapidly changing climate, management targets must be innovative and nimble to navigate toward a nonstationary future in which ecosystems may respond differently than they have in the past [6–8]. The potential for ecological transformations, defined as a qualitative shift in ecosystem structure, function, or species composition, increases uncertainty about future conditions and the likelihoods of management success [9–13].

The resist-accept-direct (RAD) framework conceptually expands management options to accommodate nonstationary and ecological transformation. The RAD framework focuses on management response to intentionally shape ecosystem composition, structure, processes, or functions [14]. Resist strategies use management intervention to maintain or to restore ecological conditions within a range of historical or current natural variations. Accept is an explicit decision to allow an ecosystem to respond autonomously. Direct strategies use management intervention to shape the ecological trajectory toward conditions that are aligned with the emerging climate and to meet conservation goals [15,16].

Every management response is constrained by a decision context, defined as the interconnected social system of values, rules, and knowledge that affects how problems can be addressed [17]. Social transformation of the decision context may need to occur before a manager can effectively respond to ecological transformation [18]. To date, implementation of climate adaptation has largely been incremental, involving business-as-usual approaches that resist change [19–21]. Deliberative engagement with managers, scientists, and stakeholders can be used to expand the current decision context to provide more options for management to be responsive to situations where resistance is futile [22]. Knowledge deficits are often less of a barrier to action than the lack of social processes needed to construct a shared understanding of change, what futures are desired, and what is needed to implement actions [23]. Therefore, a critical step for implementing the RAD framework is for agency staff, partners, and other subject matter experts to engage collaboratively and iteratively about what climate change may mean for fish, wildlife, plants, and their habitats.

In this paper, we present a multi-scale blueprint for intentionally creating a decision context that supports the RAD framework. Our purpose is to increase capacity for implementation of climate adaptation strategies within the U.S. National Wildlife Refuge System (NWRS), including novel approaches to direct change. We focus on refuges in Alaska because these lands have the potential for, and are already experiencing, rapid and profound ecological change. Alaska is more highly exposed to climate change than the conterminous United States and documented impacts, such as permafrost loss, coastal erosion, loss of sea ice, increased wildfires, and glacier melt, are already occurring [24]. We utilize publicly available data and a literature review to apply the blueprint to the Tetlin National Wildlife Refuge (NWR) in Interior Alaska. By incorporating multiple future scenarios, we demonstrate how the blueprint can provide a rich starting point for deliberative engagement that facilitates implementation of the RAD framework, even under climate uncertainty.

2. Background: The NWRS

The NWRS is a national system of public lands and waters managed by the U.S. Fish and Wildlife Service for the primary purpose of conserving fish, wildlife, and their habitats. Today, there are 568 national wildlife refuges located across the United States and Territories, from the Caribbean to the South Pacific. Alaska contains the largest refuges and the most acreage in the NWRS (excluding marine monuments), with 16 national wildlife refuges totaling over 31 million hectares, including over 7 million hectares of designated wilderness.

In 1980, the Alaska National Interests Lands Conservation Act (ANILCA, P.L. 96-487, 2 December 1980) established nine new refuges, expanded seven existing refuges, and provided a guiding vision for the management of Alaska's NWRs. ANILCA established specific purposes for the National Wildlife Refuges, the primary common purpose being "*to conserve fish and wildlife populations and habitats in their natural diversity*" (e.g., Alaska Peninsula National Wildlife Refuge, id. at Sec. 302(1)(b)(i)). Therefore, with the passage of ANILCA, Alaskan NWRs became incredibly important to conservation in the United States because they are large intact ecosystems that are relatively unaltered by human disturbance, and they are set aside for the primary purpose of conservation of wildlife and their habitats. While Alaska's NWRs provide for the critical need to conserve large intact areas, they remain affected by human activities and forward thinking is required for effective stewardship of these lands.

Alaska's NWRs are also governed as part of the larger NWRS under the National Wildlife Refuge System Administration Act of 1966, as amended by the National Wildlife Refuge System Improvement Act of 1997 (NWRSAA, P.L 105-57, 9 October 1997; 16 U.S.C. 668dd). The first purpose of the NWRS is to "*provide for the conservation of fish, wildlife, and plants, and their habitats within the System*," and the second is to "*ensure that the biological integrity, diversity, and environmental health of the System are maintained for the benefit of present and future generations of Americans*." This responsibility to ensure biological integrity, diversity, and environmental health in managing the NWRS is the strongest ecological standard required of any federal land management agency in the United States [25]. Historical baselines have been used to define biological integrity and environmental health as management targets [26].

3. Blueprint for the NWRS

Our multi-scale blueprint was designed to help land management agencies build a decision context that increases their social capacity to steward biodiversity through profound climate change. The blueprint uses concepts and practices from established assessment approaches to build knowledge about alternative futures, the potential to shape change using management intervention, and how to create regional conservation strategy that addresses future conditions (Figure 1). Our intention is to create a starting point for deliberative engagement about how Alaska refuges can implement climate adaptation strategies that are grounded by empirical information. The blueprint is designed to widen the current decision context for managing wildlife refuges beyond expectations shaped by historical conditions. As presented here, the blueprint is specific to the NWRS, particularly in Alaska, because institutional values and rules differ among land management agencies. However, this blueprint should be more widely applicable for biodiversity conservation in other contexts. The blueprint is multi-scale because regional vulnerability assessment of climate change must be linked to the specific context of path-dependent and contingent landscapes to implement climate adaptation strategies at local scales. We also recognize that refuge planning and management occurs at multiple scales and that within an agency the values, objectives, and goals can be scale dependent.

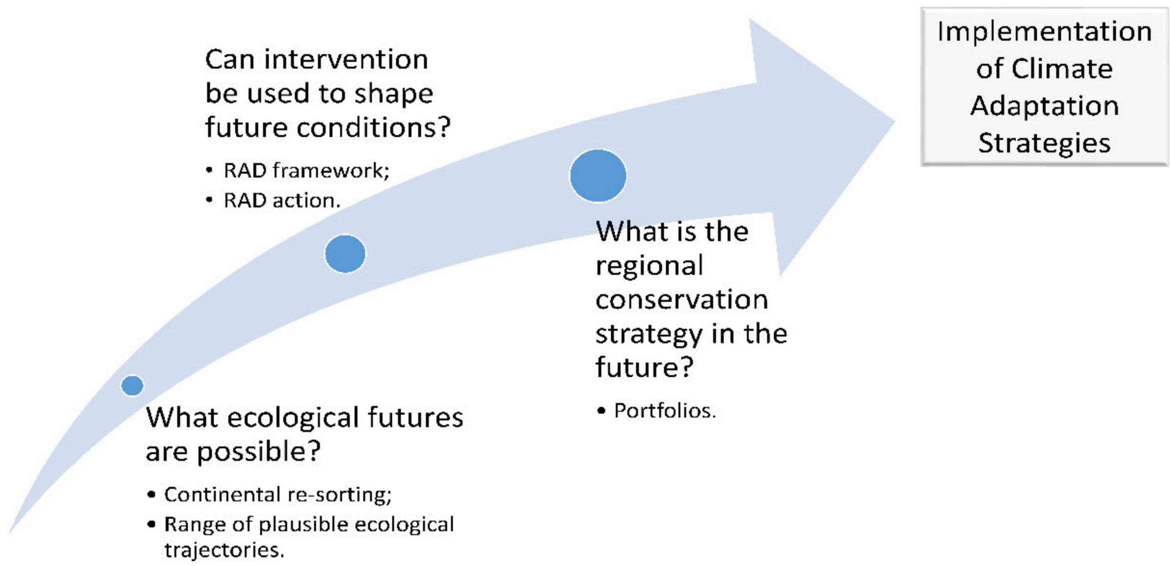

Figure 1. The blueprint identifies key questions that can help land management agencies craft and implement climate adaptation strategies that focus on stewarding biodiversity through future climate change. Each question is informed by management considerations (bulleted).

3.1. Assessment Approaches in Blueprint

The blueprint uses concepts and practices from scenario planning, adaptive management, and adaptive pathway planning because these well-established approaches are useful for managing nonstationary systems. These approaches facilitate management when multiple futures are possible and uncertainty requires iterative learning, preparedness to respond during windows of opportunity, and nimbleness to adaptively respond to emerging information and surprise.

Scenario planning is used to describe and to explore alternative futures when accurate prediction is infeasible. It is most applicable when uncertainty is high and there is little ability to control conditions [27]. Scenarios help natural resource managers prepare for a wide range of futures [28]. Managers can plan for and cope with the uncertainty and the issues outside the control of management by identifying strategies that work across alternative futures.

While scenario planning captures key uncertainties that are uncontrollable, adaptive management focuses on key uncertainties related to the conceptual understanding of how a social-ecological system works [29]. Adaptive management uses experimentation to test hypotheses about why and how an ecosystem responds to variable conditions and management interventions [30]. Adaptive management cycles are useful for iterative learning, and they are most applicable when management objectives are clear and measurable. It is useful for describing, observing, and monitoring the current system [31]. Adaptive management is relevant for RAD because it can provide information about the effectiveness of current management strategies, when and how to adjust strategies, and when management objectives become infeasible in nonstationary systems [8].

Adaptive pathway planning explores the potential and the opportunities to transform the social-ecological system toward a desired outcome. It is intended to help managers and stakeholders determine when to shift from resistance or other incremental climate adaptation strategies and to adopt transformational adaptation strategies [32]. Transformational adaptation often requires the values, rules, and knowledge of the current management regime to be reimagined and renegotiated. Pathway planning communicates desirable futures, and it explores when and how management intervention could be used across the range of plausible ecological trajectories [33–35]. Pathways are used to conceptualize action sequences that can be taken as the future trajectory unfolds [36]. The feasibility of any pathway has social constraints, such as stakeholder acceptability, cost, legislative requirements, and institutional culture. Pathway planning identifies these social limits and barriers to proactively address them before action is needed. Thresholds, disturbances, or other events identified as important via adaptive management are included in pathway planning as contingencies that will trigger a management response if they occur [35]. Adaptive management can also be used to pilot strategies identified in various pathways [16,33]. Planning multiple pathways allows managers to consider trade-offs between strategies and to identify decision points that have the potential to reduce future opportunities or result in maladaptation [18,37].

3.2. Management Considerations in the Blueprint

Focal management considerations are needed to answer key questions related to how climate adaptation strategies can be planned and implemented (Figure 1). An understanding of the potential for continental re-sorting is needed to assess the ecological conditions that are possible in the future (Figure 2). We define continental re-sorting as the global redistribution of species in response to climate change. Species redistribution challenges historical practices of conserving species in place [2]. In a changing climate, a species lost on one refuge may be preserved or become established elsewhere. Considering the potential for species to track shifting climate conditions may help refuge managers make decisions about whether to treat a colonizing species as invasive, encourage the establishment of natural colonizers, resist extirpation, or use translocation to facilitate movement in or out of the management area [38]. At global and continental scales, the NWRS has commitments and legal requirements to conserve biodiversity and to avoid extinction. Continental re-sorting scenarios can be created using alternative climate futures that explore how to best conserve biodiversity (Figure 2).

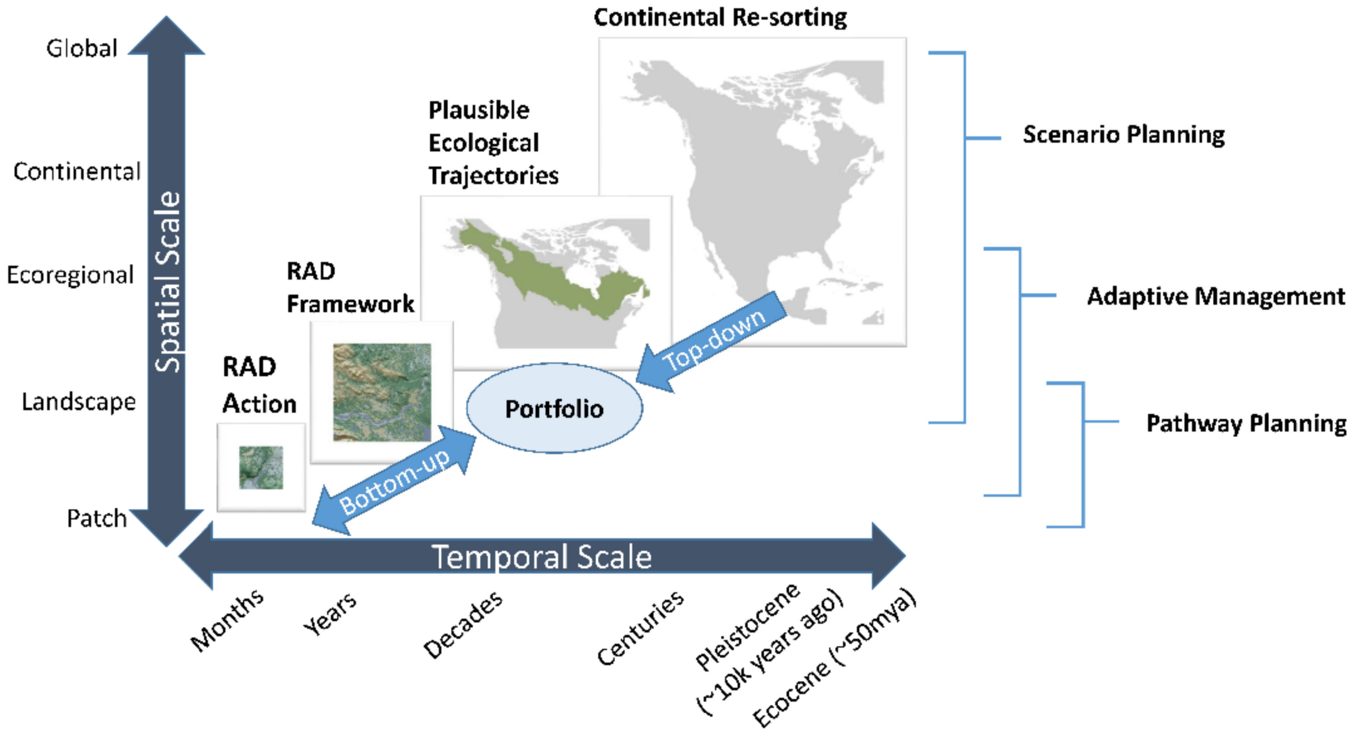

Figure 2. Blueprint for building a decision context to implement climate change adaptation on National Wildlife Refuges in the United States. The blueprint integrates multiple spatial and temporal scales, management considerations (continental resorting, plausible ecological trajectories, the RAD framework, and RAD actions), and assessment approaches (scenario planning, adaptive management, and adaptive pathway planning). The management considerations are needed to understand what future conditions are possible, how intervention can be used to shape future conditions, and to coordinate regional conservation strategies. Portfolios consist of suites of RAD strategies that are being applied in different places. Local RAD actions can be informed by and coordinated into (bottom-up arrow) a portfolio that can also be informed by regional climate vulnerability (top-down arrow). Scenario planning can be applied at large spatial scales, while adaptive management is applied at regional, landscape, and local scales. Pathway planning is context dependent and best applied at landscape and local scales.

Continental re-sorting scenarios provide insight into how climate change may influence future conditions of a particular place, but many other factors also shape future conditions. The range of plausible ecological trajectories can be considered to understand how ecological communities and ecosystem functions could change (Figure 2). Ecosystems do not move, or remain, as cohesive units in response to climate change [11]. Ecosystem change, including the potential for novel communities, is moderated by edaphic and biotic factors beyond climate. These factors, such as site conditions, legacies, colonization, mortality, and disturbance events, shape ecosystem change [35,39]. Scenarios and experimentation via adaptive management are useful approaches for increasing understanding about the range of ecological trajectories [8,40]. Considering a range of ecological trajectories is useful because how ecosystem change unfolds in a particular place is contingent on the timing and the sequence of historical and future events. These future events, called contingencies, can be identified as important even when it is impossible to predict their occurrence or timing. [35]. Contingencies are important decision points that are proactively planned for in pathway planning.

The RAD framework (Figure 2) helps managers consider alterative management responses to ecological change [1,16]. RAD expands focus from historical or current conditions to consider how the use of management intervention could be used to shape future outcomes across the range of plausible ecological trajectories [35,40]. Implementing RAD requires the development of local interventions that are both targeted to the unique natural and management history of a specific place and contextualized by regional climate change vulnerability. Adaptive pathway planning can help managers implement RAD by preparing for interventions and removing barriers to acting prior to contingency events occurring. If successfully applied, the RAD framework should result in appropriate action on the ground.

Climate change occurs across large, regional scales that are mismatched with the scope of the areas that most managers control [41]. Portfolios (Figure 2) can facilitate RAD implementation by nesting local management interventions within regional climate adaptation planning [42]. Local actions can ultimately be local choices. Portfolios can integrate these local choices into a regional response [35,43,44]. Diversity in choice by local managers can make the larger region more resilient by increasing learning about different options and hedging against any one strategy [44]. Portfolios can also be used to manage risk across a conservation reserve network by diversifying response among management units [35]. To diversify a portfolio, regional assessments and other coordinated efforts can be used to inform local choices. The NWRS already has legislative mandates to operate as a coordinated conservation reserve [45].

4. Application of the Blueprint to the Tetlin NWR

4.1. Refuge Description

Tetlin NWR (the Refuge) encompasses approximately 2800 km^2 of USFWS property. An additional 1300 km^2 within the Refuge boundary are owned and managed by Native Corporations, the State of Alaska, or private individuals. The Refuge is located northeast of the Alaska Range, in the Upper Tanana Valley. It is bordered by Wrangell-St. Elias National Park on the south, Canada to the east, and the Alaska Highway along its northern border. The large, flat basin of the Upper Tanana River is filled with sediments deposited in glacial moraines and outwash plains. The Refuge consists of rolling lowlands at elevations of roughly 500 m and reaches into the Mentasta Mountains, which contain glacier-carved peaks at elevations of up to 2400 m. The Refuge is underlain with discontinuous permafrost at or near the surface, amounting to 50–90% of the land surface [46]. The vegetation community is a complex mixture of spruce forests, mixed woodlands, shrublands, and tussock peatlands that are interspersed with innumerable streams, ponds, lakes, and other wetlands. Forest cover types dominate elevations below treeline (975 m). The southern half of the Refuge is primarily forested uplands, while the northern half consists of a low floodplain, including large areas of muskeg. The landscape provides valuable habitat for a wide variety of fish (14 species) and wildlife species (approximately 200 birds and 44 mammal species).

4.2. Potential for Continental Re-Sorting on the Tetlin NWR

We utilized three publicly available datasets to consider continental re-sorting scenarios for Tetlin NWR (Table 1). In this section, we present our analyses of these datasets and the results. The first analysis assesses the range of future climate projections and associates projected annual average temperature and precipitation with current biomes. The other two analyses use a climate clustering approach and a climate envelope model to identify geographic analogs that align with future climate conditions in Tetlin NWR.

4.2.1. Biome Plots

We use the most recent, sixth phase of the Coupled Model Intercomparison Project (CMIP6) emission scenarios to assess climate futures using spatial layers from Adaptwest [47,48]. To identify trends and divergent climate futures, we averaged the climate pixels occurring within the Tetlin NWR. The average annual temperature from the 1961–1990 climate normals was −3.5 °C and the average annual precipitation was 32.5 cm. Nine Atmosphere-Ocean General Circulation Models (AOGCMs) plus a 13-AOGCM ensemble and 4 emission scenarios selected by Mahoney et al. [49] were represented in 31 climate futures (Table 1; 9 AOGCMs × 3 emission scenarios = 27 climate futures; the 13-AOGCM ensemble × 4 emission scenarios = 4 climate futures). All 31 climate futures resulted in warmer and wetter climate conditions in 2041–2070 as compared to 1960–1991 (Figure 3). We plotted the change in annual average temperature and annual average precipitation in the 2041–2071 projections relative to the 1961–1990 historical normals for the 31 climate futures. Similar to Lawrence et al. [50], we found groupings of climate futures were based on AOGCMs and not emission scenarios (Figure 3). We used the plot to identify the warm and the wet (MPI-ESM1-2-HR, SSP2-4.5) and the warmest and the wettest (UKESM1-0-LL, SSP5-8.5) projection.

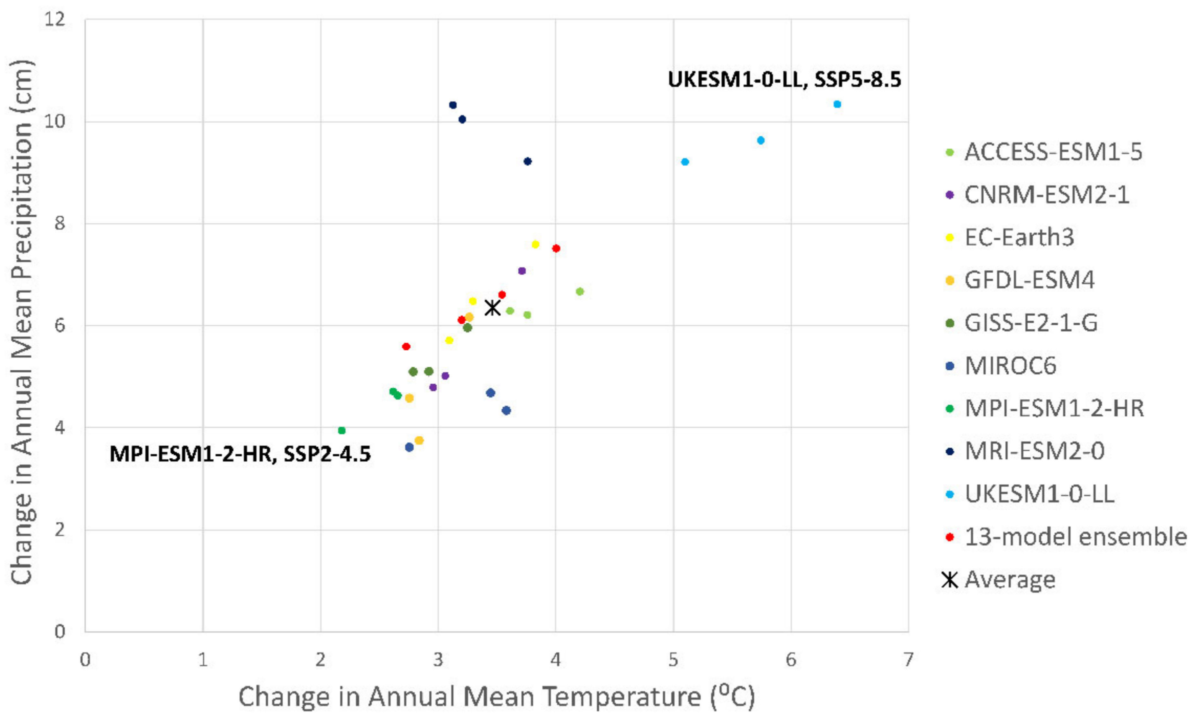

Figure 3. Spread of climate futures projected with 9 individual AOGCM and a 13-model ensemble using 4 CMIP6 emission scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5). Change in average annual mean temperature and average annual total precipitation for the 2040–2071 projection relative to the 1961–1990 historical period for the Tetlin National Wildlife Refuge. The average represents 31 projections: 9 AOGCMs × 3 emission scenarios (SSP1-2.6, SSP3-7.0, SSP5-8.5) and the 13-model ensemble × 4 emission scenarios (SSP1-2.6, SSP3-7.0, SSP5-8.5). The least warm and wet (MPI-ESM1-2-HR, SSP2-4.5) and the most warm and wet (UKESM1-0-LL, SSP5-8.5) projection extremes are labelled.

We overlaid annual average temperature and precipitation pixel values from the Tetlin NWR on a Whittaker's biome plot created in Program R [51]. The 1961–1990 period of historical normals fell predominately within the boreal forest biome with some pixels falling in the tundra or woodland/shrubland biome (Figure 4a). The average of all 31 climate futures and the least warm and wet climate future continued to predominately overlay the boreal forest biome (Figure 4b,c). The most warm and wet climate future has the potential to shift toward climate conditions aligned with woodland/shrubland or temperate seasonal forest biome conditions in the future (Figure 4d). Climate is only one consideration in what vegetation is present at any given timeframe as changes to climate are mediated by many regional factors and time lags such as dispersal constraints.

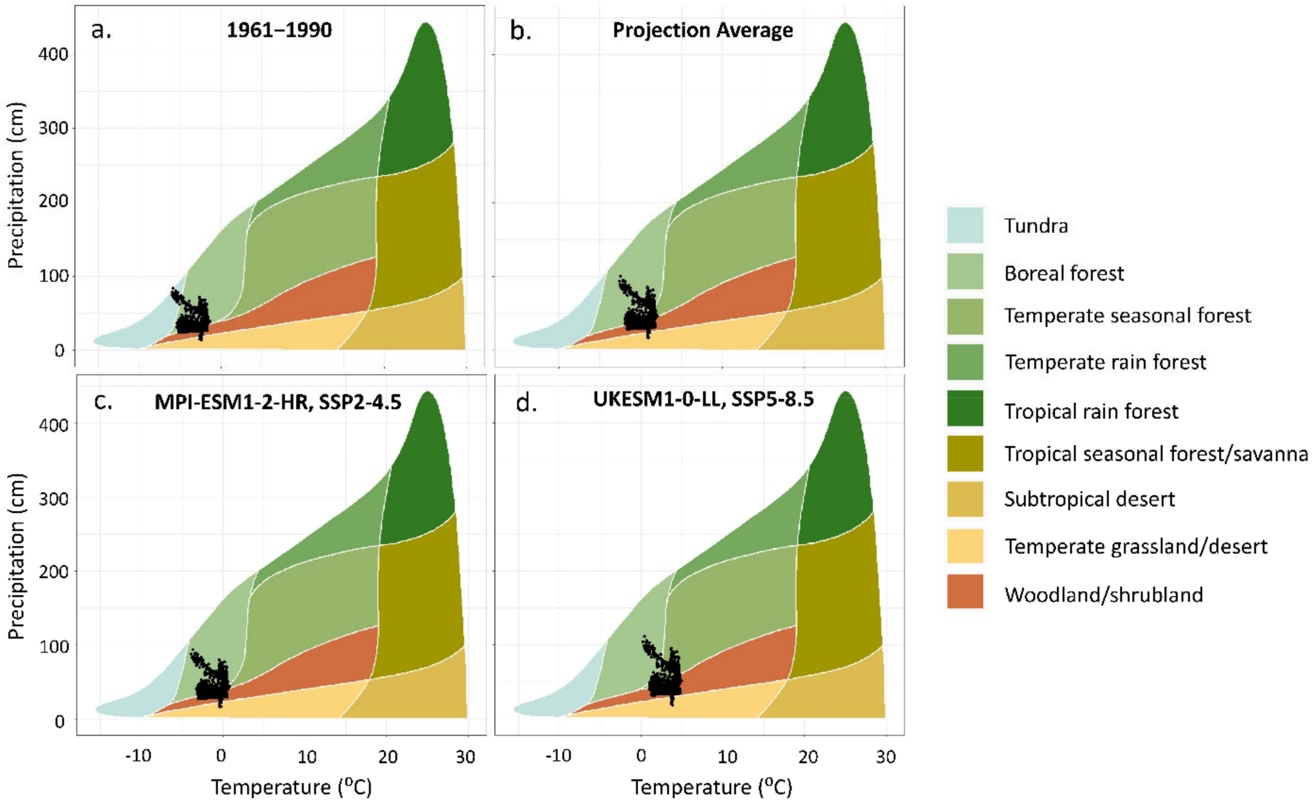

Figure 4. Tetlin National Wildlife Refuge climate space is represented by the pixel values for the average annual temperature (°C) and average annual precipitation (cm). Four Whittaker's biome plots are used to overlay the historical 1961–1990 climate normals (**a**) and 3 climate futures for 2041-2070 in the refuge (black points). The projection average (**b**) is based on 31 climate projections: 9 AOGCMs × 3 emission scenarios (SSP1-2.6, SSP3-7.0, SSP5-8.5) and a 13-model ensemble × 4 emission scenarios (SSP1-2.6, SSP3-7.0, SSP5-8.5). The MPI-ESM1-2-HR, SSP5-4.5 projection (**c**) represents the least warm and wet climate future. The UKESM1-0-LL, SSP5-8.5 projection (**d**) represents the warmest and the wettest climate future.

4.2.2. Climate-Biome Clusters

Climate analogs can be used to explore the ecological functional types and drivers of conditions that occur in places where the historical climate is similar to a climate future. In addition, refuges that may be enduring or resilient to climate change can also be identified to function as regional refugia if they are projected to not change [52–54]. SNAP-EWHALE [55] clustered historical 1961–1990 climate normals in Alaska and Canada and associated these clusters with 18 ecological types that distinguish sub-regional biomes (Climate-Biome Clusters in Table 1). The climate-biome clusters were applied to 4 time steps using 5 General Circulation Models (GCMs) and 3 CMIP3 emission scenarios (Table 1). Eight climate futures (5 individual GCMs × the a1b emission scenario = 5 climate futures; the 5-model ensemble × 3 emission scenarios = 3 climate futures) were used to forecast eight scenarios of climate-biome change. We summarized the climate-biome forecasts by calculating the percent area statistics within Tetlin NWR for each of the eight future scenarios. We calculated the average, minimum, and maximum percent area of Tetlin NWR classified as each climate-biome type at each time step. We compare the historical percent area to the range in the climate-biome forecasts to understand trends. The climate-biome clusters forecast to occur in Tetlin NWR remain boreal associated except for a prairie and a grassland signal that emerges in some GCMs, but never for an area greater than 10% of the refuge (Table 2). Southern boreal types become more common, replacing mixed and densely forested closed-canopy boreal.

Table 1. Three analyses used to assess Continental re-sorting on the Tetlin National Wildlife Refuge with publicly available datasets. Each analysis used different methodologies and climate scenarios. Emission scenarios are listed from low to high.

Analysis	Description	Extent	Emission Scenarios	GCMs	Time Steps	Continental Re-Sorting Signal
Biome Plots	Adaptwest [48] average annual temperature and annual average precipitation were used to summarize divergent climate futures and overlay area of interest on Whittaker's biome plot.	North America—1 km^2 resolution	SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	ACCESS-ESM1-5, CNRM-ESM2-1, EC-Earth3, GFDL-ESM4, GISS-E2-1-G, MIROC6, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL and 13 model ensemble	historical (1961–1990), historical (1991–2020), 2041–2070	Boreal biome; wood-land/shrubland biome
Climate-Biome Clusters	Average monthly temperature and precipitation variables were clustered into 18 climate-biome types forecast climate futures [55].	Alaska and Northern Canada—2 km^2 resolution	b1, a1b1, a2	ECHAM5, GFDL2.1, MIROC3.2, HADLEY3, CGCM3.1, and 5-model average	2010–2019, 2030–2039, 2060–2069, 2090–2099	Southern boreal biome; aspen parkland biome; weaker signal for grassland biome.
Ecoregional Climate Envelop Model	Bioclimatic variables were used to predict and forecast 182 ecoregions in North America [56].	North America—1 km^2 resolution	rcp4.5, rcp8.5	15-model ensemble	Historical (1969–1990), 2041–2070, 2071–2100	Southern boreal; aspen parkland

4.2.3. Ecoregional Climate Envelop Model

We considered the geographic locations of potential climate analogs through a third analysis. Stralberg [56] developed a climate envelop model to predict 182 ecoregions in North America using historical 1961–1990 bioclimatic variables (Ecoregional Climate Envelop Model in Table 1). Ecoregions were forecast to 2041–2070 and 2071–2090 using a 15-GCM ensemble and 2 CMIP5 emission scenarios (rcp4.5 and rcp8.5). Based on 1961–1990 historical climate normals, Tetlin NWR is analogous to the northwestern boreal forest ecosystem in Canada (Figure 5). Model trends suggest that the climate futures for Tetlin NWR shift to conditions that are more similar to boreal forest ecoregions further east and south in the Canadian Provinces of Alberta and Saskatchewan. In all climate futures, the analyses indicate that some areas of Tetlin NWR become more similar to the historical climate conditions associated with the aspen parkland ecoregion in southern Canada and North and South Dakota. The aspen parkland ecoregion consists of aspen patches interspersed with grasslands [57].

Table 2. The average percent area of each biome-climate cluster in the Tetlin National Wildlife Refuge for the historical 1961–1990 climate norms and climate projections to 2010–2019, 2020–2039, 2060–2069 and 2090–2090. Climate projections represent 5 GCMs (ECHAM5, GFDL2.1, MIROC3.2, HADLEY3, and CGCM3) and 3 CMIP3 emission scenarios (b1, a1b, and a2). Eight climate futures (5 individual GCMs × the a1b emission scenario = 5 climate futures; the 5-model ensemble × 3 emission scenarios = 3 climate futures) were used to forecast 8 climate-biome scenarios. The percent area for each scenario at each time steps was calculated. The minimum and maximum percent area across the 8 scenarios is displayed in parentheses under the average percent area and used for interpreting trends across climate futures. Biome-climate clusters represent ecological types that are less broad than the biome types in the biome plot analysis.

Ecological Type	% Area by Time Period					
	1961–1990	2010–2019	2030–2039	2060–2069	2090–2099	Trend
Dry boreal wooded grasslands-mixed coniferous forests and grasses	20%	25% (4–80%)	30% (1–66%)	26% (4–52%)	9% (0–21%)	?
Mixed boreal forest	33%	20% (16–25%)	12% (5–25%)	0%	0%	-
More densely forested closed-canopy boreal	32%	27% (0–46%)	25% (2–64%)	12% (0–28%)	9% (0–18%)	-
Densely forested southern boreal	0%	0%	2% (0–6%)	4% (2–7%)	19% (4–44%)	+
Southern boreal/aspen parkland	14%	27% (7–36%)	33% (3–43%)	48% (6–87%)	69% (53–78%)	+
Southern boreal, mixed forest	1%	3% (1–13%)	3% (1–6%)	14% (0–44%)	0%	?
Prairie and grasslands	0%	0%	1% (0–2%)	1% (0–4%)	5% (1–10%)	+

4.2.4. Continental Re-Sorting Summary

The Tetlin NWR is within the historical (post-glacial) boreal ecoregion, and it has the potential to generally maintain the ecological function of a boreal forest refugia over several refuge planning cycles (15 years). The boreal biome and common boreal tree species are widely distributed across Alaska and Canada. Even though Tetlin is currently, and forecasted to be, broadly associated with the North American boreal forest biome, massive changes to the community assemblage are possible with some future climate analogs identified in scenarios currently occurring over 1000 km away. The analyses considered here are highly uncertain in terms of the actual ecological response to climate change [58]. Species and ecosystems are unlikely to track shifting climate exactly. The models employed by all three analyses only represent an empirical association between limited variables representing the historical climate and current ecosystem distribution. Many other factors influence how species assemblages will actually track their climate niche, such as dispersal events, disturbances, habitat availability, and species interactions [59]. For refugia, adaptive management provides a framework for validating model predictions to increase certainty about management investments [60]. We use these analyses to explore how climate may influence future possibilities and whether human action, such as translocation, could be used to close the gap between the potential and the realized climate niche by accelerating dispersal events.

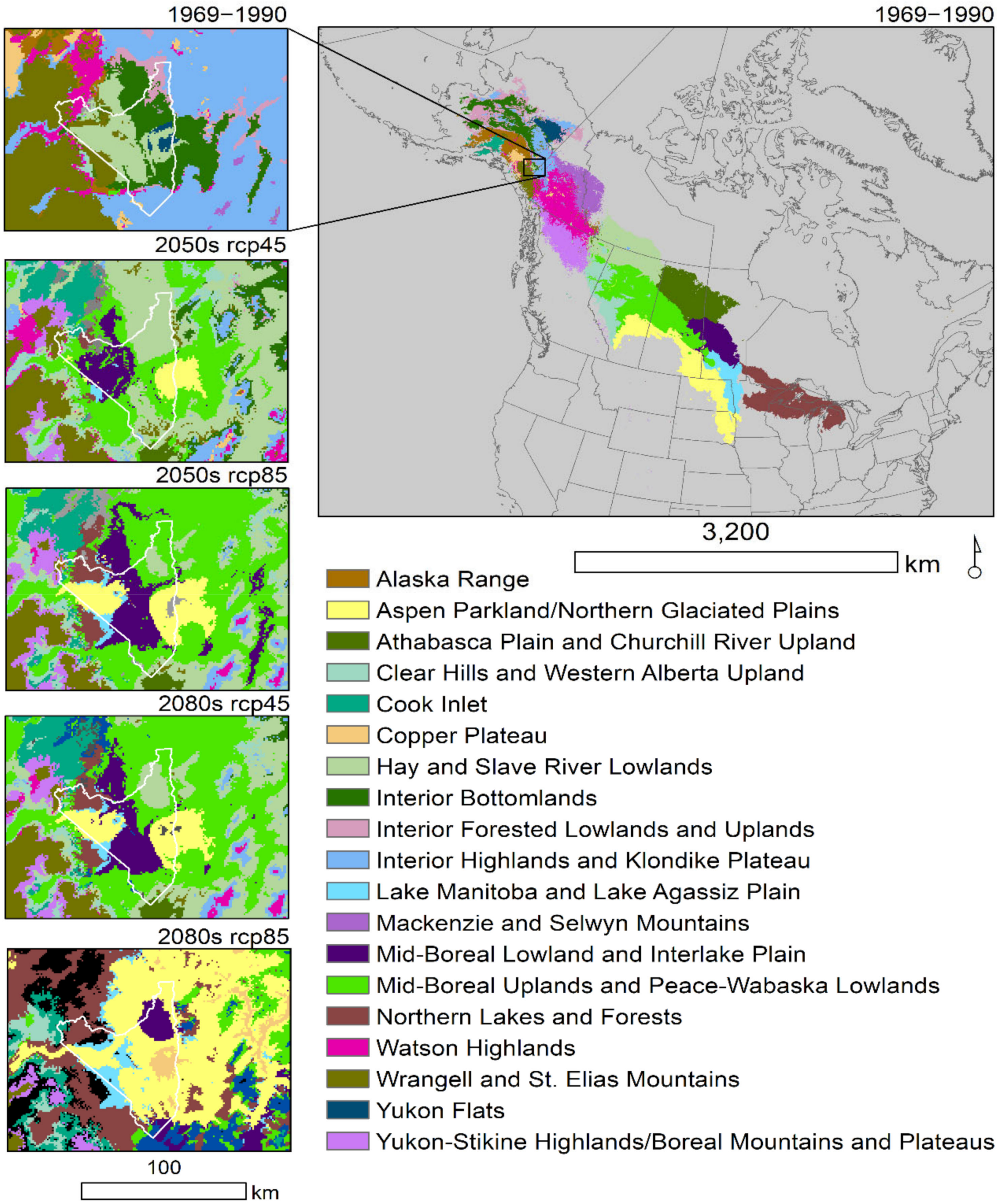

Figure 5. Ecoregional climate envelop model developed by Stralberg [56]. The model is based on bioclimatic variables using the 1961–1990 climate normals and forecast to climate futures in the 2050s and 2080s using CMIP5 rcp4.5 and rcp 8.5 emission scenarios and a 15-model ensemble. The boundary of the Tetlin National Wildlife Refuge, Alaska is the focus of the zoomed in boxes.

4.3. *Plausible Ecological Trajectories on Tetlin NWR*

The boreal forest is broad and climate change scenarios suggest that though the future climate of Tetlin is still associated with the North American boreal biome, changes to boreal forest conditions across the ecoregion will likely occur (see Section 4.2). We conducted a literature review of palaeoecological and contemporary boreal forest trajectories that have been documented in Alaska and Canada to explore how and why forests on the Tetlin

NWR may change. The boreal region has already experienced three major vegetation shifts associated with variable climate conditions in the Holocene. Open deciduous (*Populus spp*) woodlands dominated a warm and dry climate until wetter conditions facilitated a shift to white spruce (*Picea glauca*) dominance ~10,000 years ago allowing seedling recruitment and reducing fire frequency. White spruce shifted to black spruce (*P. mariana*) dominance ~6000 years ago as cooler, wetter climate conditions resulted in cold, waterlogged soils that excluded white spruce [61]. The current boreal forest region remains sensitive to climate change and since the 1970s documented impacts include melting of permafrost and increases in the size, season, and severity of wildfires [24].

In this section, we describe plausible trajectories in terms of the general conditions needed to move toward or to maintain three general ecosystem states: spruce-dominated forest, deciduous-dominated forest, and aspen parkland/grassland/shrubland. We focus on spruce-dominated forest and deciduous-dominated trajectories because they are well-developed in the scientific literature. We explore the aspen parkland/grassland/shrubland trajectories because this signal was found across the continental re-sorting analyses (Table 1). Our intention is not to exhaustively describe all possible ecological trajectories but to provide proof-of-concept for how plausible ecological trajectories are needed to develop RAD pathways. This paper is intended to be a starting point for future engagement with the Alaskan science and management community to better develop a full range of plausible ecological trajectories for the boreal forest.

4.3.1. Spruce-Dominated Boreal Forest Trajectories

The Tetlin NWR is currently dominated by forests (73%) that are predominately composed of black spruce stands (69% of forest). White spruce stands (10%) occur on better-drained south and west facing hills and along the margins of waterbodies where underlying permafrost is limited [62]. These spruce-dominated forests could be maintained, especially in cool, moist, or higher elevation locations [63]. When ecosystems are exposed to directional climate change, pulse disturbances have the potential to trigger ecological transformation [12]. In the boreal region, the timing and intensity of wildfires can profoundly alter the ecological trajectory. After a fire, black spruce forests located on poorly drained and cold sites could continue to self-replace if permafrost and Sphagnum moss cover reduce the likelihood of deep burning and, therefore, maintain the organic layer which consists of moderately decomposed plant material [64,65]. Black spruce recruitment requires uncompromised and abundant aerial seed sources on the site after disturbance [65]. Less frequent and severe fires increase black spruce reestablishment. When the thick organic layers are consumed by fire, permafrost degradation may also accelerate, creating drier conditions that are more suitable for white spruce establishment [66–68]. Therefore, black spruce stands could shift to white spruce if a seed source were available. White spruce establishment will primarily occur in close proximity to a parent tree. Unlike the semi-serotinous cones of black spruce that retain seeds for multiple years in the canopy, white spruce depends on annual seed production for regeneration. Therefore, white spruce is categorized as an off-site colonizer, requiring a seed source from adjacent unburned areas [69].

4.3.2. Deciduous Dominated Forest Trajectories

Across the boreal forest, post fire recruitment of trees and shrubs is an important determinant of the future ecological trajectory and it is largely controlled by the thickness of the soil organic layer. This thickness determines the distance seedling roots need to travel to reach mineral soil and stable moisture, which influences colonization and the dominant vegetation on a site [70]. In the past 30 years, boreal forest fires have become larger with deep burning of the organic layers occurring on well-drained sites and during late season fires [64]. Increased consumption of the organic soil layer can occur with the onset of larger and more severe fires in the boreal ecosystem, exposing seedbed conditions suitable for alterative ecological trajectories, such as conversion of spruce to deciduous stands.

Alaska birch (*Betula neoalaskana*) stands currently occupy 20% of the Tetlin NWR and quaking aspen (*Populus tremuloides*) and balsam poplar (*Populus balsamifera*) trees are present in the landscape [62]. Black spruce forests, currently occupying 69% of the refuge, can shift to deciduous after a high severity fire. This state change from black spruce to deciduous is already occurring in Alaska [71]. Severe fires consume the organic layer and expose mineral soil, where deciduous species can rapidly establish if a seed source is available. Deciduous trees create more litter, which increases nutrient cycling, and it inhibits moss cover. Under these conditions, soils become warmer and drier making deciduous dominance more likely [65]. Eventually stand-level deciduous conversion can reduce the flammability of the landscape creating a fire regime that is more similar to Alberta's boreal mixed wood forests [72]. Deciduous-dominated stand conversion can be a resilient forest type when the fire return interval is less than 50 years because frequent and severe fires exhaust the seed source for black spruce. Mixed forest types are more likely when longer-fire intervals occur, seed-sources are distant (>500 m), and heavy browsing reduces deciduous cover, giving black spruce an advantage [73].

4.3.3. Aspen Parkland/Shrubland/Grassland Trajectories

Open woodlands, shrublands, or grasslands can emerge on warmer, drier sites when spruce and deciduous seed sources are limited or recruitment fails [74]. Across the boreal forests of Alaska and Canada, recruitment failures are already being observed [71]. Aspen parkland is a transitional zone between the prairie and boreal forest that currently occurs in Canada, where potential evapotranspiration exceeds precipitation. After this climate threshold is crossed, southern boreal forests become dry enough to transform into a mixture of aspen forest parkland and grassland [57]. Aspen is more drought tolerant than birch and spruce, and it has the potential to predominate when warmer temperatures cause moisture stress in other tree species, reducing overall forest biomass [63].

A different trajectory to grassland may be possible under conditions that favor bluejoint grass (*Calamagrostis canadensis*) dominance. On wet sites, the tall, sod forming bluejoint grass can quickly dominate the understory when the boreal overstory is removed. Bluejoint occurs as an understory dominant or co-dominant in many early seral to climax riparian and cool, moist forest communities [75]. It often forms dense patches, particularly after disturbances such as fire, logging, spruce beetles, and lowered water levels in wetlands [76]. Bluejoint cannot germinate under drought conditions, but it can survive drought once established. Bluejoint often produces a thick layer of litter that insulates the soil surface, causing the soil temperature to decrease during the growing season [76,77]. These cold soils can have negative effects on the germination of conifer seedlings. Dense bluejoint cover limits conifer regeneration and smothers hardwood seedlings, thereby allowing bluejoint grass to persist [75,76,78]. Prior to spring green-up, the dead plant material that accumulated from the previous year due to the low moisture content and the dry conditions becomes highly flammable. Spring, lightning-caused fires have occurred in contiguous bluejoint on the Kenai Peninsula, indicating that a qualitatively different fire regime could reinforce this grassland type [79].

4.4. RAD Options for the Tetlin NWR

The RAD framework considers how management interventions can shape plausible ecological trajectories. Adaptive management is useful for planning and learning from interventions (or the intentional lack of when accepting change), and adaptive pathway planning can help to visualize futures that are novel, such as directing to an outcome that emphasizes different values or requires institutional change [8,44]. In 2017, Tetlin NWR staff completed the identification of Resources of Concern to prioritize management of individual species, species groups, and systems of greatest importance to the Refuge. Among these, North American moose (*Alces americanus*) were identified as an important resource for multiple user groups, and they are highly prized by subsistence hunters. Moose are obligatory herbivores that consume a variety of woody species across their range, many populations consume 50–99% of their diets from willow (*Salix spp*) [80]. Moose have demonstrated biological adaptations to the chemical characteristics and morphology of their diets, which prevents them from consuming large quantities of unpalatable or undigestible grass and many forbs [80]. Concentration of moose is affected by the availability of early succession forage [81]. Density of moose are generally sporadic in areas with longer fire return intervals because early succession forage in these systems occur primarily along river and stream corridors [82].

We considered RAD options through the lens of opportunities for hunting large mammals, including an option to expand the large mammal assemblage in ecological trajectories that may lower habitat quality for moose. We developed options for two contingencies that are divergence points to alternative futures: severe fire and reburning and recruitment failure. These contingencies can be considered management triggers because the time after they occur provides opportunities to influence the direction of the ecological trajectory. We are in the very early stages of conceptualizing RAD options, and direct strategies are a less well-developed approach. Our intention in the remaining section is to envision examples of how RAD options could be linked to plausible ecological trajectories to demonstrate the potential of using adaptive pathway planning to prepare for opportunities to shape future conditions.

4.4.1. Reburning and Severe Fires

Wildfires in Alaska are projected to increase with climate change [24]. Post fire black spruce seed recruitment and survival that is necessary for forest recovery will be impacted by rising temperatures and water deficits [83]. Reburns and high severity fires could tip forests on the Tetlin NWR toward deciduous-dominated forests or shrub-grasslands if these fires occur before mature conifers have produced the seed needed for regeneration. Twenty-four large fires (>40 hectares) have burned over 78,500 hectares in the Tetlin NWR over the past 80 years (1940–2020). Thirteen areas have reburned since 1989 totaling 4342 hectares, with >90% reburning within 10–30 years (Figure 6). If the acreage of reburned or severely burned fires increases to >25% of the forested area, conversion to early seral, deciduous-dominated forests is highly likely. Accepting this shift, in other words doing nothing, would increase the quantity, and arguably the quality, of moose habitat on the refuge [84], which may be a desirable RAD option. If managers wanted to resist this type conversion, prescribed low-intensity burns and fire-breaks could be used to maintain spruce stands where topographic features and wetlands lower the likelihood of fire spread.

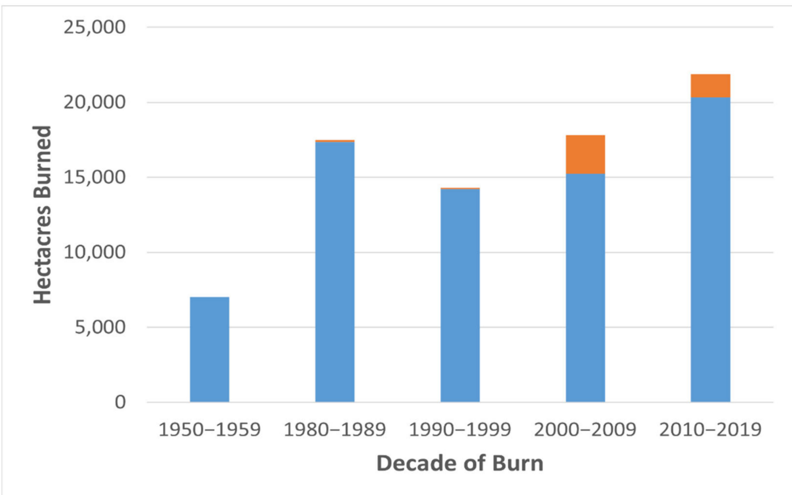

Figure 6. Area burned by decade on the Tetlin National Wildlife Refuge from 1940–2020. The 1940–1949 decade is not included because no fires occurred. Reburned area with <40 years since last burn is orange and mature forest area burned is blue.

4.4.2. Recruitment Failure

Seedlings may fail to establish when the climate shifts beyond their climate niche or when fire characteristics change site conditions. After disturbance, a drought or seed source failure would tip the ecological trajectory toward grasslands. Large contiguous areas of grass establishment could therefore increase the likelihood of the qualitative shift to springtime, high frequency fires that would further reinforce a functional grassland. Accepting this transition would likely reduce habitat quality for moose. This transition could be resisted by planting tree seedlings or disturbing the grass root mass on wet years when tree seedling establishment may be more feasible.

Directing the community assemblage of the grassland would be a novel pathway. The introduction of a functional grazer would reinforce grassland conditions by reducing woody establishment, diversifying the grassland, and providing an alternative hunting experience. Alaska Department of Fish and Game is currently reintroducing wood bison (*Bison bison athabascae*) within its historical range, which includes Tetlin NWR [85]. Cursory evaluation of habitat suitability for wood bison suggests that the current habitat on Tetlin NWR and adjacent lands may support a viable wood bison herd (B. Jamison, pers. obs.). Scenario planning could be used to explore whether a diversified grassland with bison providing hunting opportunities is a desirable outcome for stakeholders. Adaptive pathway planning could be used to explore the timing, barriers, and opportunities for directing this type of landscape change. Adaptive management could be used to test predictive models of carrying capacity and population growth of an introduced herd under new climate realities. There would also be an opportunity to use adaptive management to test the ability of a functional grazer, such as bison, to slow permafrost loss by compacting snow while grazing and therefore allowing the soil to freeze deeper [86]. These experiments would inform adaptive pathway planning on other boreal refuges.

5. Discussion

Our assessment, guided by the blueprint, found that the Tetlin NWR has the potential to remain a boreal forest refugia in terms of ecological function because climate variables remain within what is currently associated with the boreal region in North America. However, future climate conditions may be more aligned with ecoregions further east and south in the Canadian boreal forest. Therefore, the species assemblages of the current ecological communities still have the potential to transform. The severity and the timing of fire will be a key driver of future conditions. The next step for the Tetlin NWR blueprint is to verify information with refuge staff and local stakeholders. This engagement will iteratively improve the knowledge base with place-based observations and local knowledge. Understanding when, where, and how resources may be impacted by climate change is complex and therefore enriched by a diversity of expertise, disciplines, and backgrounds coming to the table to share information. Identifying desirable future conditions and the pathways to those futures will require deliberative engagement and pathway planning exercises.

The RAD framework builds on over a decade of efforts to help natural resource agencies to prepare for managing dynamic and directionally changing ecosystems [14]. Strategies for identifying and for managing refugia, defined as areas where persistence is more likely due to buffering from contemporary climate change, include protecting areas with relatively low climate change exposure, reducing other non-climate stressors and increasing connectivity [52]. Conceptually, refugia can serve as an *in-situ* conservation strategy in which protected areas and ecosystem management are used as strategies to resist change and to maintain current or restore historical conditions [87]. Boreal mountain regions and other boreal forest elements, such as peat-forming wetlands, may serve as refugia for the older spruce-dominated forest that is currently widely distributed [54]. More information and monitoring are needed to identify where local- to landscape-scale refugia may remain in Tetlin NWR.

Maintaining or restoring connectivity amongst protected areas to allow species movement in response to climate change is another well-established strategy. Enduring features, such as topography, can be used to design connected conservation reserves that are relatively resilient to climate change [88]. This strategy, called conserving nature's stage, assumes that biodiversity can ultimately be protected by "conserving the stage for ecological and evolutionary processes" [1,89]. The RAD framework is intended to put explicit focus on whether and how management interventions are used to intentionally shape ecological trajectories [14]. Within the RAD framework, conserving nature's stage would be classified as an accept strategy because species and ecosystems are intended to respond autonomously. Alaska refuges are already using geodiversity to design climate resilient connectivity among conservation areas as part of multi-jurisdictional planning processes [90].

Resist and accept strategies utilize well-established conservation strategies. Several recent reviews of implemented climate change adaptation strategies find that most are business-as-usual and incremental as opposed to transformational. Direct strategies require a paradigm shift that will challenge many institutional preferences for conservation, such as the preference to resist change and natural solutions that maintain humans as separate from nature [14,26]. Transformational climate adaptation, such as direct strategies, often require the decision context of the management system to transform as much as the ecosystem [17,18]. Scenario planning and adaptive pathway planning are still needed internally to explore how agency values and rules constrain or provide opportunities for transformative adaptation.

The blueprint was designed to increase the capacity for resisting, accepting, and directing change in Alaska's refuges. The multi-scale approach and management considerations may be applicable for smaller refuges outside of Alaska and for other land management agencies interested in stewarding biodiversity. The plausible ecological trajectories for smaller refuges will likely be highly influenced by the land use of the surrounding multi-jurisdictional landscape. These anthropogenic drivers can be incorporated into alternative trajectories and the tactical constraints into RAD pathway planning.

Climate change is often viewed as an overwhelming issue where uncertainty can stifle action. Conceptually, uncertainties about the future can never be accounted for fully. GCMs represent a highly constrained set of plausible climate futures and unpredictable futures may emerge [91]. Social-ecological response is also highly uncertain, and it includes the potential for surprise [39]. Within the range of possible outcomes, some futures may be more likely depending on site conditions within the refuge. For example, mechanistic modelling indicates that deciduous-dominated forest is the most likely outcome of accepting ecological change for many areas on the Tetlin NWR [63,73]. However, no future outcome can be predicted with absolute certainty. Shrublands, grasslands, and aspen parklands are less likely outcomes, but they are possible if future conditions mimic the driest climate projection and not the averaged climate projection [68]. Additionally, we cannot predict the timing of contingency events, such as drought and fire, or if a surprising outcome will force reconsideration of how existing models are conceptualized and parameterized. The species assemblage available to respond to change is also highly influential, but colonization events are difficult to anticipate [39]. For example, the empirical ecological shifts in the boreal forest linked to climate change in the Holocene resulted in different ecosystems across the global distribution of boreal forest because the tree species available to fill the opening niche in each region was different [61]. Given the realities of the decision context for climate adaptation, the blueprint presented here focuses on established assessment approaches that can increase preparedness and flexibility to respond to trajectories as they unfold in real time. The blueprint is complementary to many established decision processes such as climate smart and structured decision making [4,92]. Deliberative engagement to build knowledge about ecological transformations and to creatively explore how current management values and rules would need to shift to respond focuses on developing social networks that can creatively explore positive futures.

Alaskan NWRs have been grappling with how to integrate climate change into our planning and management for more than a decade, and many of the most recent plans incorporate some discussion and analysis of climate change. However, we have yet to determine a clear path toward successful implementation of the RAD framework to adapt to climate change. One of the main roadblocks has been that, despite the significant amounts of data and information about climate change, there has been no synthesis of these data into a shared understanding that elucidates how climate change may impact a particular refuge's resources in the future. Creating this decision context is a critical first step in addressing the uncertainty surrounding the future to a degree that allows a refuge to make informed and transparent decisions about whether to resist, accept, or direct ecological transformation.

As we manage for a changing world, we adapt ourselves as well. To date, the success of the NWRS in ensuring "*biological integrity, diversity, and environmental health*" has been measured by comparing a refuge to its "*historic conditions*" (601 FW 3). In Alaska, unlike the contiguous United States, this has meant minimal management of fish, wildlife, and their habitats on refuges. Alaskan NWRs were already naturally diverse, minimally altered landscapes that were very close to meeting the "*historic conditions*" standard. However, the vision, purposes, and management of Alaskan NWRs may themselves need to adapt in light of climate change. While we will no longer be able to claim these vast and diverse landscapes are relatively unaltered from human disturbance, we can resist or direct ecological change. We will have to answer what does "*natural diversity*" mean when ecological transformation is happening at such a rapid pace? How do we maintain biological integrity, diversity, and environmental health when historic conditions are unachievable? These are the fundamental questions that refuges like Tetlin must grapple with in determining whether and how to resist, accept, or direct ecological change on Alaska's NWRs [26]. Our approach for building a shared decision context will push Alaskan NWRs to engage in critical conversations both internally and externally surrounding these questions.

Author Contributions: Based on the CRediT taxonomy, contributions from authors are as follows: conceptualization, D.R.M., R.M., E.Y., D.G. and E.W.; methodology, D.R.M.; formal analysis, D.R.M. and E.Y.; writing—original draft preparation, D.R.M., R.M., E.Y., E.W. and J.L.W.; writing—review and editing, D.R.M., E.W., E.Y., R.M., D.G. and J.L.W.; visualization, D.R.M. and J.L.W.; project administration, D.R.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: AdaptWest Project [48], https://adaptwest.databasin.org/pages/adaptwest-climatena/ (accessed on 30 September 2021); SNAP/EWHALE [56], http://ckan.snap.uaf.edu/dataset/alaska-canada-biome-shift-project-data (accessed on 30 September 2021); and Stralberg [56], https://adaptwest.databasin.org/pages/ecoregion-displacement-and-refugia/ (accessed on 30 September 2021).

Acknowledgments: We appreciate refuge manager Shawn Bayless for encouraging our development of the Tetlin NWR case study. Refuge wildlife biologist Brent Jamison provided feedback and offered insights about the ecology of the Tetlin NWR. Thanks to members of the Resist, Accept, Direct Alaska Refuges (RADAR) group for workshopping earlier versions of the blueprint. Thanks to Charla Sterne and Margaret (Meg) Perdue for helping to organize and facilitate RADAR meetings. Kristine Inman provided helpful feedback on previous drafts. Three anonymous reviewers provided helpful comments to improve the manuscript. Special thanks to Timothy Kittel and Terri Schultz for your substantive comments. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Beier, P.; Brost, B. Use of land facets to plan for climate change: Conserving the arenas, not the actors. *Conserv. Biol.* **2010**, *24*, 701–710. [CrossRef] [PubMed]
2. Hannah, L. A global conservation system for climate-change adaptation. *Conserv. Biol.* **2010**, *24*, 70–77. [CrossRef]
3. Heller, N.E.; Zavaleta, E.S. Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biol. Conserv.* **2009**, *142*, 14–32. [CrossRef]
4. Stein, B.A.; Glick, P.; Edelson, N.; Staudt, A. *Climate-Smart Conservation: Putting Adaptation Principles into Practice*; National Wildlife Federation: Washington, DC, USA, 2014; p. 262.
5. Jones, R.; Patwardhan, A.; Cohen, S.; Dessai, S.; Lammel, A.; Lempert, R.; Mirza, M.Q.; Storch, H.V. Foundations for Decision Making. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects*; Cambridge University Press: New York, NY, USA, 2014.
6. Chapin, F.S., III; Kofinas, G.P.; Folke, C.; Chapin, M.C. *Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World*; Springer Science & Business Media: New York, NY, USA, 2009.
7. Jackson, S.T.; Hobbs, R.J. Ecological restoration in the light of ecological history. *Science* **2009**, *325*, 567–569. [CrossRef]
8. Lynch, A.J.; Thompson, L.M.; Morton, J.M.; Beever, E.A.; Clifford, M.; Limpinsel, D.; Magill, R.T.; Magness, D.R.; Melvin, T.A.; Newman, R.A.; et al. RAD adaptive management for transforming ecosystems. *Bioscience* **2022**, *72*, 45–56. [CrossRef]
9. Cohen, J.M.; Lajeunesse, M.J.; Rohr, J.R. A global synthesis of animal phenological responses to climate change. *Nat. Clim. Change* **2018**, *8*, 224–228. [CrossRef]
10. Sergio, F.; Blas, J.; Hiraldo, F. Animal responses to natural disturbance and climate extremes: A review. *Glob. Planet. Change* **2018**, *161*, 28–40. [CrossRef]
11. Hobbs, R.J.; Higgs, E.S.; Hall, C. *Novel Ecosystems: Intervening in the New Ecological World Order*; John Wiley & Sons: New York, NY, USA, 2013.
12. Harris, R.M.; Beaumont, L.J.; Vance, T.R.; Tozer, C.R.; Remenyi, T.A.; Perkins-Kirkpatrick, S.E.; Mitchell, P.J.; Nicotra, A.B.; McGregor, S.; Andrew, N.R.; et al. Biological responses to the press and pulse of climate trends and extreme events. *Nat. Clim. Change* **2018**, *8*, 579–587. [CrossRef]
13. Schuurman, G.W.; Hoffman, C.H.; Cole, D.N.; Lawrence, D.J.; Morton, J.M.; Magness, D.R.; Craven, A.E.; Covington, S.; O'Malley, R.; Fisichelli, N.A. *Resist-Accept-Direct (RAD)-A Framework for the 21st-Century Natural Resource Manager*; National Park Service: Fort Collins, CO, USA, 2020.
14. Schuurman, G.W.; Cole, D.N.; Craven, A.E.; Covington, S.D.; Crausbay, S.D.; Hoffman, C.H.; Lawrence, D.J.; Magness, D.R.; Morton, J.M.; Nelson, E.A.; et al. Navigating ecological transformation: Resist-Accept-Direct (RAD) as a path to a new resource management paradigm. *Bioscience* **2022**, *72*, 16–29. [CrossRef]
15. Thompson, L.M.; Lynch, A.J.; Beever, E.A.; Engman, A.C.; Falke, J.A.; Jackson, S.T.; Krabbenhoft, T.J.; Lawrence, D.J.; Limpinsel, D.; Magill, R.T.; et al. Responding to ecosystem transformation: Resist, accept, or direct? *Fisheries* **2021**, *46*, 8–21. [CrossRef]
16. Lynch, A.J.; Thompson, L.M.; Beever, E.A.; Cole, D.N.; Engman, A.C.; Hoffman, C.H.; Jackson, S.T.; Krabbenhoft, T.J.; Lawrence, D.J.; Limpinsel, D.; et al. Managing for RADical Ecosystem Change: Applying the Resist-Accept-Direct (RAD) Framework. *Front. Ecol. Environ.* **2021**, *19*, 461–469. [CrossRef]
17. Gorddard, R.; Colloff, M.J.; Wise, R.M.; Ware, D.; Dunlop, M. Values, rules and knowledge: Adaptation as change in the decision context. *Environ. Sci. Policy* **2016**, *57*, 60–69. [CrossRef]
18. Colloff, M.J.; Lavorel, S.; van Kerkhoff, L.E.; Wyborn, C.A.; Fazey, I.; Gorddard, R.; Mace, G.M.; Foden, W.B.; Dunlop, M.; Prentice, I.C.; et al. Transforming conservation science and practice for a postnormal world. *Conserv. Biol.* **2017**, *31*, 1008–1017. [CrossRef]
19. LeDee, O.E.; Handler, S.D.; Hoving, C.L.; Swanston, C.W.; Zuckerberg, B. Preparing Wildlife for Climate Change: How Far Have We Come? *J. Wildl. Manag.* **2021**, *85*, 7–16. [CrossRef]
20. St-Laurent, G.P.; Oakes, L.E.; Cross, M.; Hagerman, S. R–R–T (resistance–resilience–transformation) typology reveals differential conservation approaches across ecosystems and time. *Commun. Biol.* **2021**, *4*, 39. [CrossRef] [PubMed]
21. Berrang-Ford, L.; Siders, A.R.; Lesnikowski, A.; Fischer, A.P.; Callaghan, M.W.; Haddaway, N.R.; Mach, K.J.; Araos, M.; Shah, M.A.R.; Wannewitz, M.; et al. A systematic global stocktake of evidence on human adaptation to climate change. *Nat. Clim. Change* **2021**, *11*, 989–1000. [CrossRef]
22. Kerkhoff, L.V.; Munera, C.; Dudley, N.; Guevara, O.; Wyborn, C.; Figueroa, C.; Dunlop, M.; Hoyos, M.A.; Castiblanco, J.; Becerra, L. Towards future-oriented conservation: Managing protected areas in an era of climate change. *Ambio* **2019**, *48*, 699–713. [CrossRef]
23. Keenan, R.J. Climate change impacts and adaptation in forest management: A review. *Ann. For. Sci.* **2015**, *72*, 145–167. [CrossRef]
24. Markon, C.J.; Gray, S.T.; Berman, M.; Eerkes-Medrano, L.; Hennessy, T.; Huntington, H.P.; Littell, J.; McCammon, M.; Thoman, R.; Trainor, S. Alaska. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment*; Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., Stewart, B.C., Eds.; U.S. Global Change Research Program: Washington, DC, USA, 2018; Volume 2, pp. 1185–1241.
25. Fischman, R.L. The significance of national wildlife refuges in the development of US conservation policy. *J. Land Use Environ. Law* **2005**, *21*, 1–22.
26. Magness, D.R.; Lovecraft, A.L.; Morton, J.M. Factors influencing individual management preferences for facilitating adaptation to climate change within the National Wildlife Refuge System. *Wildl. Soc. Bull.* **2012**, *36*, 457–468. [CrossRef]

27. Rowland, E.R.; Cross, M.S.; Hartmann, H. *Considering Multiple Futures: Scenario Planning to Address Uncertainty in Natural Resource Conservation*; US Fish & Wildlife Service: Washington DC, USA, 2016.
28. Wilkening, J.L.; Magness, D.R.; Harrington, A.; Johnson, K.; Covington, S.; Hoffman, J.R. Incorporating climate uncertainty into conservation planning for wildlife managers. *Earth* **2022**, *3*, 93–114. [CrossRef]
29. Peterson, G.D.; Cumming, G.S.; Carpenter, S.R. Scenario planning: A tool for conservation in an uncertain world. *Conserv. Biol.* **2003**, *17*, 358–366. [CrossRef]
30. Walters, C.J. *Adaptive Management of Renewable Resources*; Macmillan Publishers Ltd.: London, UK, 1986.
31. Williams, B.K.; Szaro, R.C.; Shapiro, C.D. *Adaptive Management: The US Department of the Interior Technical Guide*; Federal Government Series; U.S. Department of the Interior: Washington, DC, USA, 2009.
32. Colloff, M.J.; Gorddard, R.; Abel, N.; Locatelli, B.; Wyborn, C.; Butler, J.R.; Lavorel, S.; van Kerkhoff, L.; Meharg, S.; Múnera-Roldán, C.; et al. Adapting transformation and transforming adaptation to climate change using a pathways approach. *Environ. Sci. Policy* **2021**, *124*, 163–174. [CrossRef]
33. Wise, R.M.; Fazey, I.; Smith, M.S.; Park, S.E.; Eakin, H.C.; Garderen, E.A.V.; Campbell, B. Reconceptualising adaptation to climate change as part of pathways of change and response. *Glob. Environ. Change* **2014**, *28*, 325–336. [CrossRef]
34. Haasnoot, M.; Kwakkel, J.H.; Walker, W.E.; ter Maat, J. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Glob. Environ. Change* **2013**, *23*, 485–498. [CrossRef]
35. Magness, D.R.; Hoang, L.; Belote, R.T.; Brennan, E.J.; Carr, W.; Chapin, F.S., III; Clifford, K.R.; Morrison, W.; Morton, J.M.; Sofaer, H.R. Management Foundations for Navigating Ecological Transformation by Resisting, Accepting, or Directing Social-Ecological Change. *BioScience* **2022**, *72*, 30–44. [CrossRef]
36. Lawrence, J.; Haasnoot, M. What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty. *Environ. Sci. Policy* **2017**, *68*, 47–57. [CrossRef]
37. Ramm, T.D.; Watson, C.W.; White, C.J. Strategic adaptation pathway planning to manage sea-level rise and changing coastal flood risk. *Environ. Sci. Policy* **2018**, *87*, 92–101. [CrossRef]
38. Scheffers, B.R.; Pecl, G. Persecuting, protecting or ignoring biodiversity under climate change. *Nat. Clim. Change* **2019**, *9*, 581–586. [CrossRef]
39. Walker, B.; Salt, D. *Resilience Practice: Building Capacity to Absorb Disturbance and Maintain Function*; Island Press: Washington, DC, USA, 2012.
40. Crausbay, S.D.; Sofaer, H.R.; Cravens, A.E.; Chaffin, B.C.; Clifford, K.R.; Gross, J.E.; Knapp, C.N.; Lawrence, D.J.; Magness, D.R.; Miller-Rushing, A.J.; et al. A science agenda to inform natural resource management decisions in an era of ecological transformation. *Bioscience* **2022**, *72*, 71–90. [CrossRef]
41. Kemp, K.B.; Blades, J.J.; Klos, P.Z.; Hall, T.E.; Force, J.E.; Morgan, P.; Tinkham, W.T. Managing for climate change on federal lands of the western United States: Perceived usefulness of climate science, effectiveness of adaptation strategies, and barriers to implementation. *Ecol. Soc.* **2015**, *20*. [CrossRef]
42. Clifford, K.R.; Yung, L.; Travis, W.R.; Rondeau, R.; Neely, B.; Rangwala, I.; Burkardt, N.; Wyborn, C. Navigating climate adaptation on public lands: How views on ecosystem change and scale interact with management approaches. *Environ. Manag.* **2020**, *66*, 614–628. [CrossRef] [PubMed]
43. Aplet, G.H.; McKinley, P.S. A portfolio approach to managing ecological risks of global change. *Ecosyst. Health Sustain.* **2017**, *3*, e01261. [CrossRef]
44. Magness, D.R.; Morton, J.M. *Implementing Portfolios of Adaptation Strategies on US Conservation Lands in the Anthropocene*; Reference Module in Earth Systems and Environmental Sciences; Elsevier Inc.: San Diego, CA, USA, 2017.
45. Fischman, R. *The National Wildlife Refuges: Coordinating a Conservation System Through Law*; Island Press: Washington, DC, USA, 2003.
46. Schuur, E.A.; Mack, M.C. Ecological response to permafrost thaw and consequences for local and global ecosystem services. *Annu. Rev. Ecol. Evol. Syst.* **2018**, *49*, 279–301. [CrossRef]
47. Staudinger, M.D.; Grimm, N.B.; Staudt, A.; Carter, S.L.; Chapin, F.S. *Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services*; United States Global Change Research Program: Washington, DC, USA, 2012.
48. Adaptwest Project. Gridded Current and Projected Climate Data for North America at 1 km Resolution, Generated using the ClimateNA v7.01 Software (T. Wang et al., 2021) [Data set]. Available online: www.adaptwest.databasin.org (accessed on 30 September 2021).
49. Mahony, C.R.; Wang, T.; Hamann, A.; Cannon, A.J. A CMIP6 ensemble for downscaled monthly climate normals over North America. *Earth ArXiv* **2021**. [CrossRef]
50. Lawrence, D.J.; Runyon, A.N.; Gross, J.E.; Schuurman, G.W.; Miller, B.W. Divergent, plausible, and relevant climate futures for near-and long-term resource planning. *Clim. Change* **2021**, *167*, 1–20. [CrossRef]
51. Whittaker, R.H. *Communities and Ecosystems*; CAB International: Wallingford, UK, 1970.
52. Morelli, T.L.; Daly, C.; Dobrowski, S.Z.; Dulen, D.M.; Ebersole, J.L.; Jackson, S.T.; Lundquist, J.D.; Millar, C.I.; Maher, S.P.; Monahan, W.B.; et al. Managing climate change refugia for climate adaptation. *PLoS ONE* **2016**, *11*, e0159909. [CrossRef]
53. Michalak, J.L.; Withey, J.C.; Lawler, J.J.; Case, M.J. Future climate vulnerability-evaluating multiple lines of evidence. *Front. Ecol. Environ.* **2017**, *15*, 367–376. [CrossRef]

54. Stralberg, D.; Arseneault, D.; Baltzer, J.L.; Barber, Q.E.; Bayne, E.M.; Boulanger, Y.; Brown, C.D.; Cooke, H.A.; Devito, K.; Edwards, J.; et al. Climate-change refugia in boreal North America: What, where, and for how long? *Front. Ecol. Environ.* **2020**, *18*, 261–270. [CrossRef]
55. SNAP-EWHALE. *Predicting Future Potential Climate-Biomes for the Yukon, Northwest Territories and Alaska*; University of Alaska: Fairbanks, AK, USA. Available online: http://ckan.snap.uaf.edu/dataset/alaska-canada-biome-shift-project-data (accessed on 30 September 2021).
56. Stralberg, D. Climate-Projected Distributional Shifts and Refugia for North American Ecoregions [Data Set]. Available online: https://adaptwest.databasin.org (accessed on 30 September 2021).
57. Hogg, E.H.; Hurdle, P.A. The aspen parkland in western Canada: A dry-climate analogue for the future boreal forest? *Water Air Soil Pollut.* **1995**, *82*, 391–400. [CrossRef]
58. Hijmans, R.J.; Graham, C.H. The ability of climate envelope models to predict the effect of climate change on species distributions. *Glob. Change Biol.* **2006**, *12*, 2272–2281. [CrossRef]
59. Urban, M.C. Accelerating extinction risk from climate change. *Science* **2015**, *348*, 571–573. [CrossRef] [PubMed]
60. Barrows, C.W.; Ramirez, A.R.; Sweet, L.C.; Morelli, T.L.; Millar, C.I.; Frakes, N.; Rodgers, J.; Mahalovich, M.F. Validating climate-change refugia: Empirical bottom-up approaches to support management actions. *Front. Ecol. Environ.* **2020**, *18*, 298–306. [CrossRef]
61. Lynch, J.A.; Lloyd, A.H.; Barber, V.; Edwards, M.E.; Bigelow, N.H.; Finney, B.P. Holocene development of the Alaskan boreal forest. In *Alaska's Changing Boreal Forest*; Oxford University Press: London, UK, 2006; p. 62.
62. Pattison, R.; Andersen, H.; Gray, A.; Schulz, B.; Smith, R.J.; Jovan, S. *Forests of the Tanana Valley State Forest and Tetlin National Wildlife Refuge, Alaska: Results of the 2014 Pilot Inventory*; General Technical Report PNW-GTR-967 Portland; U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: Corvallis, OR, USA, 2018; p. 967.
63. Foster, A.C.; Armstrong, A.H.; Shuman, J.K.; Shugart, H.H.; Rogers, B.M.; Mack, M.C.; Goetz, S.J.; Ranson, K.J. Importance of tree- and species-level interactions with wildfire, climate, and soils in interior Alaska: Implications for forest change under a warming climate. *Ecol. Model.* **2019**, *409*, 108765. [CrossRef]
64. Kasischke, E.S.; Turetsky, M.R. Recent changes in the fire regime across the North American boreal region—Spatial and temporal patterns of burning across Canada and Alaska. *Geophys. Res. Lett.* **2006**, *33*. [CrossRef]
65. Johnstone, J.F.; Hollingsworth, T.N.; Chapin, F.S., III; Mack, M.C. Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. *Glob. Change Biol.* **2010**, *16*, 1281–1295. [CrossRef]
66. Schuur, E.A.; Bockheim, J.; Canadell, J.G.; Euskirchen, E.; Field, C.B.; Goryachkin, S.V.; Hagemann, S.; Kuhry, P.; Lafleur, P.M.; Lee, H.; et al. Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *Bioscience* **2008**, *58*, 701–714. [CrossRef]
67. Purdy, B.G.; Dale, M.R.; MacDonald, S.E. The regeneration niche of white spruce following fire in the mixed wood boreal forest. *Silva Fenn.* **2002**, *36*. [CrossRef]
68. Nicklen, E.F.; Roland, C.A.; Ruess, R.W.; Scharnweber, T.; Wilmking, M. Divergent responses to permafrost and precipitation reveal mechanisms for the spatial variation of two sympatric spruce. *Ecosphere* **2021**, *12*, 03622. [CrossRef]
69. Wirth, C.; Lichstein, J.W.; Dushoff, J.; Chen, A.; Chapin, F.S. White spruce meets black spruce: Dispersal, postfire establishment, and growth in a warming climate. *Ecol. Monogr.* **2008**, *78*, 489–505. [CrossRef]
70. Alexander, H.D.; Mack, M.C.; Goetz, S.; Beck, P.S.; Belshe, E.F. Implications of increased deciduous cover on stand structure and aboveground carbon pools of Alaskan boreal forests. *Ecosphere* **2012**, *3*, 1–21. [CrossRef]
71. Baltzer, J.L.; Day, N.J.; Walker, X.J.; Greene, D.; Mack, M.C.; Alexander, H.D.; Arseneault, D.; Barnes, J.; Bergeron, Y.; Boucher, Y.; et al. Increasing fire and the decline of fire adapted black spruce in the boreal forest. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2024872118. [CrossRef] [PubMed]
72. Mann, D.H.; Rupp, T.S.; Olson, M.A.; Duffy, P.A. Is Alaska's boreal forest now crossing a major ecological threshold? *Arct. Antarct. Alp. Res.* **2012**, *44*, 319–331. [CrossRef]
73. Hansen, W.D.; Fitzsimmons, R.; Olnes, J.; Williams, A.P. An alternate vegetation type proves resilient and persists for decades following forest conversion in the North American boreal biome. *J. Ecol.* **2021**, *109*, 85–98. [CrossRef]
74. Starfield, A.M.; Chapin, F.S., III. Model of transient changes in arctic and boreal vegetation in response to climate and land use change. *Ecol. Appl.* **1996**, *6*, 842–864. [CrossRef]
75. Viereck, L.A.; Dyrness, C.T.; Batten, A.R.; Wenzlick, K.J. *The Alaska Vegetation Classification*; Gen Tech Rep PNW-GTR-286; Pacific Northwest Research Station, US Forest Service: Portland, OR, USA, 1992; p. 278.
76. Hogg, E.H.; Lieffers, V.J. The relationship between seasonal changes in rhizome carbohydrate reserves and recovery following disturbance in Calamagrostis canadensis. *Can. J. Bot.* **1991**, *69*, 641–646. [CrossRef]
77. Haeussler, S.; Coates, D. *Autecological Characteristics of Selected Species that Compete with Conifers in British Columbia: A Literature Review*; Land Management Report, Ministry of Forests: Victoria, BC, Canada, 1986.
78. Collins, W.B.; Schwartz, C.C. Logging in Alaska's boreal forest: Creation of grasslands or enhancement of moose habitat. *Alces A J. Devoted Biol. Manag. Moose* **1998**, *34*, 355–374.
79. Hess, K.A.; Cullen, C.; Cobian-Iñiguez, J.; Ramthun, J.S.; Lenske, V.; Magness, D.R.; Bolten, J.D.; Foster, A.C.; Spruce, J. Satellite-based assessment of grassland conversion and related fire disturbance in the Kenai Peninsula, Alaska. *Remote Sens.* **2019**, *11*, 283. [CrossRef]

80. Shipley, L. Fifty years of food and foraging in moose: Lessons in ecology from a model herbivore. *Alces A J. Devoted Biol. Manag. Moose* **2010**, *46*, 1–13.
81. Brown, C.L.; Kielland, K.; Euskirchen, E.S.; Brinkman, T.J.; Ruess, R.W.; Kellie, K.A. Fire-mediated patterns of habitat use by male moose (Alces alces) in Alaska. *Can. J. Zool.* **2018**, *96*, 183–192. [CrossRef]
82. Seaton, C.T. *Winter Foraging Ecology of Moose in the Tanana Flats and Alaska Range Foothills*; University of Alaska: Fairbanks, AK, USA, 2002.
83. Boucher, D.; Gauthier, S.; Thiffault, N.; Marchand, W.; Girardin, M.; Urli, M. How climate change might affect tree regeneration following fire at northern latitudes: A review. *New For.* **2020**, *51*, 543–571. [CrossRef]
84. Joly, K.; Duffy, P.A.; Rupp, T.S. Simulating the effects of climate change on fire regimes in Arctic biomes: Implications for caribou and moose habitat. *Ecosphere* **2012**, *3*, 1–18. [CrossRef]
85. Gardner, C.L.; DeGange, A.R. *A Review of Information on Wood Bison in Alaska and Adjacent Canada, with Particular Reference to the Yukon Flats*; Alaska Department of Fish and Game: Fairbanks, AK, USA, 2003.
86. Macias-Fauria, M.; Jepson, P.; Zimov, N.; Malhi, Y. Pleistocene Arctic megafaunal ecological engineering as a natural climate solution? *Philos. Trans. R. Soc. B* **2020**, *375*, 20190122. [CrossRef] [PubMed]
87. Thomas, C.D.; Hill, J.K.; Ward, C.; Hatfield, J.H. *Facilitating Dynamic and Inclusive Biodiversity Conservation in Britain: An Anthropocene Perspective*; Leverhulme Center for Anthropocene Biodiversity, University of York: York, UK, 2021. [CrossRef]
88. Anderson, M.G.; Ferree, C.E. Conserving the stage: Climate change and the geophysical underpinnings of species diversity. *PLoS ONE* **2010**, *5*, e11554. [CrossRef] [PubMed]
89. Beier, P.; Hunter, M.L.; Anderson, M. Conserving nature's stage. *Conserv. Biol.* **2015**, *29*, 613–617. [CrossRef] [PubMed]
90. Magness, D.R.; Sesser, A.L.; Hammond, T. Using topographic geodiversity to connect conservation lands in the Central Yukon, Alaska. *Landsc. Ecol.* **2018**, *33*, 547–556. [CrossRef]
91. Knutti, R. Should we believe model predictions of future climate change? *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2008**, *366*, 4647–4664. [CrossRef]
92. Runge, M.C.; Grand, J.B.; Mitchell, M.S. Structured Decision Making. In *Wildlife Management and Conservation: Contemporary Principles and Practices*; Johns Hopkins University Press: Baltimore, MD, USA, 2013; pp. 51–72.