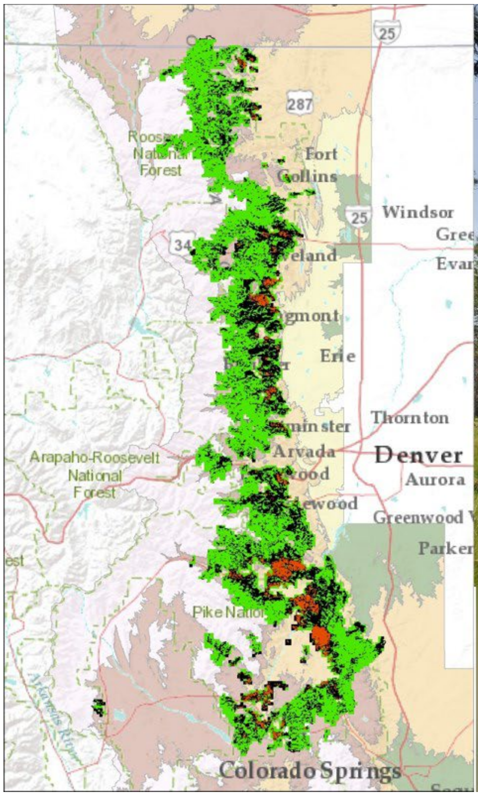
A map package and framework to inform multi-objective management of dry conifer forests along the Colorado Front range:

Report



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Bird Conservancy of the Rockies

Connecting People, Birds and Land

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Bird Conservancy of the Rockies

Connecting people, birds and land

Mission: Conserving birds and their habitats through science, education and land stewardship

Vision: Native bird populations are sustained in healthy ecosystems

Bird Conservancy of the Rockies conserves birds and their habitats through an integrated approach of science, education, and land stewardship. Our work radiates from the Rockies to the Great Plains, Mexico and beyond. Our mission is advanced through sound science, achieved through empowering people, realized through stewardship, and sustained through partnerships. Together, we are improving native bird populations, the land, and the lives of people.

Core Values:

1. **Science** provides the foundation for effective bird conservation.
2. **Education** is critical to the success of bird conservation.
3. **Stewardship** of birds and their habitats is a shared responsibility.

Goals:

1. Guide conservation action where it is needed most by conducting scientifically rigorous monitoring and research on birds and their habitats within the context of their full annual cycle.
2. Inspire conservation action in people by developing relationships through community outreach and science-based, experiential education programs.
3. Contribute to bird population viability and help sustain working lands by partnering with landowners and managers to enhance wildlife habitat.
4. Promote conservation and inform land management decisions by disseminating scientific knowledge and developing tools and recommendations.

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Executive Summary

Anthropogenic impacts have altered western North American dry conifer forests in ways that compromise their ecological structure and function. Forest management agencies engage in active forest management to mitigate these impacts and improve forest resilience. Key processes underlying ecological function and services (hereafter ecological services) operate across broad spatial scales, necessitating coordination across forested landscapes for effective management. Ongoing collaborative efforts aim to inform spatial evaluation and prioritization of dry conifer forest management along the Colorado Front Range. Much of the information generated by these efforts, however, are scattered across multiple sources, challenging integrated application to inform forest planning.

We provide an integrated framework synthesizing spatial information for informing Front Range dry forest management planning in the form of an ArcGIS map package. Our map package integrates spatial projections developed in two separate studies: 1) an initial effort assessing management opportunities for improving wildfire hazard, soil erosion, and landscape heterogeneity in dry conifer forests of the southern Front Range and 2) a subsequent study assessing potential opportunities for improving conditions for avian diversity across the entire Front Range. Our objectives were: 1) to provide an ArcGIS map package, including operational instructions and application guidelines, for displaying and synthesizing predicted management effects on ecosystem services, 2) to guide forest managers on how to apply available spatial predictions to inform landscape-scale prioritization and planning, and 3) to pair and integrate landscape-scale spatial information relevant to management planning and prioritization with resources and information describing best practices for project-scale treatment prescriptions.

We developed a map package that organizes and displays predicted services and additional supporting spatial layers within an interactive ArcGIS framework. We describe map package structure, contents, and operational instructions in this report, along with where and how to access the map package. We also provide guidelines for how and where the map package can be applied to inform planning decisions concerning where to prioritize management efforts for multiple ecosystem objectives. Finally, we summarize current best practices and principles for forest management relevant to development of treatment prescriptions for particular project areas. We distinguish between planning decisions, potentially informed with spatial layers provided in the ArcGIS map package, and treatment prescriptions, best informed with forest restoration principles largely concerned with fine scale forest structure and composition. We provide a worked example further demonstrating application of information provided in this report for both management planning and subsequent treatment development.

Acknowledgements

This report and the accompanying map package are the product of collaboration between the Science and Stewardship teams at Bird Conservancy of the Rockies. We thank the Natural Resources Conservation Service, U.S. Department of Agriculture, Conservation Effects Assessment Project for funding this work (Grazing Lands and Wildlife Component agreement numbers 68-3A75-17-470 and NR203A750023C012, respectively). C. Rewa, L. Metz, J. Feinstein, and R. Truex provided valuable feedback on this report and presentation of spatial layers within the map package. Bird Conservancy of the Rockies implemented avian monitoring, including field surveys and analysis, required for informing the avian community model used to predict management outcomes for birds. We thank the many partners and field technicians of the Integrated Monitoring in Bird Conservation Regions program for providing the foundation for avian monitoring. We also thank R. Sparks, D. Pavlacky, K. Nafziger, T. Woodward, L. Quattrini, C. Latimer, and staff of Bird Conservancy of the Rockies for their support and respective contributions. Bird Conservancy of the Rockies, The Jones Center at Ichauway, and Colorado Forest Restoration Institute supported author time at various stages of this project. We thank B. Calk, I. Routley, and M. Stubblefield for bird photos in the cover image (downloaded from the Macaulay Library, Cornell Lab of Ornithology).

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Introduction

Anthropogenic impacts have altered dry conifer forests of western North America in ways that compromise their ecological structure and function (Brown et al. 2004). The most severely impacted forests include lower montane ponderosa pine (*Pinus ponderosa*) forests and upper montane dry mixed conifer forests (Moir et al. 1997, Schoennagel et al. 2004, Bock and Block 2005, Saab et al. 2005, Hessburg et al. 2007). Fire suppression and forest management have increased vegetation density and homogenized forest structure (Covington and Moore 1992, Agee 1993, Schoennagel et al. 2004). These changes increase the extent and severity of wildfire and bark beetle outbreaks, raising the potential for permanent forest loss or persistent degradation, and threatening key ecological services (Noss et al. 2006b). A warming climate exacerbates these trends (Hurteau et al. 2014, Waring et al. 2009), increasing the urgency for mitigation.

Forest management agencies engage in active forest management to mitigate these impacts and improve forest resilience (Schultz et al. 2012, Addington et al. 2018, Cannon et al. 2018). Active management in dry conifer forests generally aims to reduce canopy and understory density using mechanical thinning and prescribed fire (i.e., fuels reduction), while encouraging large, fire- and drought-tolerant trees like ponderosa pine (Fulé et al. 2012, Agee and Skinner 2005). Forest restoration additionally encourages vegetation structures characteristic of historical forests, including relatively uneven age tree distributions, more extensive canopy gaps, and spatial heterogeneity at multiple scales (Hessburg et al. 2007, North et al. 2009, Churchill et al. 2013, Addington et al. 2018, Cannon et al. 2018). Because these conditions align with the evolutionary histories of species associated with dry conifer forests, ecologists expect restoration to benefit biodiversity more so than treatments narrowly focused on fuels reduction (Noss et al. 2006a, Hutto et al. 2008, Reynolds et al. 2013, Matonis and Binkley 2016).

Key processes underlying ecological function and services (hereafter ecological services) operate across broad spatial scales, necessitating coordination across forested landscapes for effective management. For example, ecologists expect landscape heterogeneity to promote niche diversity and facilitate resource partitioning, resulting in a greater diversity of species supported (Tews et al. 2004). Several federal initiatives fund collaborative, multi-stakeholder frameworks for coordinating forest management across public and private lands (Villar and Seidl 2014, Schultz et al. 2012, Cyphers and Schultz 2019). These initiatives share goals of improving ecological services that transcend ownership boundaries, including water and air quality, wildlife habitat, and ecosystem resilience. Coordinating management across the wildland-urban interface is especially critical for meeting these goals. Lower elevation forests adjacent to and intermixed with human settlement are most impacted by human land use and proportionately the most privately owned (Schoennagel et al. 2009). Numerous landowners with independent and potentially conflicting priorities pose particular challenges for coordinating management in these forests. In order to weigh landowner and programmatic objectives, and to monitor program accomplishments, managers and resource specialists need tools to evaluate and prioritize management opportunities while considering landscape context (Bestelmeyer et al. 2011, Schultz et al. 2012, Stevens et al. 2016).

Ongoing collaborative efforts aim to inform spatial evaluation and prioritization of dry conifer forest management along the Colorado Front Range. Cannon et al. (2020) initially mapped projected benefits with simulated forest management for wildfire hazard, fire-related soil erosion, and landscape heterogeneity in the southern Colorado Front Range (Upper South Platte Watershed). Meanwhile, Latif et al. (2020) documented empirical benefits of restoration treatments on Front Range national forests for bird species richness. Latif et al. (In Review) then extended Cannon et al.'s (2020) simulations to include dry conifer forests across the entire Front Range and mapped expected management implications for birds based on their relationships with canopy cover. Following this line of work, available maps of potential ecological services with Front Range dry forest management include wildfire hazard, soil erosion, landscape heterogeneity, and avian diversity.

Avian model predictions offer especially valuable information for evaluating and planning management of Front Range dry conifer forests. Available data represent multiple species with a broad range of life history traits relevant to various aspects of ecological function (Latif et al. 2020). Furthermore, available models allow us to evaluate management effects for subsets of the community for particular objectives (Latif et al. In Review). Although some managers may prioritize wildfire hazard and soil erosion, these ecological services were universally improved (albeit at spatially varying magnitudes) with simulated management regardless of approach (i.e., restoration versus fuels reduction; Cannon et al. 2020). In contrast, simulated avian community responses depended on management approach, spatial scale, and forest type, and although on average positive, responses were negative in some areas (Latif et al. In Review). Landscape heterogeneity was particularly improved under simulated restoration, but the primary expected value of heterogeneity is to support biodiversity (Cannon et al. 2020), and projected avian responses were not necessarily more positive with restoration compared to fuels reduction, which did not improve heterogeneity (Latif et al. In Review). Thus, we may more effectively inform forest planning by evaluating biodiversity directly rather than evaluating conditions thought to promote biodiversity.

Many studies document positive contributions of environmental heterogeneity to species diversity, but these effects depend strongly on spatial scale (Tews et al. 2004, Weisburg et al. 2014). A substantial body of literature establishes the value of forest restoration principles informed by historical reference conditions for project-scale prescriptions (Reynolds et al. 2013, Addington et al. 2018). Despite limited avian relationships with landscape heterogeneity (Latif et al. In Review), heterogeneity and other structural features at finer scales could influence avian occupancy in Front Range forests. For example, non-uniform tree spacing and retention of coarse woody debris promoted by restoration principles can promote nesting and foraging habitat for some species (Reynolds et al. 1992, Brown et al. 2003). At a project scale, forest management treatments initially focused on fuels reduction, leaving even-aged and spatially uniform tree distributions, and reducing understory vegetation and coarse woody debris (i.e. surface fuels). More recently, treatments incorporate restoration principles by targeting more heterogeneous and historically relevant tree distributions. Considering the strong foundation for applying restoration principles at project scales, we acknowledge the value of restoration treatments to holistically benefit multiple ecosystem services. Nevertheless, broader scale patterns suggest relatively limited value of historical reference conditions to inform planning decisions regarding where to implement treatments and how to vary the intensity of treatments across landscapes.

Considering the differing spatial scales and extents of currently mapped ecosystem services, as well as the differences in spatial patterning of responses to management, we describe an integrated framework for synthesizing spatial information relevant to Front Range dry forest management. Thus, we pursued the following objectives in this report:

1. Provide a GIS map package, including operational instructions and application guidelines, for displaying and synthesizing predicted management effects on avian conservation and other ecosystem services.

2. Guide forest managers on how to apply available spatial ecosystem service predictions to inform landscape-scale prioritization and monitoring of dry conifer forest management along the Colorado Front Range.

3. Pair and integrate landscape-scale spatial information relevant to management planning and prioritization with resources and information describing best practices for project-scale treatment prescriptions.

4. Provide an example of how mapped ecosystem services can contribute to a workflow for resource specialists responsible for outreach, planning, and project development with private landowners.

Map package

General description

To facilitate application of existing maps of ecosystem services with Front Range dry forest management (Cannon et al. 2020, Latif et al. In Review), we developed a map package that organizes and displays predicted services and additional supporting spatial layers within an interactive ArcGIS framework (ESRI 2019). We describe the structure, contents, and operational instructions for this map package here. We mapped model-predicted gains (and losses) in ecosystem services with two simulated active forest management scenarios relative to a passive management (reference) scenario. Simulated active management primarily represented reductions in remotely sensed 30m resolution canopy cover (%) presumed to arise from mechanical thinning. Active management scenarios were 1) a restoration scenario wherein management targets historically referenced spatial distributions of canopy cover and 2) a fuels reduction scenario representing across the board 30% reduction in canopy cover without regard to historical conditions. We compared these scenarios to a passive management scenario representing vegetation structure recorded in 2018. Cannon et al. (2020) and Latif et al. (In Review) comprehensively describe how these scenarios were simulated, the predictive models quantifying ecosystem services (hereafter ecosystem service models), and the application of ecosystem service models to management scenarios. We initially developed the map package described here to display and organize avian metrics and their supporting layers (Latif et al. In Review), and then later included fire hazard and soil erosion where available (Cannon et al. 2020). The map package structure reflects this history, and will like evolve as additional ecosystem services models are included. In this report, we describe and document the map package for users limited in familiarity with ArcMap. Primary spatial layers currently included in the map package are listed and described in Table 1. Primary layers represent groups of sub-layers that together integrate the display of projective ecological responses to simulated management. We describe the structure of group layers and guidelines for navigation in the following subsections.

Table 1. Primary spatial layers appearing in the ArcGIS map package displaying dry forest management implications for ecosystem services along the Colorado Front Range. Many layers listed here consist of group layers (indicated with ‘G’) composed of multiple components. Organization and guidelines for navigating these group layers are provided in the text.

Layer Type	**Spatial layer**	**Description**	**Reference**
Ecosystem service (Avian)	Species richness (G)	Total number of bird species present	Latif et al. (In Review)
	Specialist richness (G)	Number of bird species present that specialize on ponderosa pine forest (*max* = 29)	Latif et al. (In Review)
	Specialist-generalist ratio (G)	The number of ponderosa pine forest specialists divided by the number of generalist species	Latif et al. (In Review)
	Species occupancy (G)	The probability of occupancy for 18 individual species that specialize on ponderosa pine forest and for which available data included ≥ 30 detections	Latif et al. (In Review)
Support (Avian)	Avian model covariates (G)	Covariates used as inputs for modeling avian species occupancy and richness. Individual metrics quantify canopy cover and topography.	Latif et al. (In Review)
Ecosystem service (Fire)	Wildfire hazard (G)	Various metrics from wildfire behavior modeling	Cannon et al. (2020)
Ecosystem service (Erosion)	Soil erosion (G)	Various metrics from post-fire soil erosion models	Cannon et al. (2020)
Ecosystem service (heterogeneity)	Heterogeneity (G)	Two metrics quantify landscape heterogeneity with respect to 10% canopy cover bins: 1) Shannon's evenness index (H) and 2) relative contagion (RC) measuring adjacency of like patches	Cannon et al. (2020)
Support (General)	Hayman Fire	Fire perimeter for the Haman Fire (2002), which was excluded from management simulations	Latif et al. (In Review), Cannon et al. (2020)
Support (General)	Catchments	Analysis units for forest management simulations	Latif et al. (In Review), Cannon et al. (2020)
Support (General)	Life Zones	Ecological setting used to define historical conditions targeted under the restoration scenario.	Kaufmann et al. (2006)

Resolution and geographic extent of ecosystem service layers

Avian ecosystem service layers predict each avian species or community metric (Table 1) at two resolutions: 1) 250 m pixels (15.4 acres) and 2) 1 km pixels (247.1 acres). These two resolutions reflect the scales at which data informing predictions were collected (Latif et al. In Review). Finer resolution predictions (250 m) are nested within coarser resolution predictions (1 km). All avian layers map ecosystem services and predicted management effects across dry conifer forests of the Colorado Front Range, including regions both north and south of Denver.

Non-avian ecosystem services (wildfire hazard, soil erosion, and heterogeneity; Table 1) are quantified at various scales, but management effects quantifying differences with active relative to passive management are summarized at the catchment scale (mean: 1144 acres; range: 101–12,350 acres). The latter represent the layers most directly capable of informing management planning. Non-avian ecosystem services were originally quantified for the southern portion of the Front Range (i.e., the South Platte Watershed; Cannon et al. 2020). Wildfire hazard and soil erosion remain constrained to this relatively limited extent, whereas heterogeneity metrics have since been extended to include the entire Front Range (Latif et al. In Review). Additionally, users may notice a slight difference in southern Front Range catchments represented in wildfire and soil erosion layers versus heterogeneity (and avian) layers. This discrepancy reflects slight differences in 2014 versus 2016 LANDFIRE imagery used to inform catchment filtering (min = 75% catchment-level forest cover) applied by Cannon et al. (2002) versus Latif et al. (In Review), respectively.

Group layers

Considering the number of ecosystem service and supporting layers displayed, the map package organizes individual layers into ‘group layers’ to facilitate management of their display. The display of a group layer can be toggled off and on, and each level within the table of contents can be can be expanded to show the sub-layers within a group.

To toggle a group layer off or on, click the □ box just left of the layer name in the map’s table of contents. Even if they are turned on, sub-layers will not display unless all higher level group layers containing them are also turned on. Additionally, the map’s table of contents is arranged by drawing order, with layers at the top drawn on top of layers listed further down. Thus, you may need to turn off layers that are higher up in the map’s table of contents in order to view layers listed below them in the table of contents.

The table of contents for each group layer can be expanded or collapsed, using the smaller +/- box to the left of the □ box used to toggle the layer on or off. Expanding a group layer allows you to see the sub-layers contained in that group. Click the plus sign to expand a group layer, and the minus sign to collapse it again. Additionally, expanding sub-layers containing predictions or data will reveal a legend indicating how display colors represent the values of a metric. To access a sub-layer in the table of contents, expand all the group layers containing it and the layer itself. After you are finished looking at a particular layer, collapse it (and its parent group layers) again to facilitate navigation of the table of contents and avoid clutter.

Organizational scheme for avian ecosystem service layers:

1. **Metrics:** The primary level of organization for avian group layers is the metric (i.e., Species richness, Specialist richness, Specialist-generalist ratio, and Species occupancy; Table 1). Within the species occupancy group layer, the secondary level of organization distinguishes species, and subsequent levels of organization parallel that of community group layers (Species Richness and Specialist-Generalist Ratio).
    a. **Scale:** The secondary level of organization (tertiary for species occupancy) separates sub-groups by resolution (i.e., Point or Grid). Model predictions are available at the 250-m (15.4 acre) resolution and the 1-km (247.1 acre) resolution. These two scales correspond with spatially nested survey point-level and 1-km grid cell-level predictions, respectively, derived from hierarchical modeling and estimation (see Latif et al. In Review).
        i. **Management Scenario:** The next level of organization distinguishes 'passive management', 'fuels reduction', and 'restoration' scenarios (for details, see **Description** above and Latif et al. In Review). For the passive management scenario, the raster indicated by the primary label (i.e., species richness, specialist richness, species-generalist ratio, or species occupancy) is displayed at the scenario level. For active management scenarios, the scenario level distinguishes additional sub-layers.
            1. **Metric:** For active management scenarios, this sub-layer is the raster quantifying the avian parameter indicated by the primary label (i.e., species richness, specialist richness, species-generalist ratio, or species occupancy).
            2. **Difference from passive management:** For active management scenarios, this sub-layer is a group layer containing two rasters that together quantify the difference in metric values (positive or negative) between the active and passive management scenarios (hereafter difference group).
                a. **Statistically supported difference:** This sub-layer is a raster that delineates areas where the difference from passive management was statistically supported (i.e., the 95% credible interval either excluded zero) and positive (green) or negative (red).
                b. **Difference:** This sub-layer represents the median estimated difference between active and passive management predictions (active minus passive).

Organizational scheme for avian covariate group layers:

1. **Avian model covariates:** Raster layers representing covariates used in the predictive model for avian community metrics are organized together in a single group layer labeled "Avian model covariates".
    a. **Topography covariates:** Rasters for topography covariates (Topographic wetness index and Heatload) are listed at the secondary level within the avian model covariate group.

   b. **Management scenario:** For canopy cover covariates, the secondary level of organization is the management scenarios because canopy cover changed with simulated management.
      i. **Canopy cover covariate:** Rasters for canopy cover covariates (Percent gaps, Percent open forest, perimeter-area ratio of open forest, and percent canopy cover) are listed at the tertiary level. The scale of each covariate (1km or 250m) is labeled in parentheses. For category definitions (gaps, open forest), see Latif et al. (2020, In Review).

Organizational scheme for non-avian ecosystem service layers

1. **Ecosystem service:** The primary level of organization for layers displaying non-avian ecosystem services is the service (i.e., wildfire hazard, soil erosion, and heterogeneity; Table 1).
   a. **Management Scenario:** The secondary level of organization is the management scenario. Scenarios represented are 'passive management', 'fuels reduction', and 'restoration' (for details, see **Description** above and Latif et al. In Review).
      i. **Metric:** The layers depicting the metrics are presented within each management scenario's group layer (for details, see **Description** above and Latif et al. In Review), or within the fire weather type group layers for the wildfire hazard metrics. For the wildfire and erosion metrics, these are raster layers, while for the heterogeneity metrics, these are polygon layers (with the given metric summarized by catchment).
      ii. **Difference layers:** The active management scenarios contain an additional group layer depicting the differences in the metrics between passive management and the given scenario. Unlike the difference layers presented for the avian model predictions (which are rasters), the differences in other (non-avian) ecosystem services are summarized by catchment, and presented as polygon layers
      iii. **Fire weather type (Wildfire Hazard):** Wildfire hazard layers contain two group layers within each management scenario layer corresponding with two different types of weather. "Prescribed fire conditions" refer to minimal winds and moderate fuel moisture, whereas "97th Percentile Fire Weather Conditions" refers to high winds and dry fuels. Each of these fire weather group layers contain raw metrics representing various aspects of fire behavior (Fire Line Intensity, Flame Length, and Crown Fire Activity)

Default display

To facilitate map package navigation, we have set the default display to show ecosystem service layers we anticipate will be of greatest value to the broadest set of users. Specifically, the default display (i.e., the display when first downloaded) shows layers mapping statistically supported changes with forest management in richness of bird species that specialize on ponderosa pine forests. Moreover, the default mapping order places point scale specialist richness changes under the fuels reduction scenario on top, such that this layer will be immediately visible when first opening the map package. We suggest most users start with this layer, and then navigate to other layers according to their planning questions and objectives. Additional guidance on matching individual layers to particular objectives is provided below.

Troubleshooting

If you have trouble viewing a layer, check the following:

1. your map Table of Contents is set to view by 'drawing order', (the left-most box under the words Table of Contents),
2. all group layers that contain the target layer are switched on,
3. all layers above the target layer within the same group are switched off, and
4. all group layers above the target layer in the table of contents (i.e., in drawing order) are switched off.

Importing and exporting layers

If you are interested in creating a map visualizing a particular study area for analysis, publication, or presentation, you may wish to add layers to the map (e.g., a layer delineating your study area) or export layers from the map package to a different map. You can add additional data layers to the map as needed, manipulate the extent, etc. Alternatively, you can export any of the raster layers contained in this map package so that it can be added to another map. To export a layer:

1. Expand all group layers that contain the layer you want to export.
2. Right click on the name of the layer of interest.
3. From the drop-down menu that appears, click 'data'. From the next menu, click 'export data'.
4. In the lower right region of the dialog box, click the folder button to choose the output location for your dataset.
5. Choose a name for your exported dataset, and a format if you wish.

Access and metadata

The map package and associated files are available here as a zipped folder (please be advised, the file is 1.7 GB, and may take some time to download). ArcGIS (ESRI 2019) is required to view and operate the map package. Detailed metadata for all spatial layers in the map package are included as an excel file bundled with the map document and this report in the zip file. The zipped folder will also contain a .pdf version of Cannon et al. (2020) and Latif et al. (In Review), which provides a detailed explanation of the modeling effort used to generate the predicted metrics contained in this map package.

Crediting modeling results:

For permission to distribute spatial files mapping ecosystem services from this map package, please contact Quresh Latif (quresh.latif@birdconservancy.org) for avian layers or Jeff Cannon (jeffery.cannon@jonesctr.org) for non-avian layers. If you would like to present the data in published maps or presentations, please cite the data as Latif et al. (In Review) or Cannon et al. (2020), respectively.

Landscape-scale planning

Considering the resolution of ecosystem service data layers and reliance on remotely sensed canopy cover for simulating management effects, we consider the map package (described above) primarily applicable for informing landscape-scale planning and monitoring. We use the term "planning" to refer to decisions concerned primarily with where on the landscape to pursue forest management focused on thinning or reducing forest vegetation (especially tree) density. In contrast, much of established guidelines, principles, and practices for forest restoration concern project-scale forest conditions, such as tree sizes, species, and spatial distributions to target with thinning and prescribed fire prescriptions (Addington et al. 2018). Distinguishing landscape-scale planning from project-scale prescriptions (*sensu* Figure 12 in Addington et al. 2018) is critical to appropriately apply information in our map package and this report. A substantial body of literature establishes the value of historical reference conditions for informing project-scale management prescriptions aimed at forest restoration (Larson et al. 2012, Brown et al. 2015). At landscape scales, however, planning targets do not necessarily need to include historical reference conditions for management to improve some key ecosystem functions (e.g., Cannon et al. 2020, Latif et al. In Review). We therefore focus first on describing appropriate application of the map package to inform landscape-scale planning and monitoring, and then subsequently review principles of forest restoration for designing treatment prescriptions (see **Project scale treatment prescriptions**).

Geographic and environmental extent

Our map package and suggested planning framework currently apply solely to dry conifer forests of the Colorado Front Range, including both public lands managed by the U.S. Forest Service (Pike, Arapaho, and Roosevelt National Forests) and non-industrial private forests (Figure 1). We recognize two primary forest types within this extent. At lower elevations, ponderosa pine forests are historically characterized by low densities of large, uneven-aged, and patchily-distributed ponderosa pine trees interspersed with openings containing extensive components of grasses, forbs, and shrubs maintained by frequent, low-severity wildfire (Kaufmann et al. 2001). Dry mixed conifer forests occur at somewhat higher elevations and latitudes, where moister conditions have supported higher tree densities and historically favored less frequent, mixed-severity wildfire (Battaglia et al. 2018), conferring greater heterogeneity at landscape scales (Malone et al. 2018). These two forest types occur within the lower and upper montane life zones, respectively (Kaufmann et al. 2006), delineated in the Life Zone layer included in the map package (Table 1). Contemporary conditions include substantial components of Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), limber pine (*Pinus flexilis*), aspen (*Populus tremuloides*), and juniper (*Juniperus* spp.), with Englemann spruce (*Picea engelmannii*), blue spruce (*P. pungens*), and subalpine fir (*Abies lasiocarpa*) as secondary components at upper elevations (Kaufmann et al. 2001, Underhill et al. 2014). The map package and framework presented here are not applicable to other vegetation types, such as riparian systems or higher elevation subalpine forests.

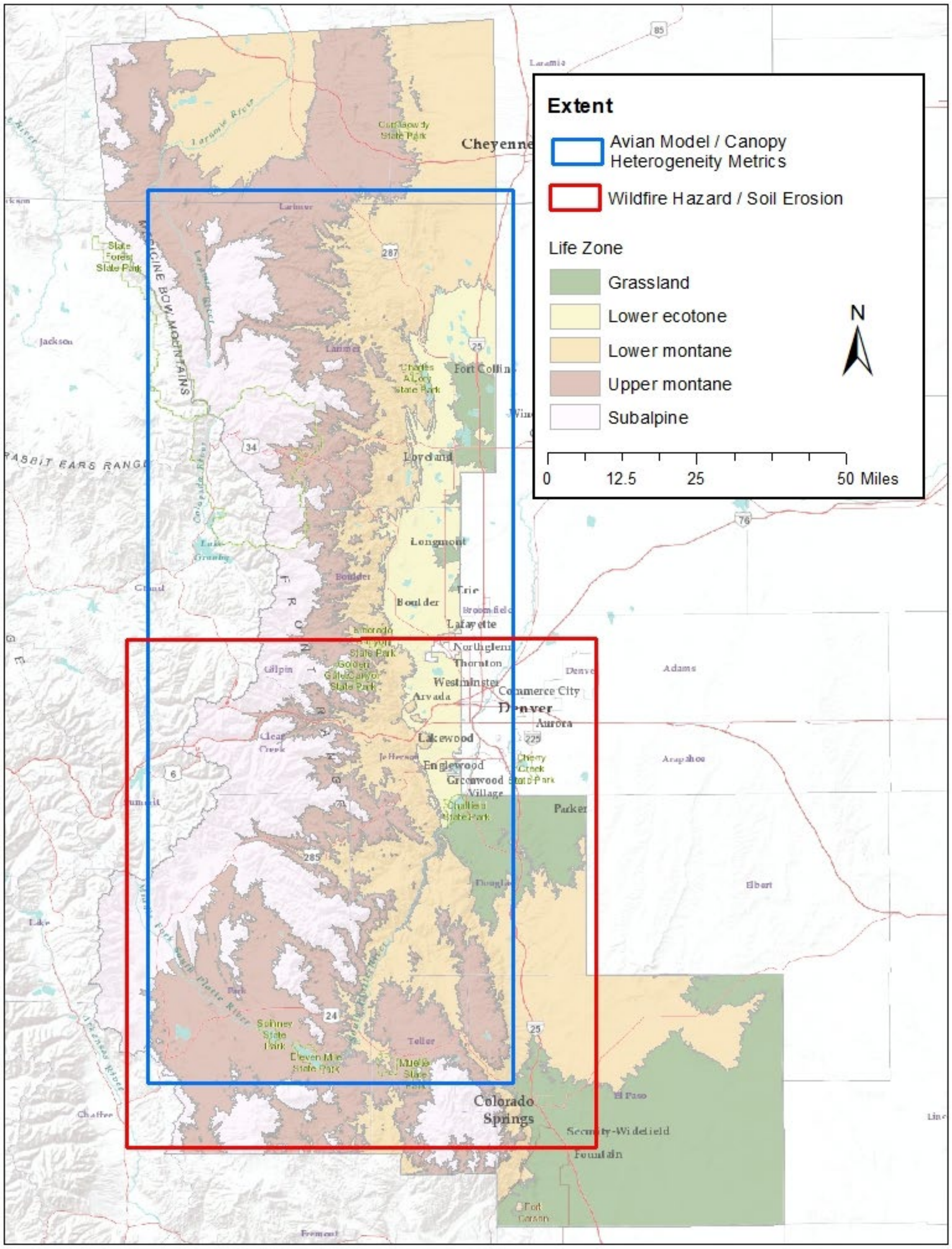

Figure 1. Extent of ecosystem service metrics included in the map package.

Matching focal metrics with management objectives

Where and how spatial data provided in our map package can inform forest planning will depend on management objectives. Depending on the region of interest, available data layers can inform forest planning objectives that include wildfire, soil erosion, avian diversity, and/or landscape heterogeneity

(Figure 1). While broad in scope, these ecosystem services are by no means comprehensive, and available layers are even more limited in the northern Front Range (Figure 1). Managers may therefore wish to include supplemental spatial data representing additional ecosystem services (e.g., air quality or other components of biodiversity) into the map package to maximally inform their planning. For cases where spatial data are unavailable for mapping key ecosystem services, managers may need to assume some synergy among objectives to inform their planning. For example, treatments that reduce canopy cover and promote open forest conditions (10–40% canopy cover) generally benefit both fire-related ecosystem services and forest bird diversity (Cannon et al. 2020, Latif et al. In Review). Thus, we can be confident that management for the northern Front Range informed primarily by projected avian responses will also likely improve fire-related ecosystem services. Nonetheless, areas where management will most benefit avian diversity do not necessarily coincide with areas with greatest potential for management to improve fire-related ecosystem services (Table 2). We therefore encourage managers to seek out spatial data quantifying their priority objectives or work with researchers to generate such data to best inform planning.

For each ecosystem service represented in our map package, we provide several data layers that managers can choose from to inform forest planning (see Table 1 for broad overview; see metadata described under **Access and metadata** for detailed descriptions). Available layers quantify 1) model-predicted ecosystem service metrics under alternative management scenarios (hereafter metric layers) and 2) differences in predicted metric values with active management scenarios (i.e., fuels reduction and restoration) compared to passive management (hereafter response layers; all response layers include “difference” in their labels). We expect response layers will most directly inform planning, whereas metric layers can provide reference and context to understand predicted management responses.

Response layers represent projected ecological outcomes at various resolutions, with implications for how they can inform planning. Wildfire hazard, soil erosion, and heterogeneity layers map responses to management at a relatively coarse catchment resolution (mean: 1144 acres, range: 101–12,350 acres). Avian layers quantify species and community responses at both coarse (247 acres) and fine (15.4 acres) resolutions. Moreover, coarse-scale avian predictions (247 acres) represent avian relationships with canopy cover metrics assessed over a larger neighborhood (776 acres; for modeling details, see Latif et al. In Review). Projected responses at finer scales will likely be interpretable as expected management outcomes of individual projects (depending on project size), whereas coarser scale projections more so represent potential contributions of management to larger landscape units (i.e., expected outcome if the entire catchment, pixel, or pixel neighborhood were treated).

Table 2. Pearson's correlation coefficients relating projected avian community responses to management with non-avian ecosystem service responses (heterogeneity, soil erosion, and wildfire hazard). Correlated responses were summarized for watershed catchments in the southern Front Range where both avian and non-avian responses were assessed (*n* = 253). The metadata table accompanying this report (see **Access and metadata**) provide complete descriptions of all ecosystem service metrics represented here.

Scenario	**Avian metric (scale)**	**Heterogeneity**		**Erosion (3 year)**	**Wildfire hazard**		
		H[a]	**RC[b]**		**Surface**	**High severity**	**Integrated fire hazard**
Fuels reduction	Species richness (247 ac)	-0.39	0.38	-0.33	0.32	-0.23	-0.38
	Species richness (15 ac)	-0.32	0.35	0.43	-0.12	0.53	0.39
	Specialist richness (247 ac)	-0.33	0.32	-0.40	0.34	-0.30	-0.44
	Specialist richness (15 ac)	-0.26	0.25	-0.58	0.37	-0.47	-0.59
	Specialist-generalist ratio (247 ac)	0.00	0.02	-0.48	0.32	-0.43	-0.50
	Specialist-generalist ratio (15 ac)	-0.16	0.15	-0.64	0.37	-0.53	-0.65
Restoration	Species richness (247 ac)	0.58	-0.53	0.05	0.16	-0.09	0.07
	Species richness (15 ac)	-0.31	0.37	0.65	-0.17	0.59	0.73
	Specialist richness (247 ac)	0.67	-0.64	-0.29	0.28	-0.35	-0.35
	Specialist richness (15 ac)	0.70	-0.63	-0.15	0.21	-0.26	-0.12
	Specialist-generalist ratio (247 ac)	0.47	-0.50	-0.63	0.33	-0.55	-0.77
	Specialist-generalist ratio (15 ac)	0.70	-0.67	-0.41	0.28	-0.44	-0.45

[a] H = Landscape diversity index (Shannon and Weaver 1963)

[b] RC = Relative contagion index (Li and Reynolds 1993) is inversely related with heterogeneity.

We accommodate additional flexibility in planning objectives by mapping projected responses of various aspects of individual ecosystem services to management. For wildfire hazard, we project outcomes with respect to extent of high severity fire, area available for prescribed fire, and an integrated metric that indexes overall wildfire behavior. We expect the integrated metric to serve most management targets that include generally desirable fire behavior, but specific attributes of wildfire behavior are also available for customized applications. For avian diversity, we map projected responses for three avian community metrics and occupancy probabilities for 18 species strongly associated with ponderosa pine forests. Considering the particularly acute management concerns for lower elevation forests dominated by ponderosa pine, we expect richness of ponderosa pine forest specialists to most often align with biodiversity objectives. Considering the likelihood of the ponderosa pine range moving up in elevation with warming temperatures, management targets may include ponderosa pine and associated species even in the upper montane life zone. Nevertheless, we provide additional avian metrics to allow flexibility in biodiversity objectives, and the model used to generate avian predictions allows an even greater range of projections beyond those provided in the map package (Latif et al. In Review). We encourage map package users to closely review descriptions of available response layers to ensure the most appropriate application and interpretation for their particular planning objectives (see metadata described in **Access and metadata**).

Most contemporary forest management programs aim to holistically improve dry conifer forest ecological function by targeting multiple objectives and ecosystem services. Our map package provides the means for synthesizing spatial projections for multiple ecosystem services to inform planning within Colorado Front Range dry conifer forests. Managers could simply identify areas where management is projected to maximally benefit individual ecosystem services, and then identify where such areas intersect across ecosystem services. To integrate a large number of data layers while navigating tradeoffs among ecosystem services, more formal tools for systematic management planning may be necessary (e.g., Lehtomäki et al. 2009, Kukkala and Moilanen 2013, Pohjanmies et al. 2019). Regardless, overlaying spatial projections of expected responses by key ecological attributes to management provides the basis for integrating multiple planning objectives. We provide an example demonstrating application of the map package to inform forest planning in Appendix A.

Management scenarios

For appropriate application of the map package, users need to decide whether to inform forest planning with data layers representing the "fuels reduction" or the "restoration" scenario. Fuels reduction simulates an across the board percentage reduction in canopy cover, whereas restoration represents landscape-scale canopy cover targets that approximate historical reference conditions. Thus, under fuels reduction, simulated canopy cover is more uniformly moderate (20–40%), whereas the restoration scenario simulates a landscape more extensively characterized by relatively low canopy cover (0–20%), particularly on south-facing slopes and in the lower montane life zone. The scenario most appropriate to inform planning is the one that best approximates the expected effect of management treatments on landscape-scale canopy cover. Management expected to moderate canopy cover relatively uniformly across the landscape will be best informed by the fuels reduction scenario, whereas management that includes treatments of sufficiently varying intensity to generate or extend large canopy gaps (i.e., areas ≥ 15 acres of low canopy cover) may be better informed by the restoration scenario.

We stress that management scenarios in the map package are intended to represent a range of potential approaches and our uncertainty in management outcomes for landscape-scale canopy cover. As such, we do not recommend designing treatment prescriptions to match simulated scenarios. Rather, planners should reference simulated scenarios that best approximate intended management. Counterintuitively, we expect the simulated restoration scenario to be inappropriate for most contemporary forest management, including projects that incorporate fine scale restoration principles and practices into their treatments (e.g., uneven tree species, age, and spatial distributions). Considering the logistical and political infeasibility of intensive thinning necessary to generate or extend canopy gaps (Cannon et al. 2018), much forest management likely resembles the fuels reduction scenario or something in between fuels reduction and restoration scenarios (Barrett et al. 2021).

Scenario applicability may also depend on life zone. In the upper montane life zone, a 30% reduction in canopy cover represented in the fuels reduction scenario may be inappropriate considering the higher levels of vegetation density historically characteristic of forests there. Moreover, by explicitly targeting historical conditions, the restoration scenario entailed less intensive thinning and therefore may approximate management better in the upper montane compared to the lower montane zone. In practice, neither scenario may exactly match intended management targets. Nevertheless, response layers can inform planning decisions in so far as management outcomes for landscape canopy cover fall somewhere along the spectrum defined by simulated fuels reduction and restoration scenarios.

Project-scale treatment prescriptions

At finer scales (i.e. project and treatment unit), the term “fuels reduction treatment” implies a singular goal of altering forest structure to reduce wildfire hazard and the risk of active crown fire. Typically, the above goals are achieved through reducing ladder and surface fuels, and increasing canopy base heights and tree crown spacing (Agee and Skinner 2005). The singular focus of fuels treatments may result in homogenous stand conditions that lack structural diversity (Addington et al. 2020, Larson and Churchill 2012). Fuels reduction treatments may explicitly aim to reduce habitat features that are important for wildlife, such as coarse woody debris and herbaceous forage.

As with fuels reduction, forest restoration treatments reduce wildfire risk and encourage more desirable wildfire behavior, but they also further a broader suite of ecological goals. In particular, including restoration principles in management treatments furthers wildlife conservation goals by explicitly targeting ecological features and processes that support and enhance wildlife habitat. Restoration principles can be included in any treatment to whatever extent is feasible to increase benefits for broader ecological function.

We conducted a literature review and compiled information on forestry practices that reflect restoration principles and enhance wildlife habitat. The resulting guide (Appendix B) is intended for use after landscape-scale planning has been completed. This guide is intended to assist in treatment unit layout, prescription development, and tree marking. The information in this guide can inform treatments in conjunction with other considerations, such as historical reference conditions, landowner/public priorities, and safety (e.g. snag locations).

Future directions

We envision several potential avenues for expanding on tools presented here to improve and consolidate information for dry conifer forest planning. First, developing and adding data layers projecting management outcomes for additional ecosystem services could broaden the utility of the map package and mapping framework. For example, data layers mapping benefits for air quality or additional components of biodiversity (e.g., mammals, predators, or grassland birds), or management costs would likely add substantial value to the map package. With additional layers, tools to facilitate formal synthesis of data layers (e.g., calculation of a weighted summary of benefits) could also improve utility. Geographic extensions could expand applicability of the mapping framework by allowing development of map packages for other regions facing similar management concerns. Formal engagement with forest management professionals facilitated with decision science tools could help weigh potential costs and benefits for the various possible extensions (Sutherland et al. 2011).

Along with geographic and data extensions, automation of the spatial simulation and analysis process would help facilitate application of the mapping framework with ongoing landscape change. The density, distribution, and composition of dry conifer forests are continually changing with wildfire, ongoing climate change, and forest management. ArcGIS provides the means of automating simulation of management scenarios and application of ecosystem service models to map projected management costs and benefits in the form of ArcTools. We envision incorporating existing spatial analysis scripts into an ArcToolbox that would allow users to plug in updated canopy cover (and any other needed data layers) to automatically update projections for ecosystem service responses to management. Such automation would facilitate updates to spatial prioritization of forest management effort. Automation of our mapping process would also facilitate the related activity of landscape-scale monitoring. By tracking landscape change through the lens of projected ecosystem services and opportunities for management, resource professionals could update their planning while simultaneously evaluating where and how management has successfully improved ecological function.

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Appendices

Appendix A – Map package application example

We demonstrate the use of the map package as a landscape prioritization tool by identifying high priority properties where forestry treatments could increase ponderosa pine forest bird diversity. We sought to identify relatively large properties or contiguous sections of private land that overlap areas with the greatest predicted increases in richness of ponderosa pine forest specialist species. We additionally favored properties adjacent to contiguous areas of public land with potential for cross-jurisdictional projects. Considering our primary interest in promoting open forest conditions to support bird diversity rather than creating or extending large canopy gaps (even where historically appropriate), we referenced spatial layers representing the "fuels reduction" scenario. We also verified projected improvements for wildfire behavior and wildfire-related soil erosion with management at identified properties.

Planning steps:

1. Display the following layer – PIPO Specialist Richness > Point Level (250m) > Fuels Reduction Scenario > Difference from no action > Statistically supported difference
2. Add layers showing public and private land ownership, including individual parcels.
3. Zoom to a scale fine enough to recognize individual property boundaries (1:150,000 scale maximum).
4. Visually identify broad areas with high predicted increases in ponderosa pine specialist species richness. With the current map symbology, these will be large, green swaths of the priority surface.
5. Display other ecosystem service layers. Here we used Integrated Fire Hazard and Post-fire Sedimentation. Wildfire Hazard > Fuels Reduction Scenario > Differences From Passive Management > Integrated Fire Hazard (Index). Soil Erosion > Fuels Reduction > Difference from passive management, Sedimentation Delivery (3 years post fire).
6. Visually check how well other ecosystem services align with the priority area created from PIPO Specialist Richness.
7. Zoom to the priority area until individual properties are easily discernable (approximately 1:50,000 scale).
8. Visually identify large, contiguous areas of private property that overlap the priority areas. Display ecosystem services again to visually check how well they align with priority properties identified from avian models.
9. Contact producers and conduct outreach, using maps of priority surface as an outreach tool.
10. If producers are interested, conduct site visit to determine existing conditions on the ground. Use model scenarios in combination with forest inventory to determine type of treatment.
11. Contact any neighboring land management agencies to determine potential for cross-jurisdictional treatments.

The above steps led us to a focal area in the northeastern corner of the county. A finer scale inspection identified two large properties overlapping high priority areas. These properties are a girl scout camp and a Christian camp, 880 acres and 600 acres respectively. Both properties are adjacent to National Forest on multiple sides. They have good access to a state highway and appear to contain relatively low-angle terrain. The next steps will be to contact producers, using priority mapping as an outreach tool to communicate the need for treatments. If work ensues, we will apply restoration principles and best practices (see Appendix A) and consider stand conditions determined during site inventory to inform treatment prescriptions. Primary treatment goals will likely include reducing canopy cover to approximately 10%-40%, introducing fine-scale spatial heterogeneity, and maintaining relatively large ponderosa pine trees.

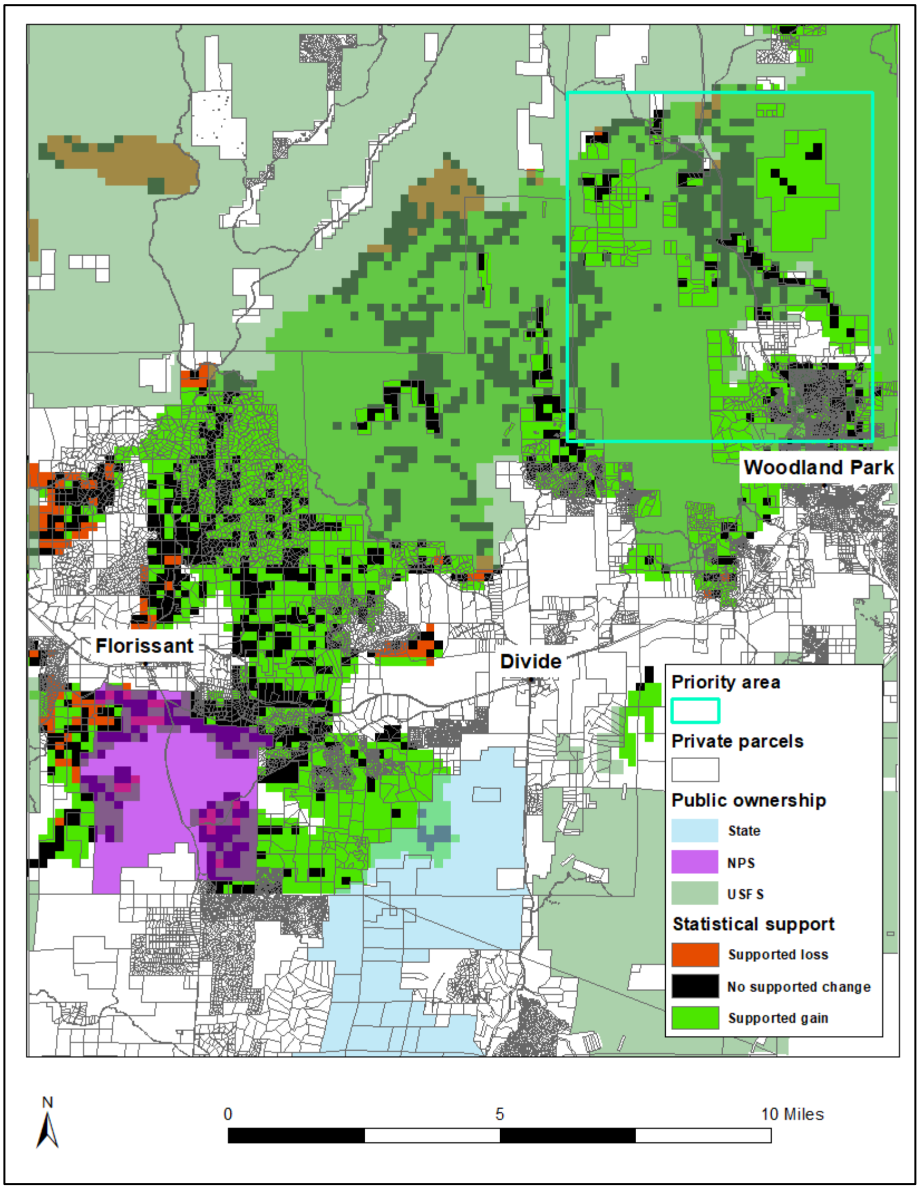

Figure B1. For the initial step, we displayed the predicted change in PIPO specialist richness and land ownership layers at a scale where individual properties are visible, in this case the northern half of Teller County (1:125,000). In this map the turquoise polygon represents a priority area that, based on visual inspection, contains some of the greatest predicted increases across the largest area. Additionally, the priority area contains large properties and is adjacent to National Forest.

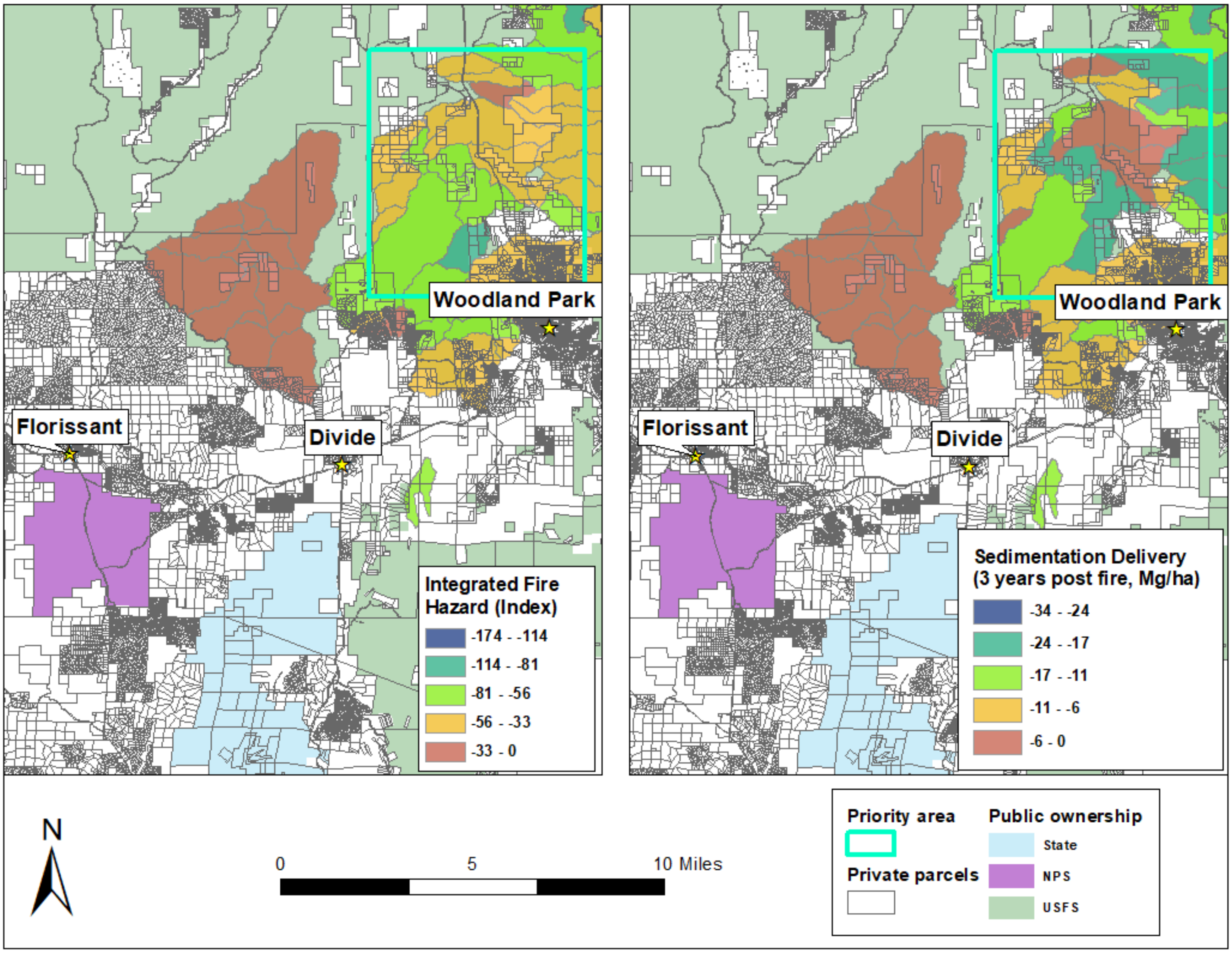

Figure B2. We also display the difference from passive management for wildfire hazard and post-fire sedimentation. There are predicted reductions in both metrics within the priority area, with particularly great reductions in post-fire sedimentation.

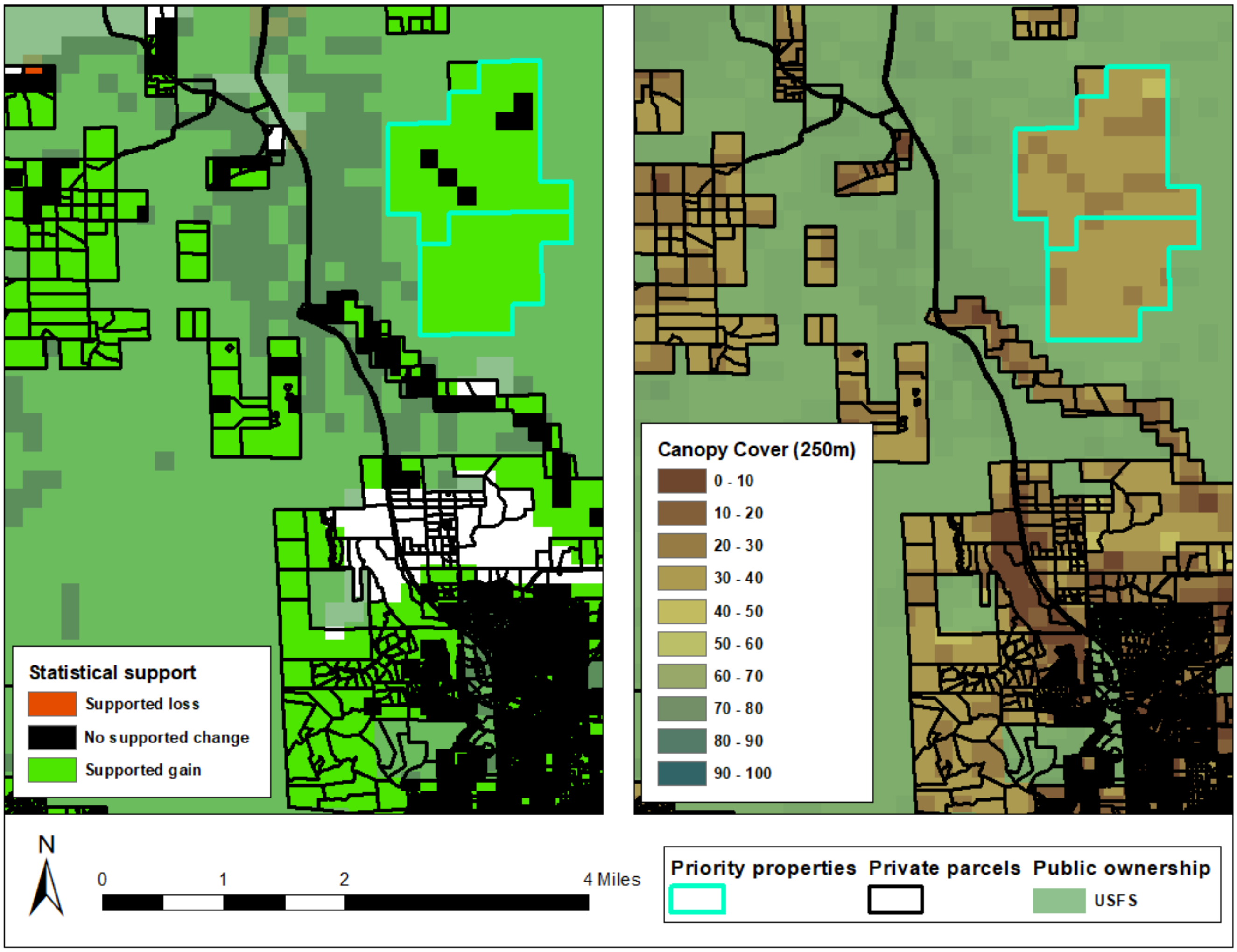

Figure B3. A finer-scale map allows us to identify the specific properties on which to pursue work. Overlaying the simulated canopy cover resulting from the fuels reduction scenario, which predicted the gains in species richness, allows us to estimate the target canopy cover. In this case the target is approximately 30-40%.

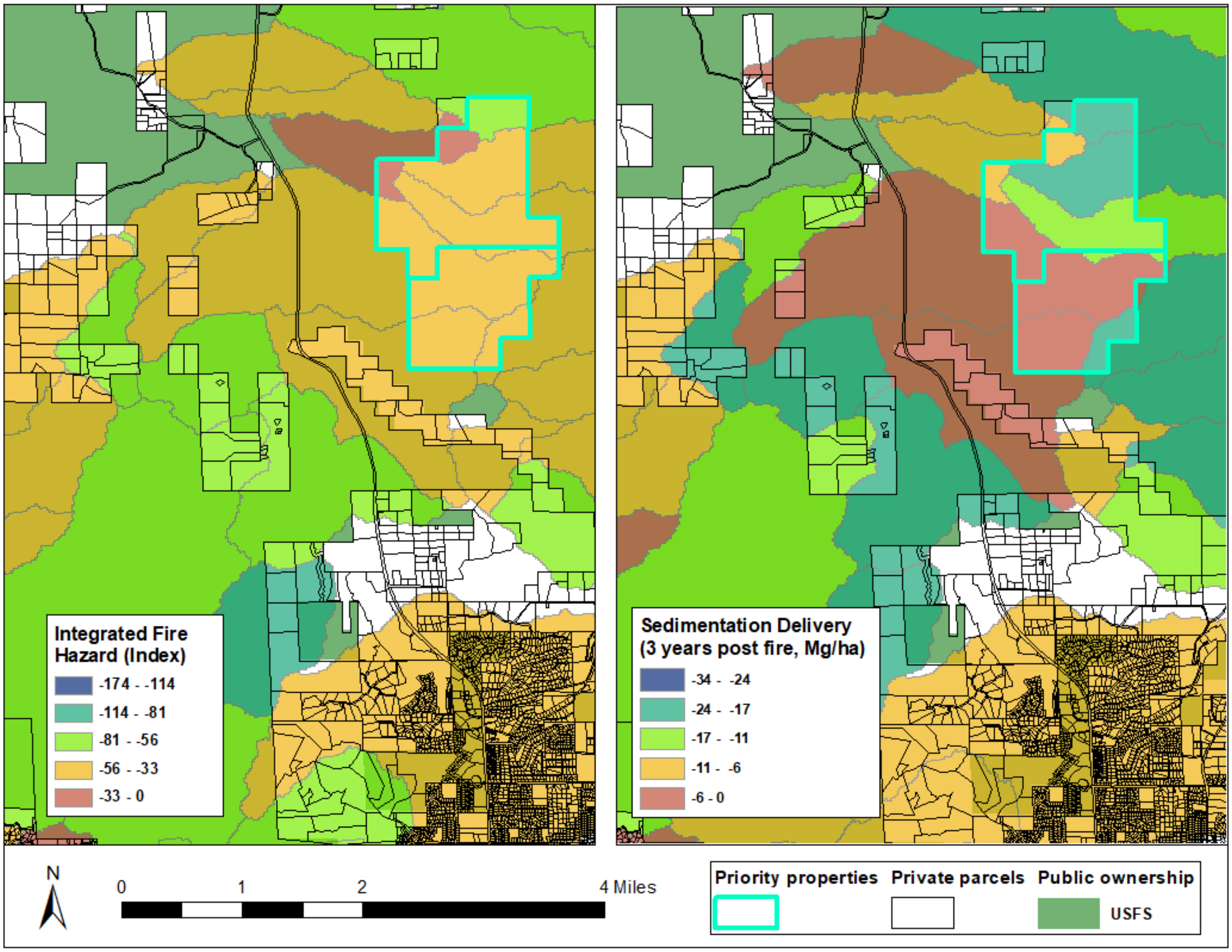

Figure B4. Overlaying the ecosystem services on the finer-scale map allows a more accurate examination of predicted changes. Along with the other finer-scale map, it also creates a good outreach tool for producers, the public, and partners.

Appendix B – Project- and treatment-scale guidance

Practices to enhance wildlife habitat in Southern Rocky Mountain forestry treatments

Intended for use by natural resource professionals across forest types, together with practices necessary for other goals.

Element	Benefits	Implementation
Spatial heterogeneity	• Increases biodiversity by providing diverse habitat for multiple species[1,2,11] • Meets multiple habitat requirements for an individual species in close proximity (e.g. elk forage adjacent to cover)[4,19] • Interlocking tree crowns provide important cover for nesting birds, squirrels, and other wildlife	• Retain most trees in groups (of varying size)[1,2,3,4] • Inform retention with local clues (grouped vs lone old stumps, large logs, old trees), reference conditions specific to area/forest type when available, and biophysical conditions (moister sites = larger groups)[1,2,3,4,5] • Avoid arbitrary constraints such as diameter limits for tree cutting[6] • Avoid thinning old tree groups[2] • Maintain interlocking, or nearly interlocking, crowns within groups[4,7] • Vary tree spacing both within and between groups[1,2] • Emphasize rare or declining tree species or age classes when site appropriate[1,2,3,4,5,8]
Openings (grass-forb-shrub interspace)	• Increases forage for a broad suite of herbivorous wildlife[10] • Enhanced native pollinator habitat[14,15] • Increased prey abundance for carnivores and insectivores[7,11,12,13] • Provides space for birds to forage aerially[11,12]	• Maintain some visual cover around and within openings, especially in larger openings or those adjacent to high human use areas[9] • Avoid very wide, contiguous openings. Aim for long, irregularly shaped openings with feathered and/or meandering edges[16,17] • Retain/create some coarse woody debris • Avoid chip depth exceeding 3” depth or 30% of area • If understory response is poor, treat weeds and/or plant native seeds[10] • More/larger openings in drier spots on southern aspects or ridge tops[1,2,5]
Snags	• Provide nesting and feeding sites for over 75 wildlife species in the western US[18] • Particularly important to woodpeckers and cavity-nesting birds/bats[20] • Creates down, coarse woody debris once fallen[20]	• Retain at least 3-5 snags/acre on average. Aim for groups of snags (7-10).[18,20] • Focus on retaining/creating large-diameter (>10 in. DBH) snags[18,20] • Can create through girdling or topping (below crown)[21] • Retain/create snags within tree groups (will stand longer), and in the open (will have more rapid decay and more bird use)[18,20] • Retain/create snags across a variety of habitat types[20] • Retain any snags with cavities or signs of nesting • Where snags are not appropriate, nest boxes can benefit cavity nesting birds
Cover	• Down, coarse woody debris provides cover for birds, small mammals, reptiles, amphibians, and insects[20] • Patches of dense vegetation provide cover for nesting, escape, thermal refuge, and stalking [13,19]	• 5 to 20 tons/acre for warm, dry conifer forest and 10 to 30 tons/acre for cool, moist conifer forests (based on wildlife-fuel balance)[20] ○ 5% cover = ~11 tons/ac of 6” DBH or ~21 tons/acre of 12” DBH • Retain/create downed, branchy limbs/trees, ideally hinged from a high stump • Retain dwarf mistletoe when timber production is not main goal[22] • Retain patches of shrubs, saplings, and dense vegetation. Focus retention to visually block areas of high human use.[9,23]

Additional Considerations

Nest avoidance

Under the Migratory Bird Treaty Act, it is illegal to "take" or kill migratory birds (1,026 bird species). Destruction of nests/eggs/birds through forestry practices is included in the law. Individuals and organizations should be aware that felling trees during the nesting season puts them at risk of violating federal law. Avoidance is the best way to minimize risk.

- **Temporal avoidance**
    - Avoid tree felling during the migratory bird nesting season of March 15 – July 15. Especially avoid the peak months of May and June. Generally, nesting begins later at higher elevations. Many raptors nest at the beginning of the season. If possible, fell prior to this period and skid/process/haul during the period. If you must fell during the period, document a justification for doing so. Consult with biologist about nest surveys prior to treatment during nesting season.
- **Spatial avoidance**
    - Large, stick nests are likely raptor nests. If you find these nests, consult with a wildlife biologist. CPW provides guidelines to reduce disturbance to raptor nests by avoiding activities within a given distance during a given period of time. Consider these guidelines when planning work near known nest sites.
    - Avoid cutting trees with large cavities or obvious nests.

Critical ungulate habitat

- **Winter range and production areas**
    - Strive for forage, hiding cover, thermal cover, and water in close proximity.
    - Increase forage through the creation of openings, focused tree removal around dense patches of shrubs and grasses, planting native understory species, and burning. Avoid deep slash or chips. Forage availability in winter range is of particular importance.
    - Hiding cover consists of dense understory vegetation that can obscure the body of an elk. Thermal cover consists of a dense overstory that will provide shade, insulation, and block snowfall. A stand can provide both hiding and thermal cover if it is multistoried or contains densely stocked pole-sized timber. Thermal cover is typically overabundant prior to treatment.
    - Strategically create these features near water and far from roads/trails. Use terrain and vegetative cover to visually block foraging sites from areas of high human use.

Riparian buffers

- Clearly mark boundaries at least 50 ft beyond banks, farther if moist areas or highly erodible soils extend far beyond banks.
- Within boundaries, retain hardwoods and bank-stabilizing vegetation, directionally fell trees away from water, and keep heavy machinery out.
- See CSFS Best Management Practices for more information.

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