Forest Service
U.S. DEPARTMENT OF AGRICULTURE

Rocky Mountain Research Station

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Climate Change Research Strategy

Rocky Mountain Research Station

Foreword

The threat of climate change is global in scale and requires scientifically informed and collective actions to avert the worst consequences. The impacts of climate change on public and private lands are becoming more apparent. The need to focus research on complex interactions among the physical climate system, ecosystems, and human systems is critical to meeting the management needs of the Nation's forest, rangeland, and grassland ecosystems.

Prompted by the recommendations set forth in the *Climate 21 Project* and the National Academies of Sciences, Engineering, and Medicine 2021 report *Global Change Research Needs and Opportunities for 2022-2031*, this strategy capitalizes on the scientific expertise in the Rocky Mountain Research Station that can contribute to the scientific understanding of climate change; identify management options to restore and maintain resilient forest and grassland ecosystems and reduce atmospheric GHGs through carbon sequestration; protect water resources; and promote sustainable bioenergy, wood products, and other bio-based materials to support rural economies.

This strategy was developed through discussions within station leadership about setting a strategic direction for research in the Rocky Mountain Research Station and with input from many station scientists. It presents recommendations for investment in RMRS climate change research priorities. The Station is developing an implementation plan for this strategy that represents an integrated, cross-program, interdisciplinary program of research and science delivery.

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Acknowledgments

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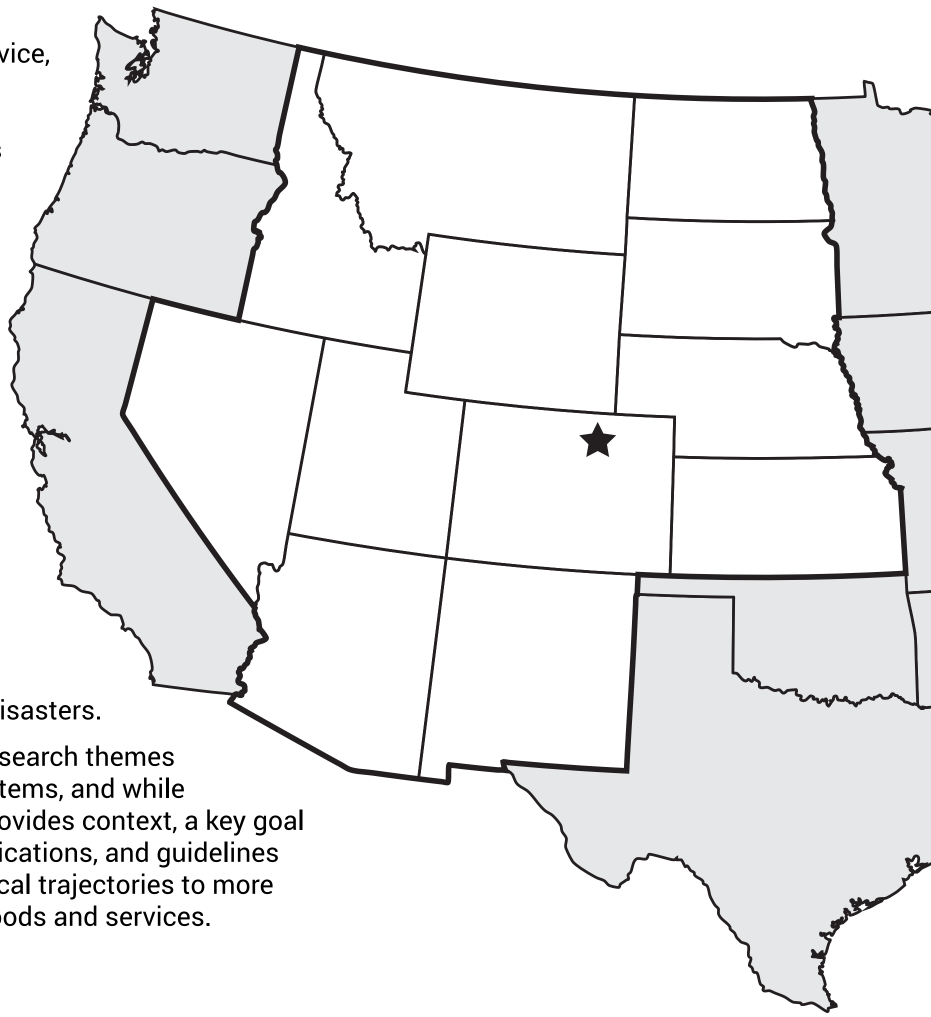
Motivation

The world and the U.S. face a profound climate crisis. The Interior West is at the epicenter of current and future impacts of climate change. Here, recent decades are the warmest of the past 1,500 years, and the record-setting years that continue to occur may be indicative of average conditions in the near future. Stable water supplies in the West depend on the winter and spring snowpack, which is declining. Snowpacks are melting earlier, and chronic, long-duration hydrological droughts are increasing. Runoff from more frequent, extreme precipitation events is increasing stream loading of nutrients, sediments, and pathogens, thus threatening water quality.[1] Rising temperatures and water scarcity are influencing species ranges; more than half of the studied plant and animal species in temperate North America are shifting their ranges. Changes in habitat and environmental conditions are allowing some nonnative species to become invasive, outcompeting and decimating native species and the ecosystem services they provide.[2] Broadly, carbon storage is projected to increase for most ecosystems in the U.S. with the exception of forests. In the West, forests are projected to continue to sequester carbon, but at declining rates. Forest carbon sequestration will be negligible by around 2050, and some forests will become carbon sources.[3] The frequency of large (thousands to hundreds of thousands of acres) ecological disturbances in forests in the U.S. is increasing, and these, in combination with accumulated fuels, have resulted in larger wildfires in recent decades. These large wildfires are harder to suppress and incur more human health and safety concerns than previous wildfire regimes.

The U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station (RMRS) conducts climate change research to provide science-based solutions to resource managers who are stewarding more than 50 National Forests and Grasslands – over 100 million acres – in the West. RMRS conducts research on:

- Water resources and drought.
- Maintaining and restoring resilient landscapes.
- Forest health and productivity and carbon sequestration.
- Wildlife populations.
- Wildfire behavior.
- Vegetation dynamics.
- Smoke emissions.
- Wulnerability of communities to natural disasters.



Climate change research is central to all the research themes at RMRS. Climate change is shaping novel systems, and while understanding historical ranges of variation provides context, a key goal in our research efforts is to develop tools, applications, and guidelines for managers that will help shift future ecological trajectories to more desirable conditions that sustain ecological goods and services.

RMRS scientists realize that we must incorporate the effects of a changing climate on management of these systems and identify climate-smart management strategies that offer recommendations to increase the pace and scale of ecologically-sound forest restoration on Federal, State, Tribal and private forest lands. This realization, along with recent calls for agencies to develop and implement a climate agenda and invest in climate change research (e.g., Climate 21 Project[4]) is the motivation behind this document. The RMRS Climate Change Research Strategy addresses the known climate change challenges across major integrating themes—water, carbon, fire—and in the context of resilience, disturbance, and recovery. It seeks to capitalize on and expand existing and historical research studies and infrastructure where long-term data exist. Herein we describe how our research programs could be enhanced to address emerging challenges. We also propose future research that would leverage new and existing infrastructure and build networks to lead climate change research across R&D.

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Current Research and Enhancement Opportunities

Water and Watersheds

From its inception, the Forest Service has been charged with the protection of watersheds and water resources. In the fast-growing American West, agricultural, rural, and urban economies are inextricably tied to water. Along with the increasing demand for water, a limited supply may be affected by projected changes in the regional climate, making it increasingly difficult to predict supply from year to year. New knowledge gained from RMRS research on the effects of climate change on the hydrologic cycle is essential to meeting the complex and extensive challenges facing western water management.

Hydrologic Responses to Watershed Disturbance

Current knowledge of watershed processes is inadequate to predict how complex biophysical factors will respond to climate change at relevant spatial scales. Climate-driven changes in hydrology and thermal regimes of air, soil, and water will cause shifts in the distribution and composition of terrestrial, riparian, and aquatic species that, in turn, may have complex feedbacks with physical watershed processes. Altered streamflow and changes in the water cycle have direct consequences for aquatic habitats and species, sediment transport, and riparian function. Future watershed research needs to integrate detailed studies of point processes into landscape- and regional-scale assessments of predicted changes in climatic drivers, disturbance regimes, vegetation distributions, physical and biological processes, and ecosystem function.

Water Quality Effects of Wildfire

Larger, more severe wildfires and increased vulnerability of western forests to insects and diseases associated with changing climate are expected to alter rates and magnitudes of hillslope erosion, wood inputs, and basin sediment yields. We study the effects of wildfires on hydrology—the long-term effects of severe wildfire in forested watersheds present management challenges for maintaining water quality, protecting water infrastructure, and watershed restoration.

Understanding the Role of High-Elevation Headwater Ecosystems in Sustaining Environmental Flows

High-elevation alpine meadows and riparian areas are among the most productive mountain ecosystems – and the most vulnerable to climate change. Headwater wetlands are critical hydrologic source and storage areas and points of high local and regional biodiversity. As changing temperature and precipitation regimes affect water supply, so might they dramatically alter the hydrology and all related ecosystem components. Our research examines hydrologic connectivity within watersheds and establishes a baseline for monitoring the short- and long-term impacts of disturbance and climate change. It is important that we accurately describe and quantify the abiotic and biotic condition of these areas and develop sound, process-based knowledge of the functions and limits of their natural variability. This will allow land managers to balance environmental instream flow requirements of these ecosystems against human needs.

Forecasting Water Availability from National Forest System Lands

To meet the ability of water managers to deliver clean, abundant water to a growing population in the West, RMRS scientists are focused on quantifying the water cycle and reducing uncertainty in water supply forecasting. Forested and mountainous locations, such as national forests, tend to receive more precipitation than adjacent non-forested or low-lying areas. Modeling research illustrates the importance of water yield from National Forest System (NFS) land to water quantity and quality and each forest's contributions to regional streamflow. Research to improve measurements of the amount of water held in snow is essential for water managers and consumers and has implications for food security, industry, and municipal drinking water supplies. Integrating field studies with remotely sensed data and models will increase our knowledge of these interacting processes and reduce uncertainty in runoff forecasts.

Carbon

Research has demonstrated how important healthy forests and grasslands are to meeting carbon sequestration goals. Terrestrial vegetation fixes millions of tons of carbon per year, and through that process returns two-thirds of the annual global precipitation falling on terrestrial ecosystems back to the atmosphere via evapotranspiration. Long-term research has shown that some western forests transition from carbon sinks to carbon sources from vegetation loss due to pests, drought, and wildfire. Our understanding of linkages of the hydrologic and carbon cycles is limited by lack of data on the biophysical controls within watersheds, particularly in high-elevation wetlands and riparian areas. Therefore, it is critical to measure and identify the controlling factors at multiple scales to balance the delivery of water and carbon ecosystem services from public lands.

Quantifying Carbon Stocks

Our research includes:

- Mapping biomass and estimating carbon budgets across all ownership categories.
- Quantifying carbon stores and fluxes in non-forest lands of the U.S.
- Identifying areas for fuel treatments to reduce fire (and carbon loss) risk.
- Using TreeMap carbon data with our national-scale fire simulations to estimate risk to carbon resources from fire.
- Using FuelMap to map the amount and extent of carbon in fuels (litter, duff, logs, etc.).

Future research will expand efforts to map forest biomass (or fuels) for fire risk (done annually since 1984) and will use FIA data to examine trends in forested area and forest health, many of which will be related to climate change. Expanding this research would require additional data collection carbon pools (e.g., soils) and capacity to create base maps showing disturbance, vegetation type, cover, and height over time.

Intensifying the Pace and Scale of Carbon Inventory.

Long-term data from the Forest Inventory and Analysis (FIA) program are being used to provide accurate information on carbon stores and best practices to enhance carbon sequestration on U.S. forests, grasslands, and rangelands, and characterize the link between conservation practices and climate resilience. FIA's forest inventory plot network is essential for monitoring U.S. forest carbon stocks and trends as well as for biomass and carbon mapping efforts. Because FIA plot surveys are conducted in wildernesses and other natural areas, they provide a basis for research into how climate change will affect carbon storage in wilderness areas as well as understand how protected status affects vegetation dynamics and habitats. Beyond carbon, space-based measurement of albedo (how much of the sun's energy is reflected back into space) on FIA forest and non-forest plots fundamentally broadens our understanding of climate change mitigation by forests. As a result, the U.S. is the first nation in the world able to estimate joint climate effects of forests from carbon and albedo.

Increasingly, FIA is being asked to answer resource questions areas without enough sample plots from which to construct estimates with adequate precision. Interest in small-area estimation stems from needs to quantify the effects of disturbances and resource trends on carbon stocks and climate effects at scales that are relevant to individual management units. The FIA program continues to develop small-area estimation approaches and estimates over smaller geographic areas using forest inventory data, remote sensing, and new statistical techniques.

Opportunities exist to expand FIA field sampling to characterize carbon dynamics on all lands as well as at finer temporal and spatial scales. Field sampling could be expanded to the non-forest wildlands (especially for NFS lands), and the sampling cycle could be accelerated from a ten-year to a five-year cycle, providing more timely estimates of change. In many areas across the country, soil carbon is a large portion of the full carbon stocks; however, the current sampling of soil carbon in the FIA network is only

12% of the annual sample. FIA could increase the intensity of soil sampling to comprise all field plots. We currently have a limited assessment of carbon on rangelands and in forest understories. FIA can also develop sampling and estimation approaches that would provide accurate estimates of carbon storage in grasses, forbs, and shrubs.

Biochar, Biofuels and The Bioeconomy

Biochar has demonstrated utility in restoring soils, mitigating toxic waste, producing energy, and mitigating climate change. Biochar can be converted into an array of products from agricultural soil amendments to filtration media. Because of the need to dispose of large amounts of woody biomass waste material and restore forest soils, the Forest Service needs to expand research on the production, utilization, and carbon benefits of biochar. RMRS's biochar research is contributing knowledge about how forest restoration and soil carbon sequestration are linked. It provides managers with an understanding of how forest restoration (thinning) can produce a higher-value product (i.e., biochar) and improve agricultural soils to increase water holding, decrease erosion, decrease wildfire risk, improve drought resistance, and ultimately improve crop production.

RMRS is also invested in research on biomass energy because of its enormous potential to address the challenge of finding markets for hazardous fuels, low-value timber, and wood residues. Advancing this research would promote biomass production as a tool to foster forest restoration, fuel thinning, and other silvicultural treatments. RMRS scientists are studying the economics of biochar production from forest biomass and exploring public-private partnerships to advance renewable biomass and bioproduct industries. Previously non-merchantable biomass can now be monetized, and this income stream would enable the Forest Service to restore more acres and ultimately reduce the risk of wildfire. RMRS research would support the expansion of regional bioeconomies that include a combination of emerging and traditional bio-based enterprises and stimulate productive use of the supply of biomass feedstock from timber harvest, fuel treatment and forest restoration. We would continue consultation and collaboration with communities to further develop public-private partnerships related to opportunities for economic development by promoting and establishing Biomass Utilization Campuses. These campuses would bring together multiple users and processors of woody biomass inputs to produce complementary value-added products like energy, biochar, waste management and recycling services, among others. Related projects include using woody biomass to generate electricity to power a micro-grid while co-producing biochar and extracting hydrogen gas as a by-product for use in fuel cells.

Managing for Resilience

Forests, rangelands, and grasslands are facing unprecedented risks due to an intersection of changing climate, changing disturbance regimes, and increasing demands for extractive and non-extractive ecosystem services. Forest densities often exceed the historical range of variability, shrublands are converting to monocultures of invasive cheatgrass, and pinyon-juniper woodlands are experiencing widespread tree mortality from drought and high temperatures. Understanding how to manage ecosystems so that they can recover to their pre-disturbance state (i.e., resilience), or how adaptive management techniques can facilitate state changes without catastrophic degradation to ecosystem services is a key focus of RMRS climate change research.

Forest and Grassland Restoration

Our current research seeks to understand post-wildfire tree regeneration to determine how, where, and why regeneration occurs (or not), with particular interest on how regeneration is influenced by fire severity, management, and climate. RMRS is also determining the influence of wildfire severity and climate variability on the success of plant restoration species, seed mixes, seed production, and reseeding and out-planting strategies. In forest areas unaffected by wildfire, we are examining different combinations of tree spacing and aggregation to determine the survival, growth, and regeneration of ponderosa pine and dry mixed-conifer forests and so evaluate forest response (growth, regeneration) against a matrix of density and aggregation (clumpiness). The ultimate goal of this work is to establish operational scale climate change adaptation strategies within several forest types.

FIA is uniquely poised to make projections about the geographic ranges and responses of individual species to climate change. FIA data have been used to quantify the climatic characteristics of the ranges of individual tree species. These data support development of models and maps showing expected future distributions as well as areas where a species may experience increasing stress due to changes in temperature and/or precipitation. Additionally, FIA collects tree cores and analyzes tree rings, which provides important long-term, annualized time series of tree growth response to climate and other factors. Collectively, the ability to measure and quantify not only growth responses but also anticipated broad-scale responses to climate change presents a tremendous opportunity to make projections about future forests.

Climate change will affect the distribution of invasive plant species, their invasiveness, and their impacts on native competitors. Work in this area evaluates how invasive plants perform under different climate scenarios and implications for their control. In grasslands, we are assessing the effects of multi-year droughts on plant populations and communities and examining the role of bud banks, the primary means of regeneration in grasslands, shrublands, and deserts. Data from this research are being used to develop conceptual and statistical models to describe and predict vegetation dynamics, as well as project the potential consequences of future changes in ecological conditions, disturbance regimes, seed production zones, and management actions. Our ability to make predictions about plant community shifts is limited because we lack fine-scale, integrated environmental data. Increased capacity to produce spatial data that has climatic, topographic, soil, water, and other environmental data that can be associated with plant traits or plant community assemblages would greatly improve our ability to make predictions about plant communities and whether species would migrate or be extirpated due to climate change.

Mitigating the Effects of Climate Change on Species of Conservation Concern

As climate change affects habitats and habitat connectivity, climate gradients and changes to physical environments can be expected to affect biodiversity. RMRS is conducting research to assess and monitor plant species of concern at range-wide scales, including dwarf bear-poppy and Holmgren milk-vetch. We are also identifying, monitoring, and modeling wildlife refugia and the connectivity of refugia using genomic data, economic optimization analysis, and modeling. Our research has already shown the effects of climate change on refugia and habitat connectivity for wolverine, lynx, sage grouse, Mexican spotted owl, and other species that are often snow-dependent, as well as population declines of many cold-water fish species (e.g., cutthroat trout and bull trout) in response to warming stream temperatures. RMRS is continuing similar work relating future climate and different management scenarios for focal species in the Great Basin, Sierra Nevada, Crown of the Continent, and Columbia River Basin. Opportunities exist to use environmental DNA (eDNA) to build species distribution and aquatic invasion models and compare historical distributions to contemporary distributions impacted by early 21st century climate change.

Climate change is already causing a global decline in insects, and pollinator services are threatened. Our knowledge of management effects on pollinators, how to restore their habitats, and how they respond to wildfires is minimal, at best. Several bee species will almost certainly be listed as endangered in the near future (including 2 or 3 species within the RMRS footprint); many insect species are also on the decline and will go the way of the spotted owls and other birds. Logging, weed spraying, and grazing will likely be halted or minimized until their effects on these species, if listed, is better understood. The USDA has pollination biologists, but their focus is almost solely on agriculture and managed bees. There is a big gap and need for work on public wildlands. Forest Service R&D only has two or three scientists working on pollinators nationwide and none are explicitly trained as pollinator biologists (entomologists currently fill this need). To address how climate change is threatening pollinator services, significant investment in permanent pollinator biologists and taxonomists is necessary, as species identification is often the bottleneck in native pollinator research.

Resilience in Urban Areas

Urban and urbanizing cores of the western U.S. house an ever-increasing proportion of the U.S. population, many of whom are part of underserved communities that are both more vulnerable to impacts on natural resources from climate change, drought, development, and wildfire smoke and have less access to nature.

RMRS is conducting research at the nexus of climate change and urban environments at the Denver Urban Field Station, one of 12 Forest Service urban field stations and the only one in the RMRS footprint. Our research includes quantifying exposure of low-income residents to extreme heat, and the role of trees and green infrastructure in increasing the resilience of cities to climate change. Other research considers the extent to which urban communities are using forests for recreational use. RMRS could expand efforts to better understand climate change effects on the interactions of urban communities, recreation, diversity and inclusion, and environmental justice, or expand spatially to other major metropolitan areas in the RMRS footprint (e.g., Albuquerque, Salt Lake City, Boise).

Socioeconomic research in RMRS integrates science on forest and rangeland systems with social, economic, and ecological dimensions of climate science and climate-smart land management decisions. RMRS would build on the unique strengths our research to focus on the human behavior component of climate-smart resource management.

Fire

Climate change is exacerbating extreme wildfire, increasing the frequency, extent and severity of fires and presenting serious challenges for managing resilient landscapes and communities. Annual area burned in the western U.S. has increased since the mid-1980s, coincident with a warming climate. The U.S. now has over a billion acres at risk of wildland fire.[5]

A major component of the RMRS climate change research portfolio focuses on understanding how climate change will alter fire regimes. Scientists are evaluating how fire-season climate has changed through time and how this change has contributed to increases in high severity fire (resulting in ≥95% tree mortality). The short- and long-term effects of these large wildfires on forests depend, in part, on post-fire restoration efforts and their success, as well as proactive forest management, which can reduce wildfire size and severity.[6] RMRS science underpins the new *10-Year Strategy for Fire* and, with the strategy's goal of creating fire-resilient forest, rangeland, and grassland conditions and forecasting future wildfire risk, it provides opportunities to increase the pace and scale of solutions. These solutions include using prescribed fire when applied models of fire behavior show that smoke and other complex interactions allow for favorable conditions. Providing tools and analytics that help managers implement these strategies under the current and future climate conditions is just one focus of our current work.

Assessing Carbon Emissions from Fire

Fire exclusion policies over the last century have built a carbon surplus in many forests as compared to pre-settlement conditions. RMRS will capitalize on our knowledge of *in situ* fire behavior specific to region, terrain, and fuels, and on our elaborate sensor arrays developed to examine carbon implications of fuels treatments and fire.

Overstocked conditions mean that today's forests will release significantly more carbon into the atmosphere when large, severe fires occur. Restoring forests to be more fire resilient through forest and fuel management will result in a short-term carbon loss but will prevent larger losses over time under future fire regimes. Research is exploring fire behavior as related to dynamic fuel loads, fuel break effectiveness, and ember transport, all of which are susceptible to a changing climate. Additionally, long-term monitoring datasets can help quantify pre-fire carbon stocks, and post-fire assessments can help quantify emissions due to fire. RMRS scientists would expand this research to predict future fire regimes under which reductions in fire extent and behavior eclipse the carbon loss from hazardous fuels reduction and provide a net carbon gain. Research on carbon implication of proactive forest and fire management could be expanded through dynamic modelling efforts.

Post-Fire Tree Mortality from Pathogens

Fire ecology studies investigate fire-climate interactions on tree mortality from pathogens and disturbance. RMRS scientists are currently working to understand whether water stress/drought increases tree mortality after fire, even after accounting for tree injury. RMRS is also involved with several projects investigating insect-climate interactions on fuels and forest flammability. Recent combustion chamber experiments include a drought treatment to study the mechanisms of water stress on a tree's ability to survive fire.

Adaptation to Increased Smoke Production and Hazardous Air Pollution Fueled by Climate Change

Wildland fires degrade air quality. Climate change has increased the severity of wildfire seasons and smoke emissions, and degraded air quality in the western U.S. RMRS plans to improve smoke emission models to provide essential input to the smoke forecasting systems relied upon by public health officials, air quality forecasters, and fire management teams to mitigate the impacts of wildland fire smoke on public health and safety.

Optimizing Forest Fuels Reductions and Biodiversity Conservation Under Climate Change

RMRS is leading research efforts to understand the climate drivers of fire extent and severity across the West and to predict the impacts of altered fire regimes on endangered wildlife species. Our scientists are working to develop better integration of mechanical thinning and prescribed fire treatments to increase the footprint of forest restoration activities and create forests that are more resilient to disturbances that will be amplified in a changing climate. We are using monitoring data to build predictive avian-habitat occupancy models and forest fuels reduction scenarios that maximize biodiversity conservation implications for consideration by land managers. Incorporating these data with new data layers, such as light detection and ranging (LiDAR), would provide important information on bird focal species and bird communities and habitat components that may be changing over time as a function of land management or climate change. This work would also provide baseline data on the effects of landscape change (e.g., fire, restoration treatments, or climate change) at broad spatial extents, and allow us to explore trade-offs through simulations of land management changes or climate change.

Firefighter and Community Safety

Scientists at the RMRS National Fire Decision Support Center (NFDSC) are at the forefront of incorporating climate and weather factors in the quantitative risk assessment strategies provided to fire management communities. Climate-driven increases in wildfire activity and season length are likely to put additional stress on the wildland fire management system, increasing the workload as well as the health and wellbeing of fire responders. The Risk Management Assessment Team is pursuing a research agenda translating climate-fire projections into operational implications, including changes in assignment amount and duration, response strategies and tactics, and exposure to hazards. Further, the team is designing more agile and efficient resource dispatch and movement systems to ensure functionality under increased workload stress. We can examine how firefighting resource demands are likely to change due to climate change if we continue to manage fires as we do now.

Fires also pose a significant threat to the resilience of wildland-urban interface communities.[7] Preparation for a wildfire event and fire risk mitigation by community residents is essential to improving community resilience. RMRS scientists work with community wildfire education programs to collect and analyze systematic social and biophysical data to support and guide evidence-based programs.

Wilderness as a Benchmark

The main themes in the RMRS strategy are considered in the context of wilderness as a benchmark. Climate change was not a consideration when the Wilderness Act was passed in 1964; the act dictates that wilderness resources are maintained “in their natural condition.” However, historical interpretation of these tenets may no longer be achievable due to climate change. Wilderness managers are faced with the “ecological intervention conundrum” (assessing the risks, tradeoffs, and uncertainties of manipulating resources toward maintaining natural conditions, or not). The Aldo Leopold Wilderness Research Institute is committed to studying the effects of climate change in the National Wilderness Preservation System (NWPS), as well as conducting research on climate change management strategies in wilderness. Wilderness also serves as a benchmark to understand conditions outside of wilderness areas in the context of a changing climate and associated changing disturbance regimes. Long-term monitoring data (e.g., FIA data) that span both wilderness and non-wilderness areas can shed light on how protected status affects vegetation dynamics and habitats. At the same time, wilderness and other protected areas can serve as refugia and stepping-stones for flora and fauna as they shift in response to climate change. Wilderness ecosystem services are of high value to the public and our research explores how climate change will affect those values.

Experimental Forests and Ranges

The Forest Service R&D is unique from academia in two fundamental ways: we conduct and maintain long-term studies that span many decades, and we have a network of Experimental Forests and Ranges (EFRs) on federally-owned land to conduct manipulative studies. RMRS has stewardship over two of the four experimental ranges in the Forest Service, and 12 experimental forests. On these areas, we conduct long-term research to determine climate change impacts on forest and rangeland water quantity and water quality, growth and productivity, and nutrient cycling, and their relationship to management. Research at several sites is conducted year-round, measuring intra- and interannual water cycles related to precipitation, atmospheric deposition, soils, and vegetation change.

Other experimental forests have been used to conduct long-term growth, development, and genetic adaptation studies that encompass a century of climate responses. Thus, they provide a foundation for monitoring and informing future management options, while identifying shifts in forest dynamics as climate change progresses. RMRS operates growing stock level research plots on several EFRs that are used to examine drought resistance and resilience of trees grown at different densities across different U.S. ecosystems. We also maintain long-term monitoring of control and experimental plantings at these locations. Additionally, we have established many long-term silviculture studies that are currently inactive. These studies could be used to evaluate climate change effects on carbon sequestration and shifts in productivity and allocation. Similarly, intensifying the FIA sample grid and/or integrating the existing FIA plot network with EFR studies could help assess applicability and representativeness of finer-scale studies to the entire landscape. A periodic, limited investment would be necessary to collect and analyze the data. Finally, the aging research infrastructure at all EFRs must be addressed for operations to continue. We need to invest in a network of instruments and research infrastructure on these EFRs to conduct cutting-edge climate change research.

Data Science and Modeling

This is the age of data. Prominent scientists have posited that new discoveries will be limited by the ability to analyze and harness data that already exist. Data scientists take something that is abstract – large sets of data – and turn it into something concrete: actionable information that informs decision-making at all levels of the organization. RMRS scientists curate a trove of long-term data and studies that could be reexamined and/or revisited to glean insight into climate change related questions for a limited investment.

We propose to exploit these legacy silvicultural, watershed, and other long-term monitoring and research studies to uncover the effects of various management approaches on long-term forest development in the past 50 to 100 years of climate change and droughts. We would apply that to provide insights into the future effects of active management. To raise the relevancy of Forest Service R&D, we propose to apply additional funds to accelerate the process of archiving and curating online data from long-term RMRS studies. Staffed by a lead data scientist and interdisciplinary professional scientists (ecologists, hydrologists, foresters) with data science skills, the proposed data support center would populate a server with data and advertise it. Taking a cue from the National Science Foundation (NSF), funding agencies are moving toward a model of only covering salaries and not funding new measurements. They are heavily invested in the NSF's Long-Term Ecological Research (LTER) sites and National Ecological Observatory Network (NEON) and want to see these data measurement networks leveraged. Forest Service R&D should be a data provider for the scientific community. The FIA program, which is integrated within RMRS and three other Forest Service research stations, is an existing example of such a supported data service, and users both within and outside the Forest Service rely on FIA data and associated analytical tools.

RMRS scientists develop our research into online tools and applications for managers based on predictive modeling. Utilizing our established long-term research studies with multiple measurement periods is a rich opportunity to examine climate induced impacts on growth, carbon, and other pertinent data relatable to climate and future forest management. For example, tree growth equations spanning climate change periods could be used to update the Forest Vegetation Simulator. This type of update could assist with determining rates of forest stand development stages and their relation to carbon storage, risk of fire, insects, and other disturbances, and help identify solutions for managing carbon sequestration under climate change. Currently, RMRS lacks the capacity and capabilities to capitalize on this line of research.

Modeling Water Quality and Availability

Long-term studies on changes in the snowpack, timing and type of precipitation, and the timing of snowmelt and runoff have allowed RMRS to develop predictive models that forecast changes in water quantity from National Forest System lands with implications for agriculture, industry, and municipal drinking water supplies. RMRS scientists conduct research on responses of water quality and quantity to disturbances (fire, drought, insect infestations, etc.) and the vulnerability of western watersheds intensified disturbance regimes in a changing climate and associated disturbances This work supports water managers responsible for meeting instream flow requirements for hydropower regulation, municipal water quality requirements, and conservation of aquatic resources and habitats, wildlife, and recreation.

National Forest Climate Change Maps

We are creating maps of different climate and hydrologic variables (temperature, precipitation, snow water equivalent, and snow residence time) for each Forest Service Region and unit in the country, and tools that provide charts of historical and projected changes over time. Developed to provide climate change information at a scale relevant to decision making and to meet the needs of National Forest System managers, data products and forecasts have been incorporated into forest plan revisions and regional climate vulnerability assessments.

Predictive Modelling of Species Distribution

Increasing climate variability is making predicting climate and related disturbance events more difficult, uncertain, and urgent. However, predictive capabilities are necessary to promote sustainable, resilient, and productive natural ecosystems. Species distribution models are needed to predict where the climate will be suitable for trees in the future; that, along with testing these models to see how well they predict. We develop conceptual and statistical models to describe, explain, and predict forest and woodland dynamics and then provide critical tools to assess and project the potential consequences of future changes in ecological conditions, disturbance regimes, and management actions. Such information is critical for management decision-making in this dynamic and changing world. The models are based on original research and knowledge syntheses and are used to understand, define, quantify, visualize, or simulate disturbance, regeneration, growth, mortality, biodiversity, and plant community organization (and disorganization). The temporal and spatial scales of these models vary considerably and include individual tree-, stand-, gap-, landscape-, and subcontinental-scale models that simulate the influences of climate, wildfires, prescribed burns, insect outbreaks, and their interactions on decadal and centuries-long forest dynamics.

To manage the nation’s forests and grasslands to conserve biodiversity in the face of a changing climate, we need effective, large-scale species monitoring. RMRS would:

- Accelerate the identification of the spatial and temporal responses of forest carnivores (e.g., Canada lynx) and their prey to climate-related disturbance.
- Further develop projects modeling climate effects on fire severity effects on threatened and endangered species.
- Project wildlife refugia and connectivity to refugia using genomic data, economic optimization analysis, and connectivity modeling.

Genomics data, such as those collected by the National Genomics Center for Wildlife and Fish Conservation (e.g., 22,000 eDNA samples in the eDNArchive), could be fully explored to reveal how changing water resources influence threatened, endangered, and invasive aquatic species and climate-mediated interactions between native and invasive trout species. Leveraging these data and understanding how aquatic resources will be affected in a changing climate will require technological developments, database management, and artificial intelligence modeling. With additional investments in personnel and equipment, the National Genomics Center (NGC) could track climate change effects on aquatic resources on a five-year cycle to augment information available for planning purposes on NFS lands.

Insects, Diseases, and Pathogens

It is important to predict how climate change will influence forest diseases caused by multiple native and invasive pathogens and other pests and develop approaches to mitigate exacerbation of forest diseases caused by climate change. Current research is heavily invested in predicting how climate change will influence specific forest diseases caused by native and/or invasive root-disease pathogens. We need to expand this work to include emerging pathogens, explore the role of tree condition under a changing climate on pathogen interactions and impacts, and conduct genomic investigations of potential adaptations to changing climate in populations of forest insects. This knowledge would provide a more comprehensive understanding of the potential risk of future tree mortality and where that mortality might occur.

We need to develop approaches to mitigate negative influences of climate change on the health and productivity of diverse ecosystems because climate influences numerous interacting ecosystem components (e.g., trees, shrubs, forbs, microbial communities, insects, wildlife, etc.) that determine health and productivity (carbon sequestration) in diverse forests and grasslands. Until we better understand the role of climatic stress on host physiological performance and its effect on pathogen infection, disease development and severity, and tree mortality, our ability to determine how non-lethal diseases affect the stress tolerances of trees and if currently non-lethal infections become more lethal under climate change, will remain limited.

Mechanistic models based on insect thermal requirements are necessary for predicting future bark beetle impacts and developing direct control measures for limiting bark beetle-caused tree mortality in urban and high-use areas such as campgrounds. Mechanistic research is also needed on the responses of trees and other plants to stresses and their interaction with pathogenic and beneficial microbes. Given the importance of forest health and resiliency more work must be done with climate models and projecting future suitable climate for root disease pathogens and their hosts. This work can be applied to other pathogens and tree species using the existing framework and computing infrastructure.

Beyond forest pathogens, wildlife diseases and their ability to enter human populations has been a national topic since the global COVID-19 pandemic. Most research suggests that wildlife diseases will be exacerbated by climate change. RMRS scientists currently conduct research on white-nose syndrome, coronaviruses, brucellosis, pneumonia in bighorn sheep, and other wildlife diseases. Further investment would allow the Forest Service to undertake actions that can mitigate wildlife diseases and their impact on both wildlife and human populations. In the long term, funding for construction of a building to house both a formal Wildlife Disease Center and the expanded NGC is also needed.

Future Climate Change Research Investment

This strategy has so far identified current research activities that we believe are important to continue and could be enhanced or expanded with additional investment. This section proposes bold investment categories for research that is not currently being conducted but *should be* and recommends the expansion of existing and the establishment of new research to address the climate crisis.

Aquatic Inventory and Analysis

Prolonged drought and climate change are converting perennial streams to ephemeral ones. Intermittent flows in areas with previous flow permanence will have profound implications for western water managers. Our knowledge of the extent of aquatic resources on NFS and other federal lands is limited, particularly on high-elevation lands that are major surface water suppliers for the U.S. population. Current aquatic assessments are basin-scale and semi-qualitative; a more accurate, detailed, quantitative assessment of aquatic resources on federal lands is required.

We propose to develop a pilot inventory program for aquatic resources on Forest Service lands. A team of scientists and technicians would develop a sampling frame in collaboration with the U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD) and test and refine indicators of status and trends that complement the U.S. EPA Office of Water's National Aquatic Resource Surveys (NARS). Initial development of sampling frameworks, indicators, and sampling protocols would require staff and budget support scaled to the level of effort. At a minimum, this would require a project manager, a research scientist (under a detail assignment, post-doc, or term employee), and three professional/technical level support staff to deploy and test field methods, plus travel. We could also explore other alternatives such as expanding the U.S. EPA NARS to sample more sites on Forest Service lands.

Research Soil Scientist capacity is greatly needed in RMRS and across R&D to begin addressing these challenges and fulfilling the nation's commitment to the Paris Climate Accord.

Carbon, Soils, and Biochar

Mitigating climate change requires sequestering carbon in terrestrial and aquatic systems. Globally, soils store two to three times as much carbon in organic form as there is carbon in the atmosphere, and organic carbon stocks in soil exceed those in plant biomass in most climatic regions. Soils are the key to terrestrial carbon sequestration. Over time, all carbon decomposes, so it's important to have soils that both resist decomposition and carbon that is easily accessible to microbes. Under the Paris Climate Accord, the U.S. has committed to increasing soil organic matter stocks by 4 per 1000 (or 0.4‰) per year as a compensation for the global emissions of greenhouse gases by anthropogenic sources. In addition to offsetting carbon emissions, increasing soil carbon has many benefits such as ecosystem carbon sequestration, increasing potential site productivity, and fostering belowground biodiversity. To increase soil carbon stocks across federal forests, rangelands, and grasslands, R&D needs to increase capacity to:

- Measure and monitor how land management, wildfire, species conversions, loss of surface organic matter, and harvest method may alter carbon stocks and turnover rates.
- Understand how carbon additions, such as biochar, might enhance carbon capture and retention for mitigating climate change.
- Understand belowground processes that promote forest health and resiliency.

Research Soil Scientist capacity is greatly needed in RMRS and across R&D to begin addressing these challenges and fulfilling the nation's commitment to the Paris Climate Accord.

Forest, Rangeland, and Grassland Restoration

Climate change is radically altering ecosystems. Regeneration following mortality from droughts, insect outbreaks, and wildfire will undoubtably play out under different climate envelopes than the original system. Demographic measurements of native trees, shrubs, and forbs that are replicated across climate zones and potential restoration zones are needed. Common garden plots established across experimental forests and ranges would exploit existing RMRS infrastructure across climate zones and link to long-term, legacy data on ecosystem structure and function. Research Natural Areas (RNAs) and wilderness areas within the RMRS boundaries could be incorporated as control/comparison sites. The research infrastructure and long-term sites and plots exist for this research, but we lack the capacity to remeasure long-term research plots. Revisiting old plots would reset baselines and recalibrate the responses of abiotic and biotic measurements to climate change. Field crews to collect the data and post-docs or research associates to analyze data are necessary investments. As proposed above, intensifying the FIA sample grid and/or integrating the existing FIA plot network with EFR studies could help assess applicability and representativeness of finer-scale studies to the entire landscape.

Pre- and Post-Fire Management Strategies

Climate change is increasing the size and severity of wildfires and may also be changing cornerstone fire characteristics such as changing fire behavior in dynamic fuel loads, fuel break effectiveness, and ember transport. Fires are only going to get bigger in the future, and imaginative post-fire management strategies will be needed (e.g., fire mosses, pollinator attracting plants, drought tolerant and fire resilient native species). Major work should expand research on post-fire management strategies to provide managers with a better understanding of how to manage and protect ephemeral and persistent fire refugia, soil and belowground communities, and ecosystem services.

Mitigation of Smoke Production and Hazardous Air Pollution Through Prescribed Fire

There is an urgent need for increased use of prescribed fire to mitigate climate change driven increases in severe wildfires and the associated fire, smoke, and air quality impacts on communities. However, smoke generated from prescribed fires in local communities remains a barrier to their widespread implementation. In particular, the long-term smoldering of large-diameter fuels and duff can result in sustained periods of poor air quality, exacerbating health conditions among vulnerable residents, and creating dangerous road conditions due to reduced visibility. This is particularly true in larger population centers where anthropogenic air pollution sources are concentrated, but it is also a hazard in rural communities where air quality monitoring equipment is scarce.

Current fuel consumption and emissions models do not reliably simulate fuel consumption and emissions rates for long-term smoldering combustion. This is a significant impediment to land managers' planning prescribed fire treatments that would avoid smoldering. Laboratory and field experiments investigating the burning rates and pollutant emission rates for the long-term smoldering of large diameter woody fuels and duff are needed to develop new, reliable smoke production models for land managers. This requires investments in highly sensitive instruments to measure greenhouse gases and pollutant emissions both in the field and laboratory settings, and the construction of a new FireLab Combustion Facility to test driving variables in controlled conditions at a scale much larger than current capacity allows. Field instruments would measure real-time observations of fine particulate matter ($PM_{2.5}$) and ozone (O_3) through a mobile monitoring network that complements the National Forest System's National and Regional Air Program. We would deploy mobile networks of smoke monitors to identify potential locations for supplemental smoke monitoring network sites to better adapt communities to severe smoke impacts.

Summary

From its inception, Forest Service Research and Development has stood at the forefront of forest and grassland research. We have presented the barest sketch of the great science at RMRS and the ways that our research informs the challenges that resource managers are facing as the climate changes. We have highlighted what we have done and are doing. Many of the stressors that are affecting our forests and grasslands are not new, but they are being intensified by climate change and are interacting in unique ways. We are prepared to focus on the research we should be doing and drive the science that produces practical solutions to the problems confronting land management across all ownerships.

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