Wildfire, Climate, and Species Distribution: Possible Futures of the Rocky Mountain White Fir (A. *concolor var. concolor*) in Colorado and New Mexico

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Abstract

Humans have altered their natural surroundings since their appearance on Earth. More recently, humans have increased their impact on natural systems causing changes in wildfire behavior, climate and species distribution to occur at a higher rate post Industrial Revolution. Unfortunately, research into wildfire, climate and species distribution tends to be narrowly focused. When investigating the effects that wildfire, climate and species distribution have on each other, it becomes clear that each variable affects the other, but the outcomes of those interactions remain unknown. In order to begin to understand these interactions, this study focuses on a single, tree species, the rocky mountain white fir (A. *concolor var. concolor*), in Colorado and New Mexico. This study sets the foundation for future work on forecasting the future distribution of rocky mountain white fir due to these interactions through the creation of a binary model to produce an updated species distribution map of rocky mountain white fir in the study area. The results of the binary model, specifically in Colorado, exposed weaknesses in current research regarding environmental factors that affect the growth and regeneration of rocky mountain white fir. Further research into controlling environmental variables for the rocky mountain white fir are imperative to forecasting the future distribution of the species. After analysis of current research as well as the results of the binary model, it becomes evident that with the different ways rocky mountain white fir could respond to changes in wildfire regimes, climate and the distribution of other species in Colorado and New Mexico, future research must focus on the creation of a model to forecast possible changes. A comprehensive, multi-system forecast model would give new insights into how humans have affected the state of different ecosystem goods and services, and what can be done to adapt to changes that have already been set into motion that cannot be undone.

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The human fossil record suggests that humans may have been using fire as early as 1.9 million years ago to cook their food (Bowman et al., 2009). Since that time, humans have continuously altered their natural surroundings, leading to altered plant communities, wildfire regimes and climate (Bowman et al., 2009). More recently, as industrialization has occurred around the world humans have initiated changes in these three environmental areas at a much faster pace (Bowman et al., 2009). Historically, research focused on each environmental element individually (Krawchuk, Moritz, Parisien, Van Dorn, & Hayhoe, 2009). More recently, however, the focus of wildfire research has begun to take a more inclusive look at the interactions and feedbacks between wildfire, climate and species distribution (Krawchuk et al., 2009).

Wildfire and Climate

Over the past 10-20 years, global fire regimes have been changing drastically, with an observed surge in the frequency of large uncontrolled wildfires on all vegetated continents (Bowman et al., 2009). This surge is the result of both human and environmental factors; however, of all potential contributing factors to this change, climate conditions seem to be the primary driver (Balshi, McGuire, Duffy, Flannigan, Walsh, & Melillo, 2009; Bowman et al., 2009; Littell, McKenzie, Peterson, & Westerling, 2009). Analysis of historical data (sedimentary charcoal records, and historical records) shows that climate was a driving factor of wildfire regimes well before human settlement (Bowman et al., 2009; Littell et al., 2009). Now, with human contributions to both climate change and wildfire ignition, wildfires have increased in frequency, extent and magnitude worldwide (Kulakowski, Matthews, Jarvis & Veblen, 2012).

The interaction between climate and wildfires is quite intricate, with a positive feedback between the two (Balshi et al., 2009; Bowman et al., 2009; Liu, Stanturf, & Goodrick, 2010; Morin & Thuiller, 2009). Wildfires influence the climate through the release of carbon from burned plants and trees into the atmosphere temperatures (Bowman et al., 2009; Liu, Stanturf, & Goodrick, 2010). Global forests serve as carbon storage for the Earth. When forests burn, they release their sequestered carbon to the atmosphere. The carbon released by wildfires contributes to already increasing amounts of atmospheric carbon, which furthers already rising global temperatures (Bowman et al., 2009; Liu et al., 2010).

Between 1997 and 2001, wildfires accounted for about two-thirds of the variability in the CO_2 growth rate, and deforestation related fires significantly contributed to global greenhouse gases in the atmosphere (Balshi et al., 2009; Bowman et al., 2009; Soja et al., 2007). This increase in greenhouse gases bolsters already increasing global temperatures (Bowman et al., 2009). Increases in global temperatures then increase the potential for wildfires, which release even more carbon into the atmosphere (Bowman et al., 2009). The important role that wildfires play in the atmospheric carbon cycle shows that carbon released from wildfires are an important source of atmospheric carbon that contributes to increasing global temperatures (Liu et al., 2010; Stanturf, & Goodrick, 2010).

The increase in global temperatures is driving changes in the length of wildfire seasons as well. The late 1980’s showed an observable increase in the average length of the fire season (Soja et al., 2007; Westerling, Hidalgo, Cayan, & Swetnam, 2006). When comparing the period from 1970-1986 with the period from 1987-2003, the average wildfire season increased by 64% or 78 days, with both earlier ignition dates and later control dates observed (Westerling et al., 2006). This increase in season length correlates with both warmer springs and longer and drier summer seasons (Liu et al., 2010; Westerling et al., 2006).

The increase in wildfire season length results in an increase in the number of wildfires globally. With warm and dry conditions occurring both earlier and later in the year, wildfires have an extended period in which they can start (Liu et al., 2010; Soja et al., 2007). This increase in the number of wildfire also occurred in the mid 1980’s with a sharp shift in the global wildfire regime from infrequent large wildfires that lasted about a week on average to frequent wildfires lasting an average of five weeks (Westerling et al., 2006).

Along with the increase in the fire season length and the number of fires, there has been an increase in global burned area (Balshi et al., 2009; Gillett, 2004). Studies show that areas burned due to wildfire increase as mean temperatures increase (Aldersley, Murray, & Cornell, 2011). Climate factors that have the largest impact on wildfire burned area are temperatures greater than 28°C, precipitation between 350mm-1100mm and long periods of low rainfall (Aldersley et al., 2011).

These global changes in wildfire ecology are also evident at a regional scale in the Western United States. In general, fire seasons in areas of higher elevation with mountain vegetation types as well as areas farthest to the north show a season peak later than locations at lower elevations and further to the south (Littell et al., 2009). These areas show distinct differences in which climate variables have the strongest effect on wildfire occurrence. Wildfires in northern and mountain areas in the Western US have a strong correlation with warm and dry seasonal conditions in seasons before a wildfire, which causes already abundant vegetation to dry out priming the area with fire-ready fuels (Krawchuk & Moritz, 2011; Littell et al., 2009). In contrast, wildfires in southern and lower elevation locations are associated with moist conditions in seasons before the wildfire by encouraging new growth of plants that do not grow in the normally dry conditions of the area; building up a reserve of fire-ready fuels when the area dries out again (Krawchuk & Moritz, 2011; Littell et al., 2009).

Colorado and New Mexico contain a mixture of northern, high elevation locations and southern, low elevation locations. The mixture of these different ecological zones makes it a prime area to both observe and forecast changes in wildfires based on climatic drivers. With temperatures continuing to increase, ecoregions will move further to the north and up to higher elevations, and the fire regimes of the ecoregions with them. Eventually, wildfires in the central to northern portion of Colorado currently affected by warm and dry seasonal conditions will begin to reflect characteristics of wildfires in the southern, arid regions with precipitation having the largest effect.

Climate and Species

As the global climate warms, various species of vegetation around the world are shifting to higher latitudes and elevations in response (Gonzalez, Neilson, Lenihan, & Drapek, 2010; Parmesan, Root, & Willig, 2000; Parmesan & Yohe, 2003; Zimmermann et al., 2009). Of the total species with observed shifts, about 74-91% occurred in the direction expected due to climate change, to the north and to higher altitudes (Parmesan & Yohe, 2003). Looking toward the future, studies that have projected vegetation shifts due climate change indicate that biomes could potentially move as much as 400 km latitudinally (Gonzalez et al., 2010). These vegetation shifts ultimately affect species composition in an area, which in turn affects overall forest structure (Gonzalez et al., 2010; Parmesan, Root, & Willig, 2000). The changes in forest structure due to climate change produce changes similar to invasive plant species moving into an area.

When observing altitudinal changes in vegetation, northern and subalpine forests are the best locations to observe climate driven vegetational shifts because the vegetation in these forest systems are inherently susceptible to rising temperatures, without the assistance of other types of disturbances (Landhäusser, Deshaies, & Lieffers, 2009). For example, tree-limits, or tree lines, in the Swedish Scandes have moved upslope by 100-165mm during the 20^{th} Century (Kullman, 2001). The advance of these tree-limits has happened in tandem with observed climate warming (Kullman, 2001). Research suggests that vegetation shifts and biome changes, similar to those observed in the Scandes, will affect one-tenth to one-half of all global land (Gonzalez et al., 2010).

While forecast models show vegetation shifts affecting a large area of global land, not all forest types will respond the same way, because different forest types have different vulnerabilities to biome shifts (Gonzalez et al., 2010). Temperate mixed and boreal conifer forests have the highest vulnerability in regards to the fraction of biome area affected while deserts show the lowest vulnerability (Gonzalez et al., 2010). Tundra and alpine and boreal conifer forest biomes are most vulnerable to the total land area affected by biome shift and tropical evergreen broadleaf forests have the lowest vulnerability (Gonzalez et al., 2010).

Changes in climate will drive a vast array of changes in forest ecosystems around the world (Littell, McKenzie, Kerns, Cushman, & Shaw, 2011). First, climate change alters forest composition by changing plant mortality and recruitment due to climate factors exceeding physiological thresholds for the plant species in the area (Gonzalez et al., 2010; Littell et al., 2011). The two largest climate factors that push species' beyond their physiological thresholds are temperature and precipitation (Gonzalez et al., 2010). As individual plant species reach their tipping point, other species move in and cause plant communities to adapt and form new assemblages (Littell et al., 2011). Studies show that plant communities have changed in this way before (Gonzalez et al., 2010). During the late Quaternary, changes in temperature and precipitation drove shifts in global biomes in a latitudinal direction across continents, similar to the shifts predicted with our current observed changes in climate (Gonzalez et al., 2010).

Unfortunately, vegetation responds slowly to changes in their environment, creating a lag time between the occurrence of the actual environmental change and the vegetation and biome response (Gonzalez et al., 2010; Morin & Thuiller, 2009). Vegetation response can be either positive or negative, with unfavorable climate conditions slowing or stopping plant regeneration, and decreasing range limits by increasing the species' mortality rate while favorable conditions enhance plant reproduction leading to increased range limits (Zimmermann et al.,).

In Colorado and New Mexico, there are a mix of biome types with different susceptibilities to climate change. These biomes range from deserts in southern New Mexico, to tundra in the high altitudes of the Rocky Mountains. This presents unique possibilities for climate driven species shifts in these two states. As global temperatures increases and precipitation patterns change, biomes that are now present in New Mexico will move further into Colorado and to higher altitudes than they are currently at. Similarly, biomes that are currently in Colorado will move further to the north and to higher elevations leading to diminished areas of some biomes and the complete loss of others in the state.

Wildfire and Species

Wildfire is a key component of ecological processes in forests (Soja et al., 2007). Higher wildfire frequency and severity helps to lower forest fuel loads, maintain forest age structure and diversity, as well as removing organic layers to create new seedbeds (Brooks et al., 2004; Landhäusser et al., 2009; Soja et al., 2007). Wildfires maintain lower fuel loads by keeping the accumulation of fuels to a minimum and promote the growth of early succession plant species, which in turn keeps the age of plant species in the forest relatively low (Brooks et al., 2004, Soja et al., 2007).

While wildfires work to maintain forest structure and promote the growth of new plants the presence of fire-ready fuels in a forest directly controls wildfires (Aldersley et al., 2011; Krawchuk et al., 2009; Krawchuk & Moritz, 2011). Only once fire-ready fuels have accumulated in a given area can other variables, such as road network density and percent cropland cover, begin to affect wildfires (Aldersley et al., 2011). The increase of fuel loads in an area combined with horizontal continuity of those fuels tends to increase fire intensity, frequency and extent (Brooks et al., 2004). Horizontal fuel continuity affects how the wind moves across the canopy of vegetation assemblages, which can then influence wildfire rate of spread (Brooks et al., 2004).

After a wildfire, forests begin a recovery process called secondary succession. Secondary succession after a wildfire tends to create a plant community similar to the original community ending in the growth of climax species (Horn, 1974). Secondary succession begins with some form of disturbance, which opens up areas for early succession species to take advantage of (Horn, 1974). Early successional plants are good colonizers and generally have light or bird dispersed seeds (Cook, Yao, Foster, Holt & Patrick, 2005). These plants take advantage of patches opened up by the disturbance and grow quickly (Cook et al., 2005). As slower colonizing but more highly competitive species move in, they replace the early colonizers (Cook et al., 2005). This process continues until the forest area returns to its original state.

As new plant species move into a biome, however, they directly change the fuel properties and wildfire regime of that biome (Bowman et al., 2009, Brooks et al., 2004), acting similarly to invasive plant species. The four-phase invasive plant-fire regime cycle (Brooks et al.,

2004) can then aid in understanding how changes in fire regime occur as new species move into an area. First, researchers must understand both the evolutionary history of the new species and their fuel characteristics so that future changes to the current fire regime can be understood (Brooks et al., 2004). Next comes the introduction of the new species region, which requires the species to overcome various barriers to dispersal (Brooks et al., 2004). In phase three, the new plant species has become abundant across a large enough portion of the biome that they have changed the properties of native populations, communities or ecosystem properties including wildfire characteristics (Brooks et al., 2004). Finally, with the perpetual presence of changed fuel conditions and wildfire characteristics the fire regime has fully changed (Brooks et al., 2004).

Wildfire, Climate and Species

Wildfire, climate and species distribution are all interrelated and co-dependent. Fires influence ecosystem distribution, biome diversity, the carbon cycle and atmospheric chemistry which all work together to affect global climate (Aldersley et al., 2011). As wildfire contributes to changes in global climate, the climate then affects fire regimes by altering species composition, as well as natural wildfire ignitions and weather conditions that are conducive to the propagation of a wildfire (Soja et al., 2007). The distribution of species in an area controls the local wildfire regime. Finally, climate drives changes in species distribution, which then affects the area's fire regime.

Rocky Mountain White Fir as an Indicator Species

Colorado and New Mexico sit at an interesting position in terms of climate as well as species and fire regime change. With deserts in New Mexico and tundra in the high portions of the Rocky Mountain in Colorado, climate driven species shifts to the north and to higher elevations will be observable. In order understand how these multiple systems, wildfire, climate and species distribution, will change the composition of forests, the author chose a single, tree species, rocky mountain white fir (A. *concolor var. concolor),* as an indicator species. The author chose the rocky mountain white fir as an indicator species for two reasons. First, the distribution of rocky mountain white fir in the study area, on a boundary where researchers could easily observe changes in wildfire and climate conditions moving to the north and to higher altitude. Second, rocky mountain white fir is not a well-studied species in the Colorado/New Mexico area.

Rocky mountain white fir is a large, coniferous tree found in the mountains of central and southern Colorado and extends south into New Mexico (Abies concolor, n.d.) that have greenish-grey needles with a white stripe (PLANTS database, n.d.). They can reach a height of 125 feet (38 meters) and a diameter of 3 feet (0.9 meters) (Abies concolor, n.d.). Bark on young trees is smooth and grey, which changes to thick, hard and deeply furrowed as it ages (Abies concolor, n.d.). The roots of rocky mountain white fir tend to be shallow, but can adapt to local conditions and extend deeper if necessary (Abies concolor, n.d.).

As a species, they reach 300-400 years of age (Abies concolor, n.d.). They mainly reproduce by seeds contained in a cone (Abies concolor, n.d.) produced in three to nine year cycles (Abies concolor Gord, n.d.). They can start producing cones around 40 years old with cone production continuing beyond 300 years (Abies concolor, n.d.). Rocky mountain white fir require partial shade to become established, but grow best in full sunlight after establishment (Abies concolor Gord, n.d.). Rocky mountain white fir grow in areas with an annual precipitation range of 510-890 mm (Laacke, 1990), an elevation range of 7,900-10,200 feet in Colorado (DeVelice, Ludwig, Moir, & Ronco, 1986) and 6,400-10,200 feet in New Mexico (Stuever & Hayden, 1996).

The rocky mountain white fir tends to be a climax species in 11 major habitats (Abies concolor Gord, n.d.). Following a wildfire, various brush species can move in and dominate the burned area, creating perfect conditions for the growth of rocky mountain white fir seedlings in partial shade transitioning to full sun after the tree is established (Abies concolor Gord, n.d.). The rocky mountain white fir generally grows in forest types that tend to have mixed fire regimes (where fires occur at different severity and frequency) (Abies concolor, n.d.). The rocky mountain white fir does not have a consistent response to wildfires (Abies concolor, n.d.). Following stand-replacing wildfires, re-establishment takes place through wind-dispersed seeds (Abies concolor, n.d.). Due to the necessity of partial shade, rocky mountain white fir seedlings tend to reestablish quickly after a wildfire if some canopy remains (Abies concolor, n.d.). Seedlings can still reestablish themselves in the area with the full removal of the canopy; however, it will take several years (Abies concolor, n.d.). Wildfire can also encourage the growth of rocky mountain white fir in an area by removing other competing species (Abies concolor, n.d.).

First Steps in Forecasting Future Species Distribution of Rocky Mountain White Fir

With changes in climate, wildfire regimes and species distribution occurring, forecasting the future movement of species becomes important. The first step in understanding the future movement of species requires accurate data regarding the current location of that species. Species distribution maps tend to be reliable sources for the current location of plant species, but because studies of the rocky mountain white fir are rare, E.L. Little’s *Abies concolor* map from 1971 remains the only species distribution map for the rocky mountain white fir. Other types of distribution data comes in the form of either ecological zone maps that include the rocky mountain white fir in different forest types, or data that show rocky mountain white fir as a codominant species in Colorado and New Mexico. Although the movement of tree species is a slow process, rocky mountain white fir may have shifted northward or to higher elevations in accordance with climate change in the past 40 years (McKenney, Pedlar, Lawrence, Campbell, & Hutchinson, 2007).

In order to get an updated species distribution map for the rocky mountain white fir in Colorado and New Mexico the author created a binary model based on available ecological information for the rocky mountain white fir. The goal being that the resulting map would suffice as a new species distribution map of the rocky mountain white fir.

Methods

With a small amount of reliable information available on significant ecological drivers in the growth of rocky mountain white fir, only three factors were consistent across the literature, elevation range, an annual precipitation range, and nine different landcover types that include rocky mountain white fir. The datasets used in the model were a North American DEM for the elevation ranges, the precipitation data was gridded climate data from PRISM, and the landcover data was from the Southwest Regional GAP analysis project. The author classified all datasets into areas where rocky mountain white fir would or would not be present based on the environmental ranges found in the literature. Following reclassification of environmental variables, the author created the binary model. The reclassified datasets (where variable ranges that support rocky mountain white fir had a value of 1, and unsupported ranges had a value of 0) were combined using the following expression:

("Landcover" == 1) & ("Annual Precip" == 1) & ("Elevation" == 1).

Results

Areas where the three reclassified environmental variables overlap (Figure 1) predicted the presence of rocky mountain white fir in the binary model. Initial runs of the binary model included presence of rocky mountain white fir by county from the USDA Plants database (coded as abco) as a fourth variable. Upon analysis of the results, however, it appeared that including rocky mountain white fir by county “mixed” data types, environmental data and literature citations/political boundaries and therefore was not useful in the model.

The inclusion of the USDA rocky mountain white fir presence by county data (Figure 1) showed that there were counties not listed by the USDA database that could have rocky mountain white fir present. The USDA counties with presence (Figure 1) also indicated the binary model would spatially refine areas within counties where rocky mountain white fir is located. Full binary model results (Figure 2) indicate overall refinement of rocky mountain white fir distribution from Little’s map. Notably, the binary model results in New Mexico closely match Little’s distribution, while in Colorado, the binary model follows Little’s distribution in the south but also suggests areas of rocky mountain white fir not found in Little’s map or USDA sources.

New Mexico specific results. The binary model for New Mexico matches Little’s distribution map fairly well in terms of the locations of rocky mountain white fir distribution, but the spatial resolution of the model is much finer (Figure 2). For the most part, the range borders predicted by the model follow the range borders on Little’s map. A few small areas on Little’s map have no prediction of rocky mountain white fir presence in the model. Additionally in the model, some areas (likely of higher elevation and/or higher/lower precipitation) are cutout of the distribution prediction. Other areas appear to have slightly west-shifted populations in the model predictions, particularly in areas to the north. It is unclear if these shifts are due to climate change, other environmental factors or are the result of an artifact of model error (e.g. an issue with projection).

Colorado specific results. In contrast to the New Mexico results, the first run of the Colorado binary model does not match closely with Little's map or the distribution of rocky mountain white fir by county from the USDA PLANTS database (Figure 2). Most notably, the model over-predicts rocky mountain white fir in the west-central portion of Colorado, the northwest part of Colorado, and along the northern Front Range. For example, Little's map shows the presence rocky mountain white fir in Park and Fremont counties that does not exist in the binary model. In the south, the model refines Little's distribution, especially in the San Juan mountain range, showing rocky mountain white fir along the edge of the distribution range, and sparser distribution in the mountainous interior. In all, the binary model refines and redistributes rocky mountain white fir within the boundaries of Little's map as well as the USDA presence by county map, but the accuracy of that refinement is questionable; herbarium records do not suggest the presence of rocky mountain white fir in NW Colorado. While rocky mountain white fir may have advanced north with changing climate even in a relatively short time frame (McKenney et al., 2007), it does not seem feasible that the distribution of rocky mountain white fir would expand from the south to nearly the entire western half of the state in just 40 years.

With the extreme inaccuracy of the model, other, less common ecological variables were included in subsequent model runs in an attempt to improve the accuracy of the results. First, adjustments to the rocky mountain white fir elevation range in Colorado made the model consistent with US Forest Service's Colorado elevation range for rocky mountain white fir. This refinement did not affect the binary model, because the first model run already eliminated the lower elevations.

One literary source stated that, “the upper latitudinal limit of white fir may coincide with a mean max January temperature between -1 and 0” (Mauk & Henderson, 1984). A third iteration of the model included this range of January temperatures (Figure 3). This iteration of the model resulted in a reduced distribution of rocky mountain white fir across the entire state and restricted the presence of rocky mountain white fir further into the northwestern portion of the state. This indicates that the max mean January temperature does not affect the distribution of rocky mountain white fir in Colorado.

Looking at Figure 1, landcover appears to be the most refining or limiting of the three environmental variables making it the variable that, if better understood, could produce a better model. In order to examine the landcover types to see if there were any in northwestern Colorado that might be less representative of rocky mountain white fir, the SWReGap landcover types were separated into individual landcover classes. Upon investigation, no correlation between the anomalous distribution in the west-northwest portion of the state and landcover types could be found as most landcover types were scattered between likely and unlikely areas of distribution throughout the state. Potentially, some cover types, like gambel oak or aspen woodland, may exaggerate presence of white fir, indicating that weighting the landcovers may be a direction worth pursuing.

A second vegetation data set, the Kuchler vegetation types, were used in the model, both instead of, and in conjunction with SWReGap landcovers (Figure 4). This model iteration (Figure 4) refines overall rocky mountain white fir distribution (seen in Figure 2,) but does not fully eliminate the questionable distribution areas in west-northwest Colorado. Without additional supplementary data such as field studies to corroborate the model results and provide an estimate of model error, we have no way of knowing the accuracy of the model.

Figures 2 and 4, as well as other researchers, suggest that the Uncompahgre Plateau, in western Colorado, has rocky mountain white fir not included in Little's species distribution map or the USDA species distribution by county (Lyon, Stephens, Siemers, Culver, Pineda & Zoerner, 1999). This discrepancy reiterates the need for an updated distribution map. This model, while likely not fully accurate, is a first step. The inability to create a fully believable Colorado model based on data sets alone supports the importance of ground-truthing, local knowledge, and traditional methods of botany such as herbarium records and field studies to support if and where rocky mountain white fir has moved in the last 40 years.

To show the probability of occurrence of rocky mountain white fir in Little's map based on the binary model, the author created a probability surface model by converting the binary model raster to point data and completing a point density analysis using Little's species distribution map as a mask. The results show that rocky mountain white fir is more likely found on the SW side of the San Juan mountains, and in the montane forests of northern New Mexico (Figure 5) within the boundaries of Little's map. The results also show there is a lower probability of rocky mountain white fir to the north of the San Juan Mountains and in Southern New Mexico. An overall point distribution of rocky mountain white fir in Colorado and New Mexico would not be useful, because it would continue to reflect our anomalous points in northwestern Colorado.

Future Research Directions and Conclusion

The results of the binary model, as well as a distinct lack of literature specific to the rocky mountain white fir, reveals the need for ground truthing studies of the rocky mountain white fir in Colorado and New Mexico. These studies would serve to both expand sparse herbarium records for the rocky mountain white fir in the area as well as verify the binary model results in this study. Ground truthing could also aid in further refining other plant species tend to co-dominate areas with rocky mountain white fir. All of the results of ground truthing studies would then lead to a more detailed map of the location of rocky mountain white fir.

These ground truthing studies also open the possibility of conducting long-term studies of the responses of rocky mountain white fir to various environmental conditions at different locations in the study area. The results of such long-term studies would expand the currently narrow understanding of what environmental factors encourage or inhibit the growth of rocky mountain white fir.

Finally, after the creation of a more vigorous database on the rocky mountain white fir, it becomes possible to work with other researchers in different fields of study to create a robust model, which takes into account changes in wildfires and climate, to forecast possible future distributions of rocky mountain white fir in Colorado and New Mexico.

The future changes of the distribution of rocky mountain white fir in the study area range from a proliferation to a total disappearance of the species. As a climax species, the rocky mountain white fir might take advantage of changing wildfire regimes and climate. With wildfires clearing new areas of land of species pushed beyond their physiological limits, establishment rocky mountain white fir in new areas further to the north of current distributions becomes possible.

Conversely, due to the topographic features in southern Colorado, the rocky mountain white fir may not be able to propagate much further north than assumed locations. Both Little’s map and the binary model show rocky mountain white fir in the southern portion of Colorado following the terrain where the San Juan Mountains, the Sangre de Cristo Mountains and the Sawatch Range all come together. This could indicate that the topography in the area prohibits the movement of rocky mountain white fir to the north, due to seed dispersal by windblown cones as opposed to seeds carried by birds or the wind. However, if the rocky mountain white fir propagates up to higher altitudes in accordance with changes in temperature, it becomes possible for the species to begin to take advantage of areas opened up by wildfires.

As a climax species, the rocky mountain white fir also takes significantly longer amounts of time to establish itself in a new area. This lag could lead to the loss of the species in Colorado as increasing temperatures continue to push the range of the species to higher elevations while they are trying to adapt to new locations.

The complex possibilities of outcomes for the rocky mountain white fir illustrate the need for more complex, multi-systems analyses of exactly how wildfire, climate and changing species distributions work together to affect species assemblages, forest structure, biomes and ecoregions. Forecasting the results of these interactions can give new insight into how ecosystem goods and services that we currently rely on could change or disappear within any given area in the future, allowing for the possibility of early societal changes to adapt to changing conditions.

A single researcher, or even multiple researchers in a single field of study cannot complete the task of forecasting the future distribution of all plant species; it will take the collaboration of many scientists in fields ranging from geography to ecology to applied mathematics and computer programming. Only through group effort on the front of multiple systems analysis, can humans understand and adapt to ecological changes far into the future.

Acknowledgements

All work on the binary model presented in this thesis is the result of collaboration between the author, Melissa Dozier and Karen Schlatter. Without their assistance, the binary model would not have been completed.

Figures

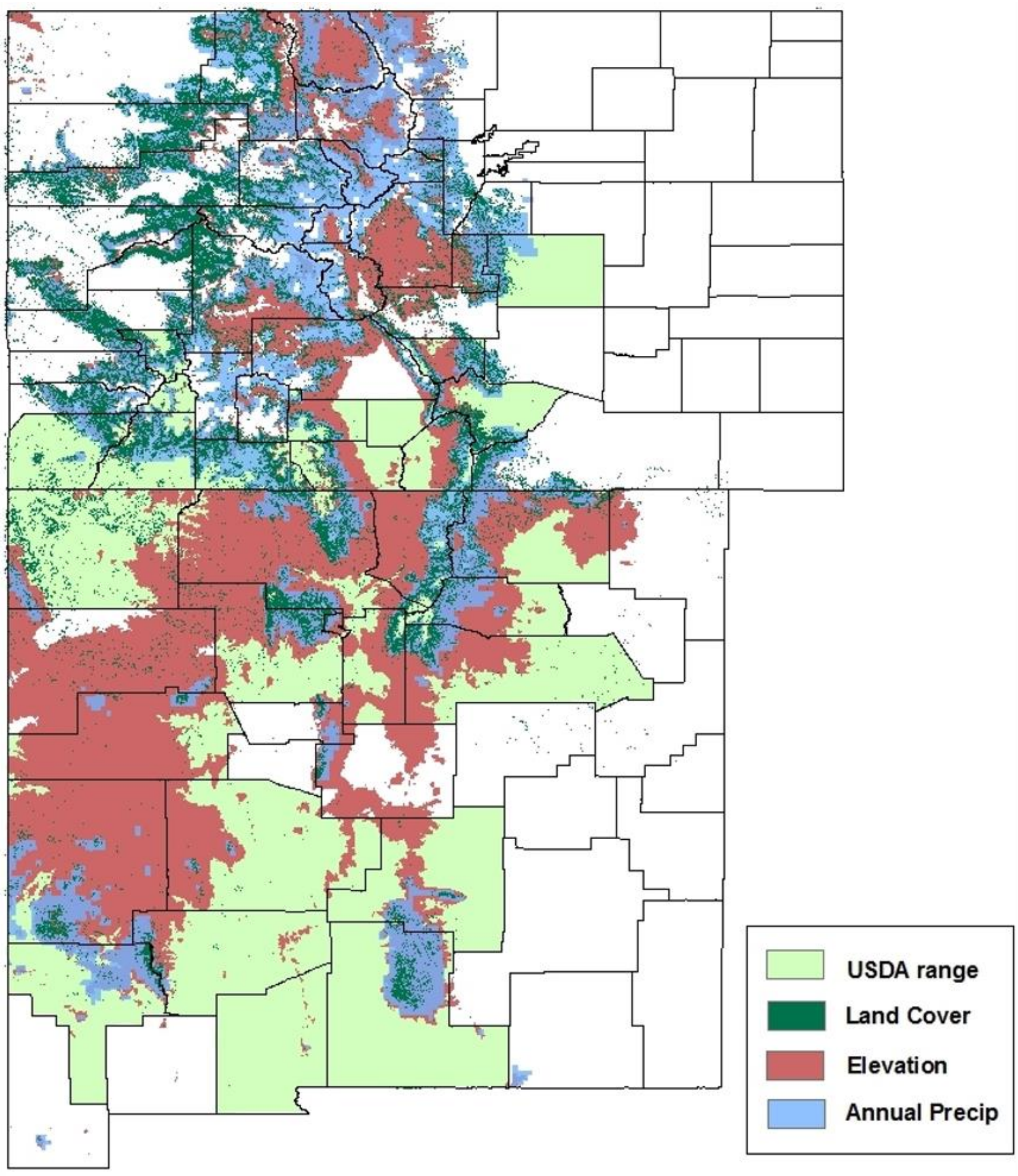

Figure 1. Classified environmental variables used to build the binary model in Colorado and New Mexico overlaid on the USDA Plants database layer indicating the presence of rocky mountain white fir by county.

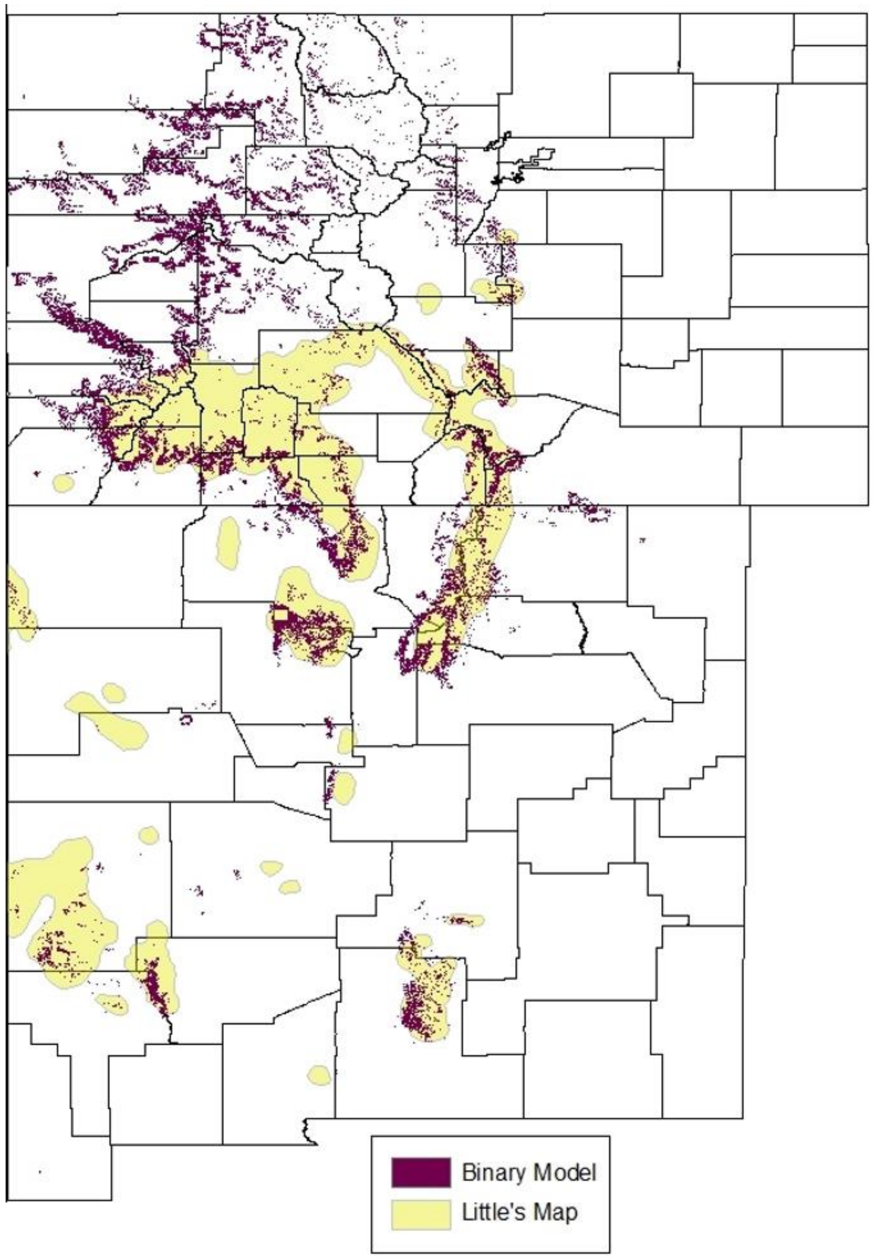

Figure 2. Binary model results for rocky mountain white fir distribution in Colorado and New Mexico overlaid on E.L. Little's rocky mountain white fir species distribution map from 1971.

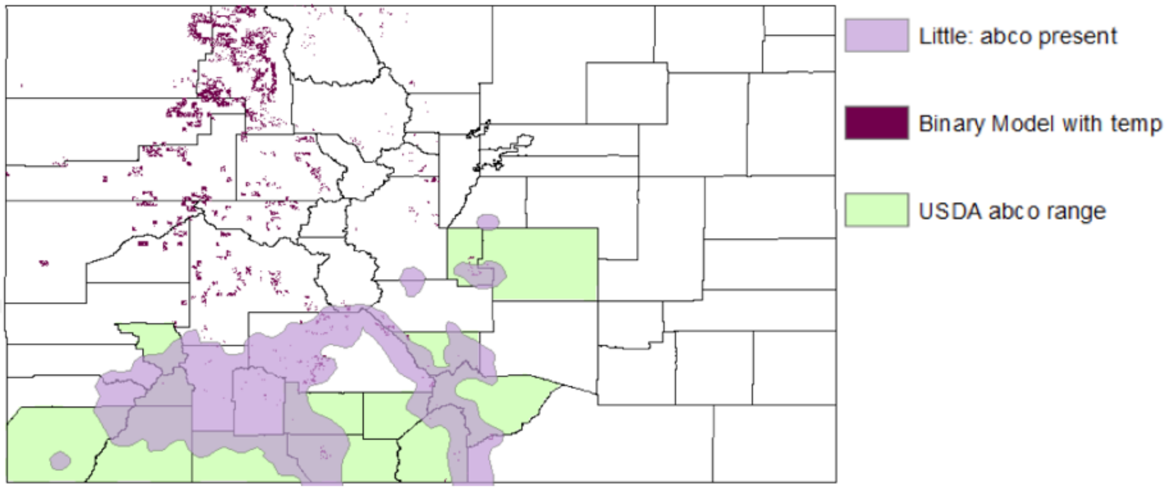

Figure 3. Rocky mountain white fir binary model result including Mauk et al. mean max January temperature variable over laid on Little's species distribution map of rocky mountain white fir and USDA rocky mountain white fir presence by county.

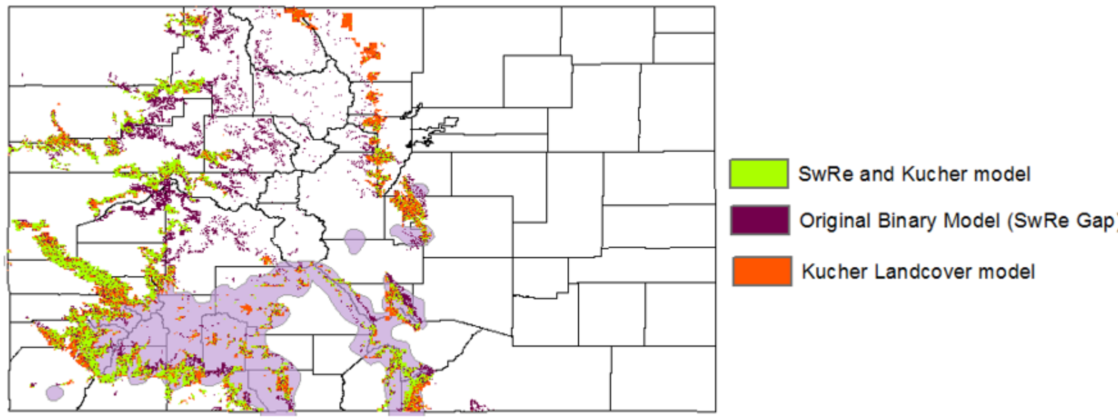

Figure 4. Rocky mountain white fir binary model results using three different landcover inputs: SwRe Gap and Kucher landcover types together, model results with just the Kucher landcover types, and the original binary model results using just the SwRe landcover types.

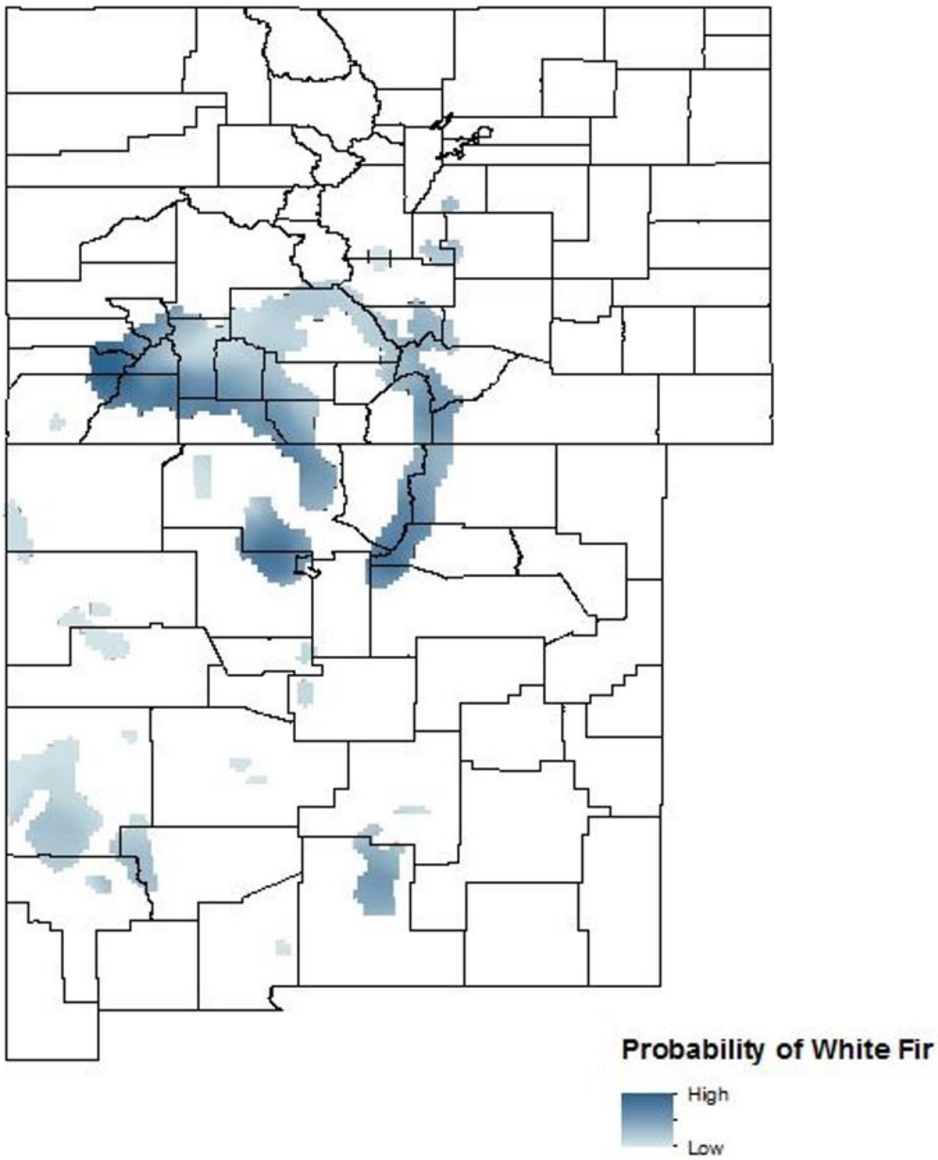

Figure 5. Probability surface showing the likelihood of finding rocky mountain white fir based on the binary model, and clipped to Little's species distribution map.

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