

Citation

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Abstract

The Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA) mandates a periodic assessment of the conditions and trends of the Nation's renewable resources on forests and rangelands. The 2020 RPA Assessment will evaluate the future of the Nation's renewable natural resources through 2070. This publication describes the process used to select a set of four integrated scenarios to represent a plausible span of socioeconomic and climate futures that underpin the natural resource analyses. These four scenarios, and their associated assumptions about population change, economic growth, and climate change, are also described in this document.

Keywords: RPA Assessment, scenarios, Representative Concentration Pathways, Shared Socioeconomic Pathways

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INTRODUCTION

The Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA) (P.L. 93-378, 88 Stat. 475, as amended) mandates a periodic assessment of the condition and trends of the Nation's renewable resources on forests and rangelands. The RPA Assessment provides a snapshot of current forest and rangeland conditions in the United States and trends on all ownerships, identifies drivers of change, and projects renewable resource conditions and trends 50 years into the future. We analyze trends in outdoor recreation, fish and wildlife, biological diversity, wilderness, forests, rangelands, water, urban forests, and landscape patterns, as well as the potential effects of socioeconomic and climate change on these resources. Previous RPA Assessments, supporting publications, and links to recorded webinars are available at <http://www.fs.fed.us/research/rpa>.

The 2020 RPA Assessment is the sixth assessment prepared in response to this mandate (USDA Forest Service 1977, 1980, 1989, 2001, 2012a). Beginning with the 2010 RPA Assessment, a set of integrated scenarios has been used to frame the resource analyses. This report describes the selection process for the 2020 RPA Assessment scenarios and the qualitative and quantitative components of the chosen scenarios that will be used to support 2020 RPA Assessment resource analyses.

Framing the RPA Assessment

The original RPA language focused primarily on an economic evaluation of whether resource supplies could meet consumer demand. The RPA Assessment has broadened to assess resource conditions, ecosystem health, and sustainability to recognize the interrelationships between ecological and socioeconomic conditions in meeting the needs of the American public. While improving the ability to report on economic supply and demand, this broader and more flexible approach enhances our ability to evaluate current and future conditions of the Nation's forests and rangelands.

The 2020 RPA Assessment framework builds on the 2010 RPA Assessment, which was designed to better incorporate the global links and interactions between natural resources, extend our analytical capability to evaluate the potential effects of climate change across resources, and describe more clearly the complexity and uncertainty associated with projecting future conditions and trends (USDA Forest Service 2012b). For the 2020 RPA Assessment we continue this approach to select future scenarios for the United States. These scenarios are tied to global scenarios that depict a coherent interdependent future for global and U.S. population dynamics,

socioeconomic factors, and climate change. These scenarios provide both qualitative and quantitative connections for the domestic resource analyses, which project resource conditions and trends for 50 years.

Scenarios for the RPA Assessment

Scenarios are used to explore alternative futures and are intended to provide a framework for objectively evaluating a plausible range of future resource outcomes. This approach is particularly useful when there is considerable uncertainty about the trajectory of the driving forces behind political, economic, social, and ecological changes (Alcamo et al. 2003; IPCC 2007). A globally linked scenario approach is important for the RPA Assessment because global conditions and trends increasingly affect domestic natural resources. Well-defined global scenarios provide a coherent framework for evaluating outcomes across resource analyses.

A scenario approach can use both qualitative and quantitative methods in visualizing alternative futures based on different socioeconomic or institutional assumptions. The use of the term “scenario” can be confusing because scenarios can be used for various purposes, or in reference to specific types of scenarios (see Moss et al. 2008; USGCRP 2010). For the RPA Assessment, we have adopted the scenario approach used by the Intergovernmental Panel on Climate Change (IPCC). This scenario approach is intended to provide a better understanding of where there may be identifiable thresholds in biophysical and human systems. The scenarios are intended to represent plausible futures to better understand how systems may respond to different rates of change or how different decisions may alter resource trajectories (Moss et al. 2008). Scenarios are not assigned likelihoods, nor are any scenarios intended to be “accurate” per se. Rather, these constructed scenarios provide a means of qualitatively and quantitatively understanding how a range of socioeconomic and climate conditions through time interact to create different natural resource futures.

Though other research groups have constructed their own global scenarios (see Kok et al. 2015 for an evaluation of global scenarios), the combination of the IPCC-based climate and socioeconomic scenarios was chosen as the basis for the 2020 RPA Assessment for several reasons. These scenarios provide quantitative data on both climate and socioeconomic variables over the needed time horizon, are well documented in the scientific literature, have been widely used across a large range of impact studies, and are more current than other sources.

The 2010 RPA Assessment followed the framework used by the IPCC for the Third Assessment Report (TAR) (IPCC 2001) and Fourth Assessment Report (AR4) (IPCC 2007). Carpenter and others (2005) and Nakićenović and others (2000) review examples and uses of scenario analysis in other applications. In the TAR and AR4, greenhouse gas emissions scenarios were developed that were driven by socioeconomic scenarios that in turn drove the climate

projections. As a result, global climate and socioeconomic projections were quantitatively linked in these scenarios. The 2010 RPA Assessment used three of these scenarios and nine associated climate projections to frame the U.S. analyses (USDA Forest Service 2012b).

The 2020 RPA Assessment will rely on the scenario approach used in the IPCC Fifth Assessment Report (AR5) (IPCC 2014). Unlike the sequential approach for scenario development used in TAR and AR4, AR5 used a parallel process (Moss et al. 2010). Four new scenarios representing alternative climate futures were developed independently of the five socioeconomic scenarios (Nakićenović et al. 2014; O'Neill et al. 2014).

The remainder of this document describes the process used to select global climate and socioeconomic scenarios in order to downscale global projections to the national scale and subnational scale, and to select combinations of climate and socioeconomic projections that will be used in the 2020 RPA Assessment. The selected scenarios set the socioeconomic and biophysical context for evaluating resource futures in the 2020 RPA Assessment.

CLIMATE SCENARIOS FOR THE 2020 RPA ASSESSMENT

In this section we first describe the new global climate scenarios developed as part of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) and the process we used to select national-scale climate data and to select the manageable set of climate projections to be used in the 2020 Resources Planning Act (RPA) Assessment. More details about the analysis and selection of the climate models used in the 2020 RPA Assessment can be found in Joyce and Coulson (in press).

Representative Concentration Pathways

Scenarios have been a component of the IPCC reports since 1992. As the scientific understanding of climate and the physics in climate models has improved, the process for creating scenarios has changed accordingly (Moss et al. 2010). For the AR5, a new process was developed for climate scenarios, beginning with Representative Concentration Pathways (RCPs) (Moss et al. 2010; USGCRP 2017). Representative Concentration Pathways are designed to capture the spread of radiative forcing levels found in the emissions literature, and to provide information on components of radiative forcing that are used as input for climate modeling (emissions of greenhouse gases, air pollutants, and land use) (van Vuuren et al. 2011). A large radiative force implies a larger change in the climate. Four RCPs were chosen to encompass a range of radiative forcing levels: a very low forcing¹ level (RCP 2.6, or 2.6 Watts per square meter [W m^{-2}]); two medium stabilization scenarios (RCP 4.5 and RCP 6.0); and one high forcing level (RCP 8.5). The RCP 2.6 scenario is a peak-decline pathway, where radiative forcing peaks at 3.0 W m^{-2} and then declines to 2.6 W m^{-2} by 2100 (fig. 1). Both RCP 4.5 and RCP 6.0 are considered stabilization pathways; that is, the trajectory of radiative forcing over time remains below either 4.5 or 6.0 W m^{-2} , respectively, and stabilizes at those levels by 2100. Finally, RCP 8.5 is a rising radiative forcing pathway, meaning that radiative forcing continues to increase through 2100. The RCPs provide the basis for exploring possible climate futures over a wide range of emission levels (van Vuuren et al. 2011), and are intended to aid in the creation of a new set of integrated socioeconomic and climate scenarios (Moss et al. 2008). For more information about RCPs, see Hayhoe et al. (2017).

¹Radiative forcing is the change in the net (downward minus upward) radiative flux (expressed in Watts per square meter) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide or in the output of the Sun (USGCRP 2017).

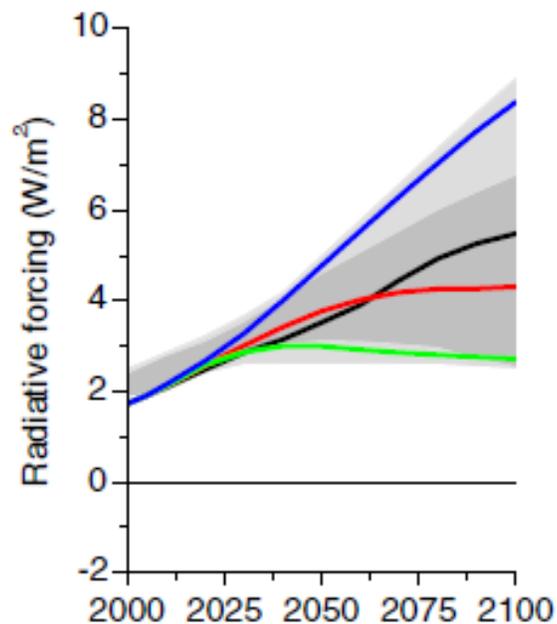


Figure 1—Trends in radiative forcing, 2000–2100, associated with each Representative Concentration Pathway (RCP) scenario. Gray area indicates the 98th (light gray) and 90th (dark gray) percentiles of the literature. Green line: RCP 2.6; red line: RCP 4.5; black line: RCP 6.0; blue line: RCP 8.5. Forcing is relative to preindustrial values and does not include land use (albedo), dust, or nitrate aerosol forcing. (Source: van Vuuren et al. 2011.)

The four RCPs provide time-dependent trajectories of atmospheric greenhouse gas concentrations, land use, and land cover. Several climate modeling institutions across the world used the RCP data to undertake coordinated experiments with different global climate models. As a result, there can be 20 or more climate projections per RCP that are available as part of the Coupled Model Intercomparison Project, Phase 5 (CMIP5) (<https://esgf-node.llnl.gov/projects/cmip5/>) (Hayhoe et al. 2017; Knutti and Sedlack 2013). The projected range of average global temperature change for three of the four RCP scenarios is shown in figure 2. These scenarios, based on more than 20 models used in CMIP5, quantify the impact of human choices and natural variability on future climate (USGRP 2017).

For the RPA Assessment, we needed to decide how many of the RCPs we would use as the basis for RPA projections. From a scientific viewpoint, exploring all available alternative futures is desirable. But resource and time constraints, as well as communication challenges, require a narrowing of choices for the RPA Assessment. We chose to follow the Fourth National

Climate Assessment² approach for framing impacts of climate change by using RCP 4.5 and RCP 8.5 as the two bounding scenarios. RCP 4.5 will be the lower radiative forcing scenario, and RCP 8.5 will be the higher scenario. RCP 2.6 is primarily interesting as a scenario requiring extensive mitigation policy to achieve the lower radiative forcing levels. The RPA Assessment emphasizes futures with no significant change from current policy, so we chose to not include RCP 2.6. We also did not consider RCP 6.0 because resource effects from that scenario are likely to fall between RCP 4.5- and RCP 8.5-based analyses. We believe using a lower end and a higher end scenario will provide a wide range of long-term outcomes and will help communicate findings.

Projected Global Temperatures

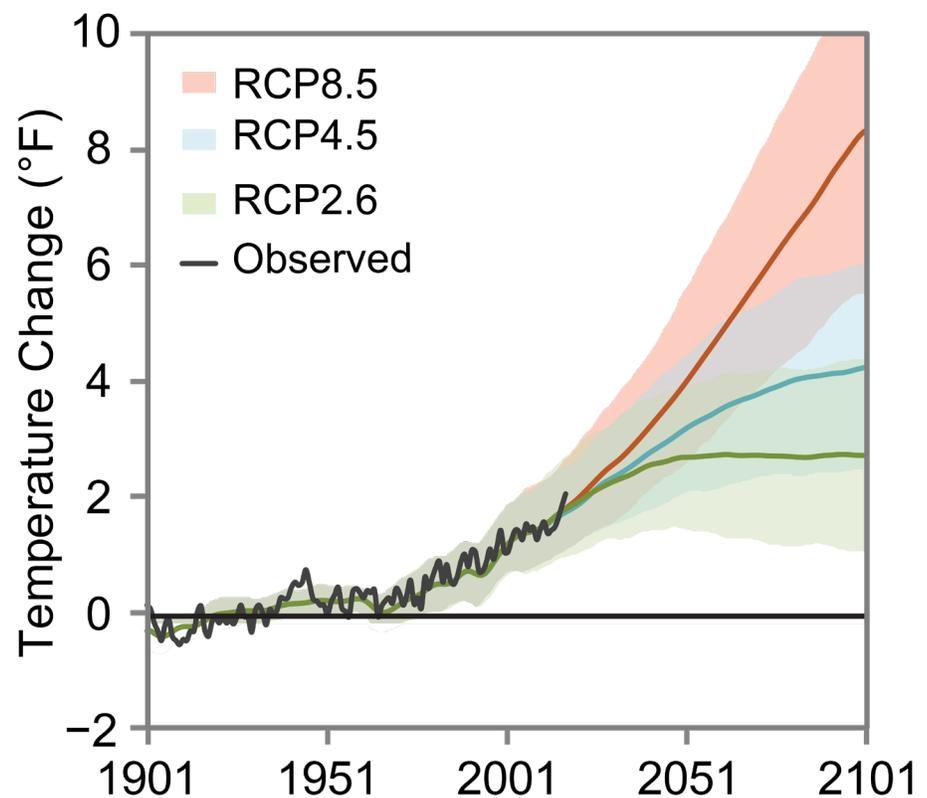


Figure 2—Multimodel simulated time-series, 1900–2100, for the change in global annual mean surface temperature relative to 1901–1960 for a range of the Representative Concentration Pathways (RCPs). These scenarios account for the uncertainty in future emissions from human activities (as analyzed with the 20+ models from around the world used in the most recent international assessment). Solid lines show the mean; associated uncertainties are depicted by shading, showing ± 2 standard deviations (5–95 percent) across the distribution of individual models based on the average over 2081–2100. (Source: USGCRP 2017.)

²The memo detailing the choice of RCPs 4.5 and 8.5 to frame the impact analyses for the Fourth National Climate Assessment can be found at https://scenarios.globalchange.gov/sites/default/files/External%20memo%20NCA4%20scenarios%20framing_20150506.pdf.

NATIONAL CLIMATE PROJECTIONS

Concern over resource and time constraints also affected the number of climate models and projections selected. To choose the individual climate models and associated downscaled projections for the 2020 RPA Assessment, we first identified the climate variables needed for the resource analyses and then developed criteria for selecting the climate models and the projections.

The 2020 RPA Assessment climate projections must provide sufficient information and data to explore the effect of climate change on multiple resources, including wildlife, rangeland and forest condition, water, urban forests, forest products, and recreation. Scientists coordinating the underlying resource analyses identified a set of required climate variables and their spatial and temporal grain and extent. The spatial extent for the RPA Assessment is the United States; however, few models are available that link climate with resource production in Alaska, Hawaii and the Pacific island territories, the U.S. Virgin Islands, and Puerto Rico. Consequently, the climate analyses in the 2020 RPA Assessment focus on the conterminous United States. The spatial grain of data required was as fine as possible.

The spatial scale of the global model output can range from 30 miles (48 kilometers [km]) to 200 miles (322 km) on a side. Several downscaling methods have been developed to bring global model output closer to the scale of historical weather observations and the scale needed for resource management and planning. The set of required climate variables was used to evaluate the ability of existing downscaled climate datasets to meet the needs of the 2020 RPA Assessment with respect to climate scenarios (Joyce and Coulson, in press).

Based on the resource analysis needs of the 2020 RPA Assessment, the downscaled dataset selected was MACAv2-METDATA (Abatzglou 2013; Abatzglou and Brown 2012). This dataset contained statistically downscaled projections from 20 different global climate models, each run under RCP 4.5 and RCP 8.5. The spatial scale for this downscaled dataset was 4 km [2.5 miles], meeting the fine-scale needs for RPA Assessment resource analyses. Both daily and monthly downscaled projections were provided, as well as the historical observed climate that was used in the downscaling process.

Although using as many climate models and projections as available can provide a greater sense of the future range of temperature and precipitation, combining for example two RCP scenarios with multiple climate projections per RCP and numerous socioeconomic scenarios and projections can quickly escalate into an unmanageable number of scenarios and projections. As a result, we developed 3 criteria to screen the 20 climate models, and limited

the number of projections to 5 that would provide an approximation of the overall projection space encompassed by the entire set of models. The five projections for each RCP would become the minimum core set for the 2020 RPA Assessment analyses.

Three criteria were used to screen individual climate models. The first criterion was to use information on historical model performance to eliminate from further consideration those models consistently rated as poor performers. We chose to use the regional rankings developed by Rupp (Rupp 2014, 2016; Rupp et al. 2013), where a consistent methodology was used across three regions in the conterminous United States. Rupp and others' analysis focused on temperature and precipitation variables, important climate variables in RPA Assessment analyses. On the basis of this analysis, 4 climate models were eliminated, reducing the set to 16 models.

The objective of selecting five models was to identify projections that capture the magnitude of change in temperature and precipitation across the entire set. Four projections were identified that represented the least change and the greatest change in temperature (least warm, hottest) and the largest decrease and greatest increase in precipitation (driest, wettest) for the conterminous United States. Ensembles have often been used to reduce the number of projections; ensembles are the average of a number of projections and as such have reduced variability. We chose not to use an ensemble, as the individual model variability may be important when these projections are used as input in resource modeling efforts such as for water, forest condition, range, and wildlife. A fifth projection was selected that would be close to the mean change in temperature and precipitation of all model projections. Two additional criteria were used to screen the models as the projections were being selected. Only one model from a modeling institution was selected to reduce the influence of modeling institution on the 10 projections. If possible, the same model was chosen for RCP 4.5 and RCP 8.5 to reduce model variability across the RCPs. This core set of 5 models provides a reasonable approximation of the overall space encompassed by the larger set of 20 models, but a greatly reduced total effort, thereby making the subsequent analysis feasible.

Based on the criteria and analysis described, we selected five models for each RCP that represent the least warm projection, the hottest projection, the driest projection, the wettest projection, and the middle of the projected temperature and precipitation space of the 16 models (table 1, fig. 3). We were able to select the same model for both RCP 4.5 and RCP 8.5. Although these models represent the magnitude of change for one climate variable, the user should be aware of what each model projects for the other climate variable. Models selected to represent the magnitude of change for one climate variable (such as temperature) may not project the mid-range value for the other climate variable (such as precipitation). The historical modeled and projected climate data used in the RPA Assessment are archived in the USDA Forest Service's Research Data Archive (Coulson and Joyce 2020; Joyce and Coulson, in press; Joyce et al. 2018).

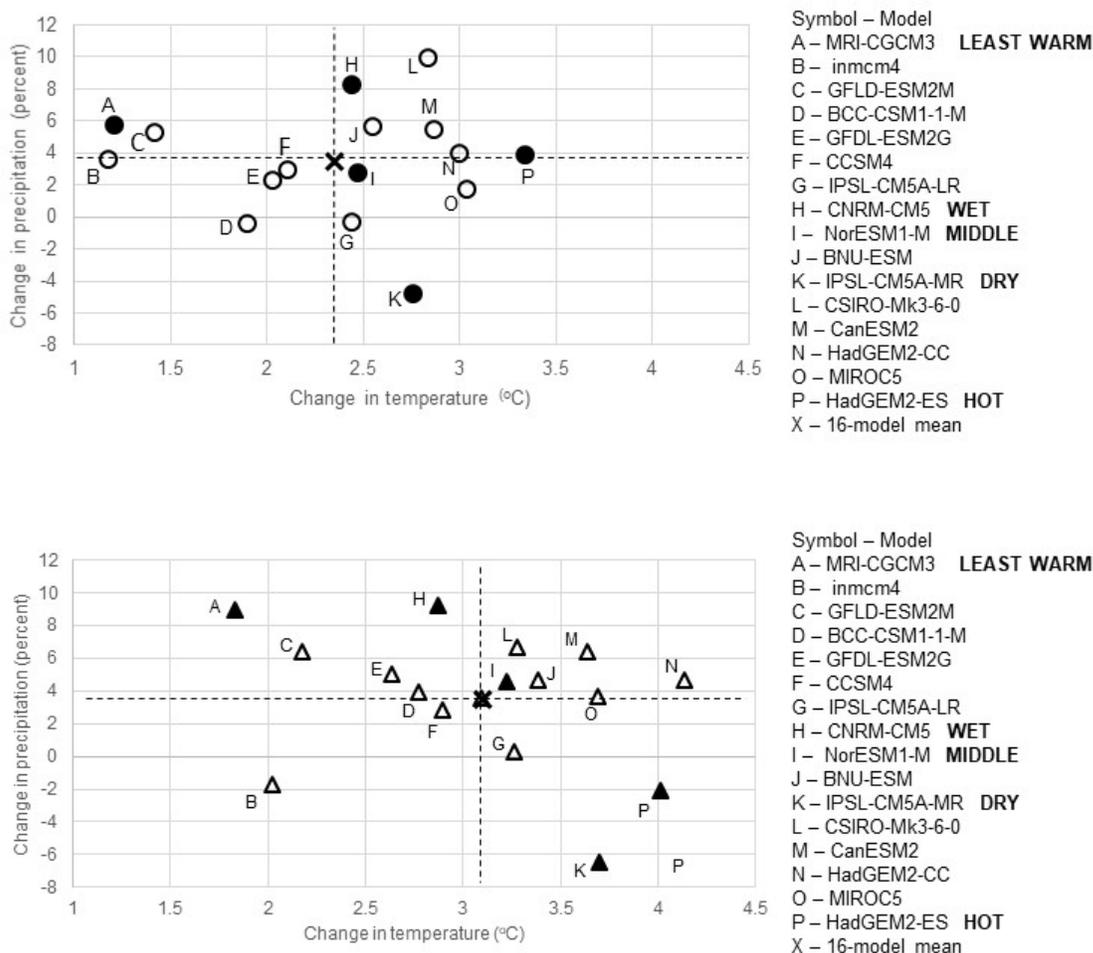


Figure 3—Precipitation change (percent) plotted against temperature difference (°C) at mid-century (2041–2070) from the historical period (1971–2000) under (A) scenario RCP 4.5 and (B) scenario RCP 8.5 for all 16 models at the scale of the conterminous United States. Individual models are denoted by open circles in the RCP 4.5 scenario and open triangles in the RCP 8.5 scenario. The black ‘X’ represents the mean temperature and precipitation change for all models in each scenario. Four of the 20 screened models were eliminated based on selection criteria. The core model projections are identified as filled circles or triangles and noted Least Warm, Hot, Dry, Wet, and Middle in legend. (Source: Joyce and Coulson, in press.)

Table 1—Core set of climate model projections for mid-century analysis in the 2020 RPA Assessment (Source: Joyce and Coulson, in press).

| | Least Warm | Hot | Dry | Wet | Middle |
|---------------------------|--|--|---------------------------------------|--|----------------------------------|
| RCP 4.5 | MRI-CGCM3 | HadGEM2-ES | IPSL-CM5A-MR | CNRM-CM5 | NorESM1-M |
| RCP 8.5 | MRI-CGCM3 | HadGEM2-ES | IPSL-CM5A-MR | CNRM-CM5 | NorESM1-M |
| Climate model institution | Meteorological Research Institute, Japan | Met Office Hadley Centre, United Kingdom | Institut Pierre Simon Laplace, France | National Centre of Meteorological Research, France | Norwegian Climate Center, Norway |

The RPA Assessment focuses on the next 50 years (through 2070), so we selected models that provided the temperature and precipitation range through 2070 compared to the historical period, which we defined as 1971 through 2000. We also evaluated whether model selection based on behavior at 2070 would be different from behavior at end of century (2070–2099). We concluded that the same core models could be used for end-of-century analysis to capture the range of climate futures. These core models were selected at the conterminous U.S. scale. We also evaluated their utility as core models for least warm, hottest, driest, wettest, and middle within regions of the National Forest System. At the regional scale, the relative comparisons are appropriate for all regions; that is, the hottest core model is always hotter than the least warm projection and the wettest projection is always wetter than the driest core model in each region. Additional details on all of the analyses can be found in Joyce and Coulson (in press).

SOCIOECONOMIC SCENARIOS FOR THE 2020 RPA ASSESSMENT

In this section we first describe the global socioeconomic scenarios developed in parallel to the Representative Concentration Pathways (RCPs) and how we selected the socioeconomic pathways to be used in the 2020 Resources Planning Act (RPA) Assessment. The remainder of the section describes the process to create nationally downscaled socioeconomic data and selection of a subset of socioeconomic projections to represent the potential range of socioeconomic change.

Global Socioeconomic Scenarios

Shared Socioeconomic Pathways (SSPs) were developed in parallel to the RCPs to provide scenarios of plausible alternative pathways of societal development (O'Neill et al. 2014). They are composed of storylines that vary across dimensions of variables characterizing uncertainty about the future: population trajectories, economic growth, technology, trade, and governance. Five SSPs were developed, and each was described in terms of the difficulties, costs, research and development investment levels, or degree of policy changes (“challenges”) involved in mitigating or adapting to climate change. Four of the SSPs describe the range of high challenges (difficult, costly, and entailing large policy shifts) and low challenges for global adaptation and mitigation, while a fifth SSP defines an intermediate case. The SSPs do not include climate feedbacks or specific policy options (O'Neill et al. 2014).

The SSPs can be described across a selected set of quantitative or qualitative characteristics (table 2). The characterization of change is relative both to current conditions and to change among the SSPs. Each SSP has a narrative and associated characteristics that make the pathway distinct from the others, although there can be considerable regional variability within a particular SSP. The trend for each scenario characteristic shown in table 2 is the general global trend. For example, global population growth is the lowest under SSP5, but population growth in the United States is highest under this SSP. Similarly, economic growth under SSP1 is higher in low-income countries than in high-income countries (see O'Neill et al. 2017 for more detailed SSP descriptions). To develop national socioeconomic scenarios linked to the global SSPs, we focused on the SSP variation in demographic and economic characteristics, which have been quantified at the country level (data available on the SSP public database at <https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome>).

Table 2—Selected global characteristics of Shared Socioeconomic Pathways (SSPs) (Source: based on O'Neill et al. 2017).

| SSP element | SSP1 | SSP2 | SSP3 | SSP4 | SSP5 |
|----------------------------|---------------------------------------|------------------------------------|--|---|--------------------------|
| Population growth | Low | Medium | High | Medium-high | Low |
| Migration | Medium | Medium | Low | Medium | High |
| Urbanization | High | Medium | Low | Medium-high | High |
| Per capita economic growth | Medium-high | Medium | Low | Low-medium | High |
| International trade | Moderate | Moderate | Strongly constrained | Moderate | High |
| Globalization | Connected markets | Semiopen globalized economy | Deglobalizing | Limited global connections | Strongly globalized |
| Technology development | Rapid | Medium, uneven | Slow | Slow to rapid by sector | Rapid |
| Energy technology | Emphasis on efficiency and renewables | Continued reliance on fossil fuels | Slow change, directed to domestic energy | Diversified, with efficiency and low-carbon | Directed to fossil fuels |
| Carbon intensity | Low | Medium | Depends on domestic sources | Low-medium | High |
| Energy intensity | Low | Uneven | High | Low-medium | High |

The country-level projections of both population and income consistent with SSP global narratives were undertaken by three modeling groups. While the projections of population were consistent across all three groups, there were variations in projections of gross domestic product (GDP). In the following comparisons, we relied on the economic projections provided by the International Institute for Applied Systems Analysis (IIASA 2018) because IIASA included more country-level projections that are important for modeling international trade flows as applied in RPA modeling of global wood products markets. The IIASA modeling methodology is described in Cuaresma (2017).

The SSP data for global and U.S. population and GDP are projected through 2100 to be consistent with the IPCC climate change projections (fig. 4). The 2020 RPA Assessment will focus on the time period 2020 to 2070. As seen in figure 4, divergence across the SSPs tends to accelerate to the end of the century.

Global and U.S. trends do not necessarily follow the same trajectory across SSPs. As shown in figure 4, global population trends and U.S. population trends diverge, with the highest population growth scenario for the United States having very little population growth globally (SSP5). Trends in GDP growth are more consistent between U.S. and global trends, although for the United States the SSP projecting the lowest economic growth is SSP3, while globally it is SSP4. In SSP1, world population begins declining after 2050, whereas U.S. population continues to grow until about 2090 and then flattens. U.S. trends for SSP2 are almost identical to SSP1, whereas globally the two SSPs diverge markedly in population but are similar in GDP trends.

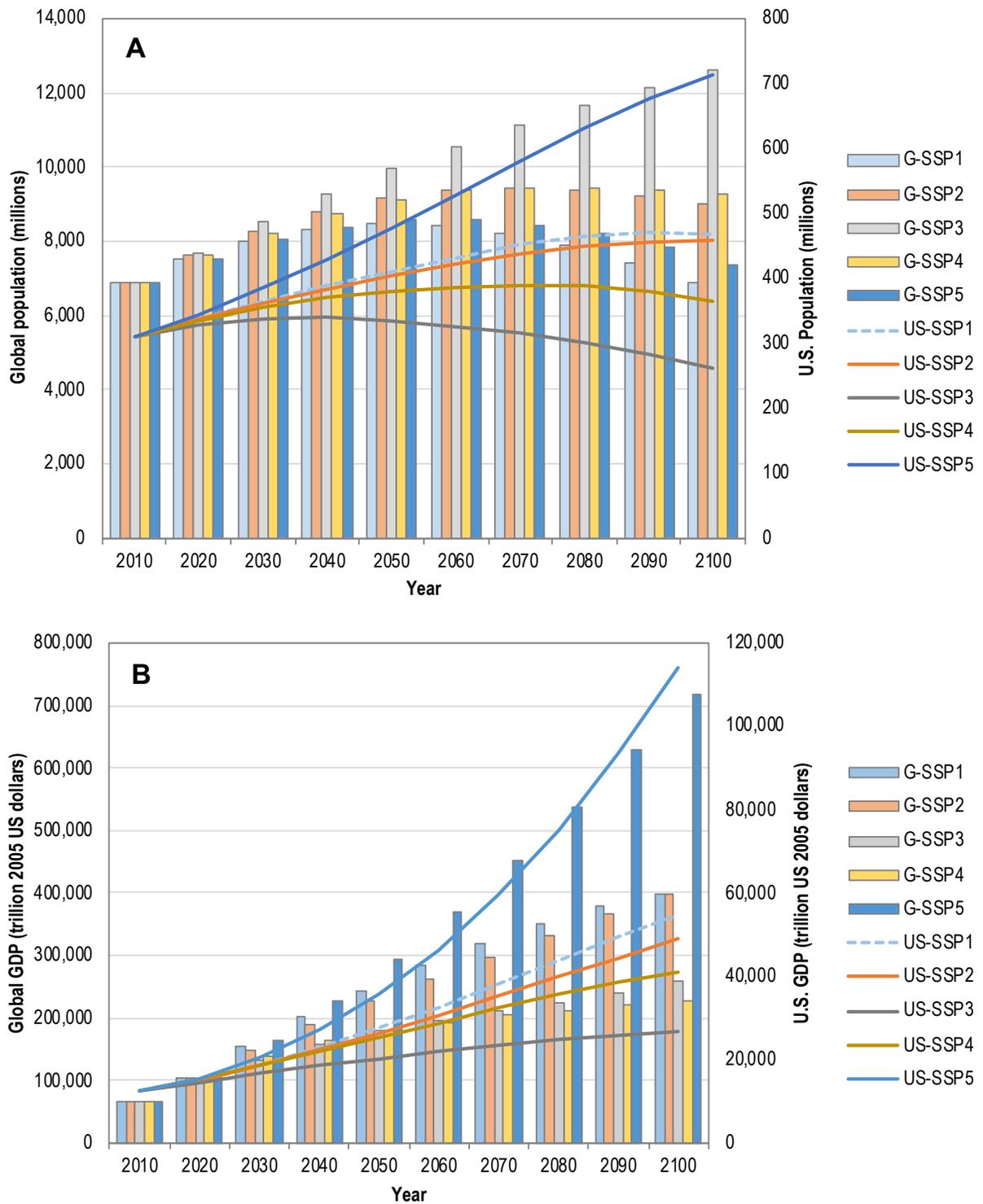


Figure 4—(A) Global (G) and U.S. population projections and (B) global and U.S. gross domestic product (GDP) projections by Shared Socioeconomic Pathway (SSP), 2010–2100.

SSP5 and SSP3 bracket the high and low changes in population and GDP for the United States, with the highest population growth associated with the highest economic growth (SSP5) and the lowest economic growth associated with a declining population (SSP3) (fig. 5). These patterns are tied to several interacting assumptions about economic growth, fertility and mortality, migration patterns, and the openness of the global economy.

National Socioeconomic Projections

The range of socioeconomic trends described by the five SSPs represents highly divergent futures to consider when we are creating national socioeconomic scenarios for the 2020 RPA Assessment. As with the RCPs, we must select SSPs to use as a basis for domestic scenarios. Before making that choice, we developed a methodology to downscale the country-level SSP data to a finer spatial scale. As described in the previous section, considerable effort by the climate science community has been devoted to downscaling climate projections. The availability of downscaled data has eliminated the need to develop our own downscaled climate data for the 2020 RPA Assessment. No similar effort has been devoted to socioeconomic scenarios—specifically to jointly downscaling the SSP-based population and economic projections. Projections of population and income that are downscaled using a consistent approach are critical inputs to various modeling systems.

Socioeconomic assumptions have long been a part of RPA Assessment assumptions, as they play a central role in natural resource impacts across the United States. The U.S. Census Bureau routinely updates official national population projections for the United States. The census projections have been used to downscale national population projections to county-level projections, but these downscaled projections provide only one projection for less than 50 years, and the methodology is proprietary (Woods and Poole Economics, Inc. 2020). The U.S. Environmental Protection Agency (2020) has provided SSP-based downscaled population projections for SSP2 and SSP5, but these projections do not extend to economic variables.

Socioeconomic projections at a finer than national spatial scale were not available to meet the needs for RPA Assessment analyses; consequently, we developed county-level projections of population and income change for each SSP. The method that we used to project these variables was based on economic theory and is consistent with county-scale historical patterns of change (Wear and Prestemon 2019).

Our approach, derived from economic growth theory (Solow 1956), assumes that population and income changes are interrelated and generally consistent with per capita income convergence across locations over time. The concept of convergence posits that factors of production, including labor and capital, will move from locations of relative abundance, where earnings are low, to locations of relative scarcity, where earnings are high. Capital and labor

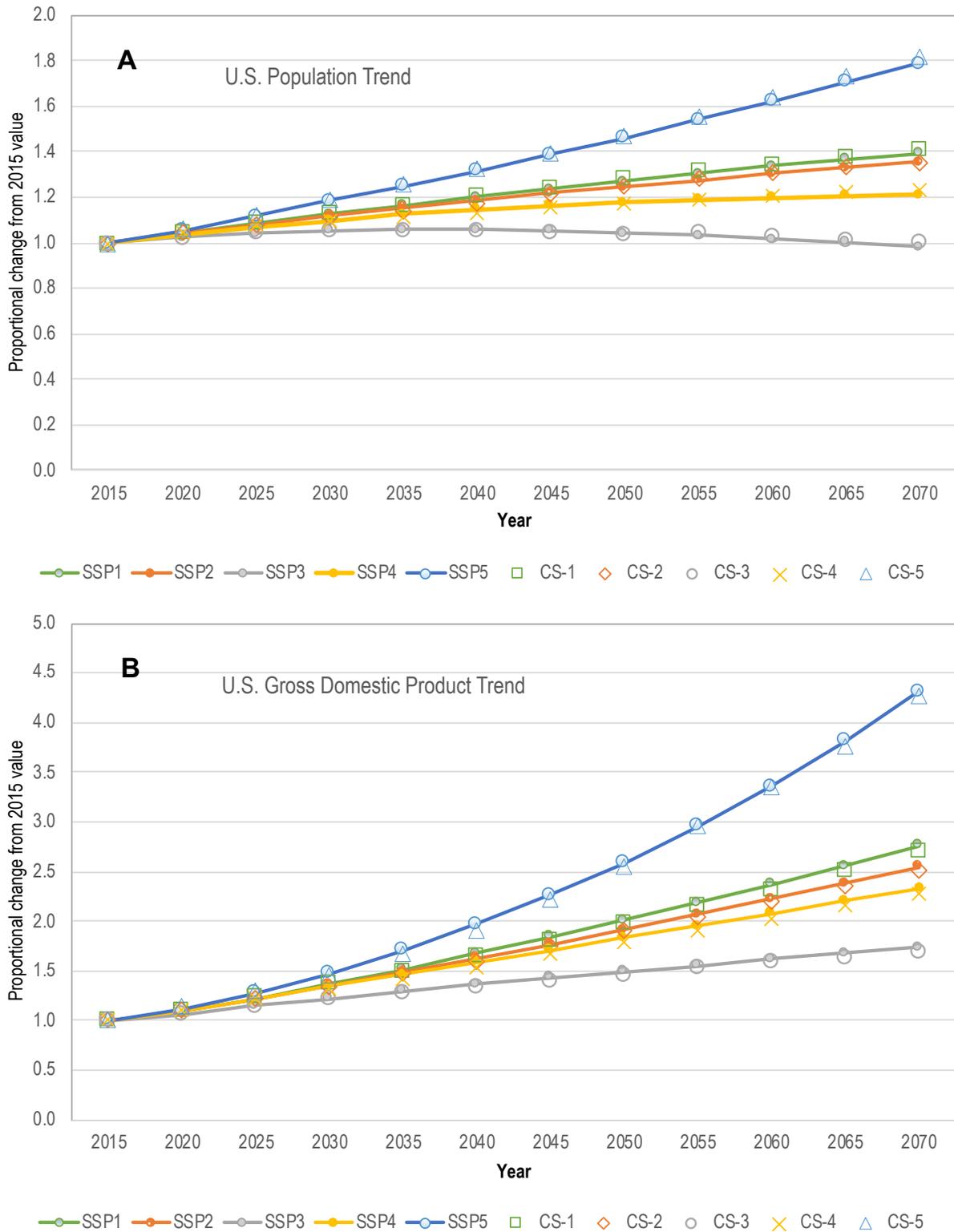


Figure 5—Projections of (A) U.S. population and (B) U.S. gross domestic product. Lines with solid circles are based on the IIASA Integrated Assessment Model for five Shared Socioeconomic Pathways (SSPs). Hollow symbols are total values from the calibrated simulations (CS) of county-level changes for the SSPs.

mobility converge toward equal relative factor abundance and earnings across locations. One measurable effect of convergence is that locations which today have lower per capita income will experience faster future rates of per capita income growth compared to locations which today have higher per capita income. If economic growth theory applies, fine-scale allocations of population and income across space should be jointly determined in the long run. Such a connection could mean that models of downscaled population and income that recognize their joint relationship would provide more accurate projections of population and income changes at fine spatial scales compared to methods that ignore their relationship. However, previous efforts to downscale national-scale population and income to spatial units that are county scale or smaller in the United States (e.g., Jones and O'Neill 2013; McKee et. 2015) have not linked population and income in a manner consistent with per capita income convergence.

Our approach to downscaling population and income is based on models that incorporate their joint relationships. Observations are explained statistically with fixed-effects cross-sectional time series panel models of population and per capita personal income at the county level, with data from 1970 to 2010 on a 5-year time-step. Furthermore, our method recognizes that econometric estimation of models based on spatially arranged data needs to account for the spatial arrangement explicitly by including spatial weights matrices (e.g. Anselin 1988), and account for temporal change processes for population and per capita income by including time lags of both variables. Given that we cannot predict which model specification would work best in producing long-term projections of population and income at fine spatial scales, we use a model averaging approach to include information from alternative models. Because our approach involves uncertainty about the model functional form most likely to minimize bias and forecast error, we sought to minimize these twin criteria by using this approach, rather than model selection (Hansen 2007). Averages of projections from a set of competing models have been shown to perform better than individual models selected using model selection criteria such as the Akaike information criterion or Bayesian information criterion (Berge 2015). Performance could improve because of the overlapping information sets involved in each individual specification (Bates and Granger 1969) or because their combination alleviates the effects of model misspecifications (Hendry and Clements 2004; Stock and Watson 2004; Timmermann 2006). Variations of the model averaging approach are widespread in the econometrics literature (e.g., Hoeting et al. 1999).

We applied the methodology to estimate county-level projections for all five SSPs. In these projections, the rate of personal income change nationwide (summed across all counties) was constrained to match the rate of GDP change nationwide as projected by IIASA (2018) for the United States for each of the SSPs. Under SSP3, population grows slowly to a peak in 2035 and then gradually declines to 2010 population levels by 2070, while income grows steadily at about 1 percent per year (from about \$13 billion in

2010 to about \$24 billion in 2070). Under SSP5, population expands by 86 percent, from 313 million to 581 million between 2010 and 2070, while real GDP grows at a rate of 2.5 percent per year between 2010 and 2070, more than quadrupling over this period. SSPs 1, 2, and 4 provide intermediate projections with population growing to between 390 million and 451 million people in 2070 and annual GDP growth rates of between 1.4 and 1.8 percent.

The cumulative distributions of county populations for the historical period and the projection period show overall outward shifts in the cumulative distribution of population for all SSPs, although the degree of shifts varies across SSPs. Maps of change in population density (fig. 6) show the influence of spatial factors and differences in growth across scenarios. Historical patterns of population growth indicate increasingly concentrated populations over time in the United States, a result aligned with the spatial and temporal autocorrelation identified in our statistical models. Likewise, our projections indicate an ongoing process of interregional population movement. We project a shift in the Nation's population away from the Northeast and Midwest and toward the South and West, although the rates of such interregional population shifts vary across SSPs; the smallest shift occurs under the lowest population growth rate. Comparing the lowest population growth scenario (SSP3) with the highest population growth scenario (SSP5) (fig. 6) demonstrates how populations would expand from existing metropolitan cores into but not much beyond the closest surrounding rural counties. A large share of the current rural United States experiences either new or continued population losses or stable population across all scenarios. See Wear and Prestemon (2019) for a comparison of projections across scenarios and for details on model specification, performance, and potential limitations.

Though we developed county-level downscaled data for all five SSPs, we decided to limit the number of SSPs to be considered in the selected RPA Assessment scenarios. We chose SSP3 and SSP5 because they bound the demographic and economic change for the United States and capture most of the range in global change as well. SSP4 has lower growth in global GDP than SSP3, but the difference is relatively small compared to variation across the other SSPs. SSP1 and SSP2 follow similar trajectories for the United States and globally; however, the underlying narrative for these pathways offers opportunities to explore differences among resource- and sector-specific variables that could have different implications for natural resources. For example, the narrative for SSP1 is more focused on low-emission energy sources, whereas SSP2 is more tightly linked to historical patterns of energy use. Therefore, we decided to retain both SSP1 and SSP2. We eliminated SSP4 because its trajectory falls between SSP3 and SSP2.

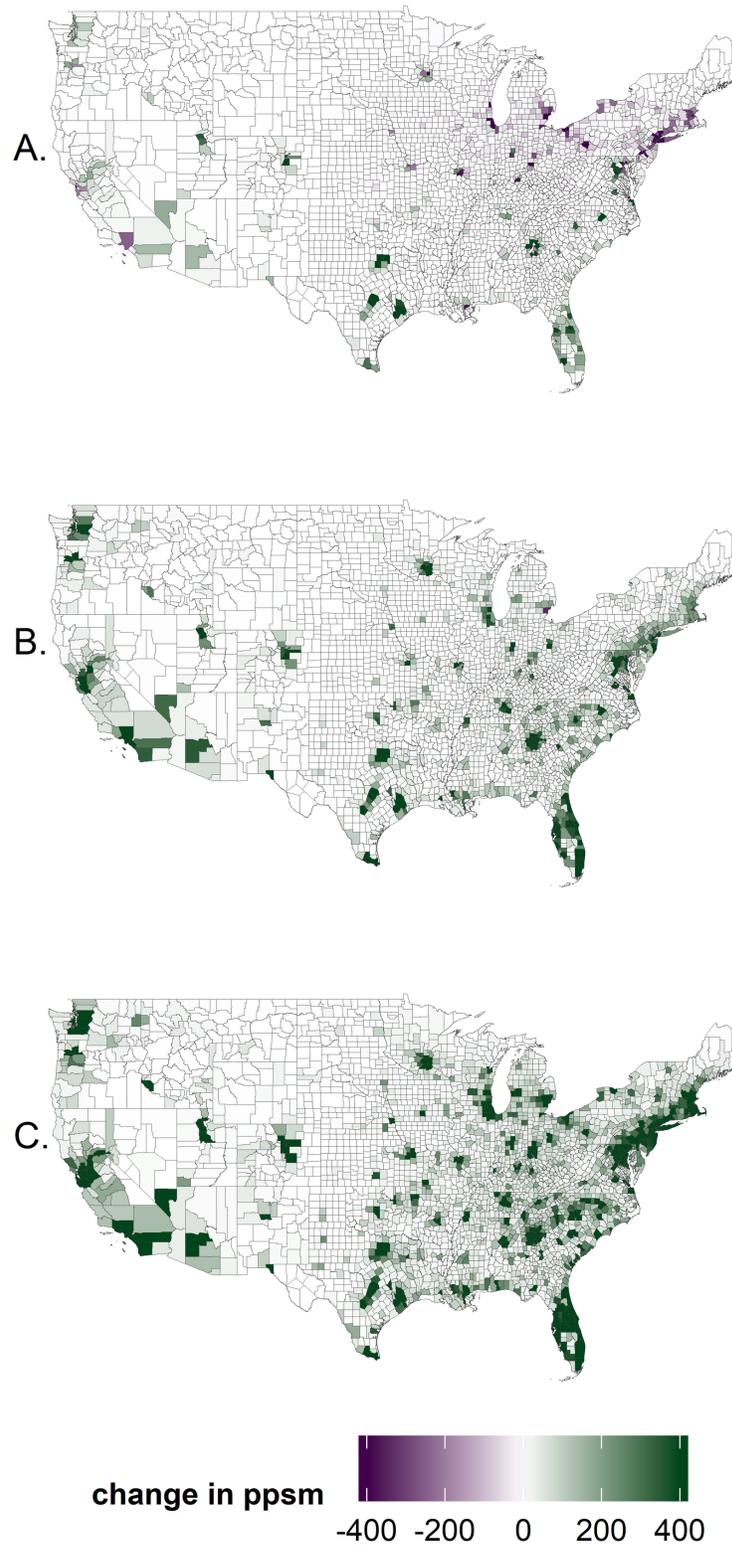


Figure 6—Projected change in population density (people per square mile, ppsm), 2010–2070, for Shared Socioeconomic Pathways (SSPs): (A) SSP3 (low growth), (B) SSP2 (moderate growth), and (C) SSP5 (high growth).

2020 RPA ASSESSMENT SCENARIOS

The Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) were developed to provide a scenario matrix architecture to assist in the development of common scenarios that can be used across different climate change research communities. The SSPs provide a range of socioeconomic trajectories that can be combined with the RCP-based climate projections to explore climate impacts (van Vuuren and Carter 2014; van Vuuren et al. 2014). While the emphasis of these products is climate change, the scenario matrix architecture is a useful mechanism to link global and U.S. scenarios, and it defines a set of integrated scenarios for the 2020 Resources Planning Act (RPA) Assessment.

The RPA Assessment requires national-scale socioeconomic futures that can be generally mapped to global climate outcomes, and it requires that data are downscaled to fine grains to match the economic and ecological context of the resource analyses. It is unreasonable to assume that U.S. economic and demographic changes can be considered outside the context of global conditions. In addition, the set of chosen scenarios should span a broad range of plausible futures to avoid anchoring in too narrow a range of effects.

Criteria for 2020 RPA Assessment Scenarios

While the RPA Assessment scenarios need to link at least at the broad qualitative level to the general worldviews of the SSP and RCP futures, they also must provide a compelling range of futures for the United States. Several criteria were considered in selecting the combination of climate and socioeconomic futures that define the 2020 RPA Assessment scenarios. As described in the *Representative Concentration Pathways* section, the selection of climate “futures” was limited by using RCP 4.5 and RCP 8.5 as bounding pathways, followed by the selection of five core global climate models per RCP to represent the potential range of climate change across precipitation and temperature gradients within those RCPs.

After choosing four SSPs, we had a choice of eight possible RCP–SSP combinations for the 2020 RPA Assessment scenarios (two RCPs and four SSPs). With 5 climate projections for each of the 8 scenarios, there were potentially 40 future socioeconomic-climate outcomes for the United States. We did not have a predetermined number of desired scenarios, but were concerned about having a manageable number of futures that would not exceed computational and personnel resources for conducting the analyses and communicating the results.

Aside from these practical considerations, we concentrated on assessing the plausibility of potential RCP–SSP combinations—a challenging task. By plausibility, we mean that the degree of global warming indicated by the RCP is consistent with the emissions generated by the socioeconomic activity depicted in the storyline for each SSP. The development of the RCPs and SSPs and their associated projections assumed that any combination of RCP and SSP is conceptually plausible. However, adjustments to assumptions, which could include policy assumptions, might be necessary for some RCP–SSP combinations (van Vuuren et al. 2014). The RPA Assessment analyses are traditionally based on continuation of current policies, so we preferred to select RCP–SSP combinations that did not require assumptions which would indicate large departures from current policies for the RPA Assessment scenarios.

Recent experiments that tested potential consistency between RCPs and SSPs provided additional information to help judge the plausibility of different RCP–SSP combinations. As summarized in Riahi et al. (2017), several Integrated Assessment Model teams undertook a set of analyses that characterized the SSPs using both the quantitative socioeconomic data described previously and quantitative interpretations of key SSP characteristics such as energy use, land use, and technology change. The modeling teams began with “baseline” scenarios that used the quantitative data from each SSP and assumed continuation of current climate policies. They then developed mitigation scenarios that explored the implications of various climate mitigation policies on emissions, for example by implementing a carbon price or imagining alternative mixes of energy sources. The data output from these analyses are available on the SSP database (<https://tntcat.iiasa.ac.at/SspDb>) at the global level and for five global regions, including the Organisation for Economic Cooperation and Development region that includes the United States³.

The results of these experiments were instructive for selecting RPA Assessment scenario combinations. The SSP baseline scenarios were of most interest because they provide an estimate of carbon dioxide equivalent concentrations and associated radiative forcing levels that are generally consistent with current policies. The SSP baseline scenarios had greenhouse concentrations that translated to a radiative forcing level by 2100 ranging from 5.0 to 8.7 W m⁻². The highest and lowest radiative forcing levels across the baseline results are shown in figure 7 for the four SSPs being used in the 2020 RPA Assessment. The results for both 2070 and 2100 are displayed. Across all of the baseline runs to 2100, only the SSP5 baseline scenario reached a forcing level of RCP 8.5, but all the others exceeded

³A special issue of *Global Environmental Change* describes these experiments (2017; Issue 42).

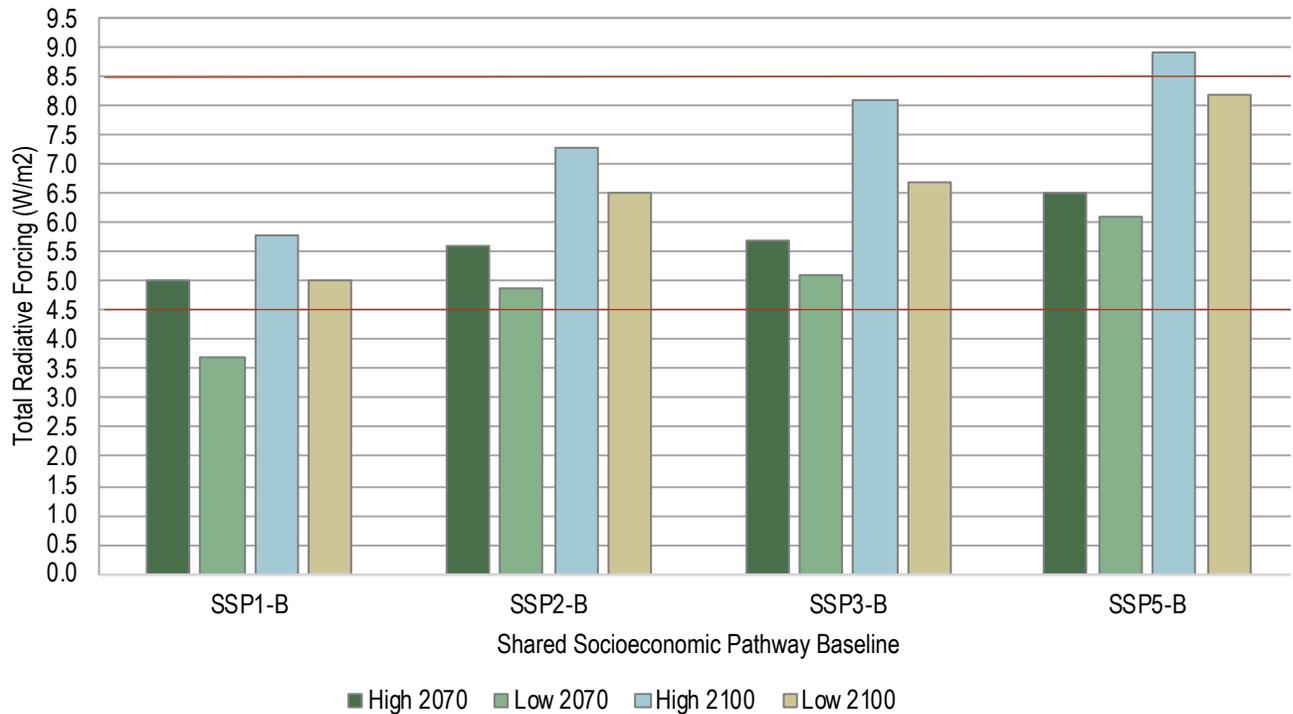


Figure 7—Range of total radiative forcing levels associated with Integrated Assessment Model baseline results for selected Shared Socioeconomic Pathways (SSPs) in 2070 and 2100.

RCP 4.5 forcing levels by 2100. Only SSP1 remained under RCP 4.5 by 2070 under some baseline results. The results of the baseline analyses indicate that achieving consistency with the RCPs of 6.0 and below would require additional technical or policy assumptions to reduce greenhouse gas emissions (Riahi et al. 2017).

SSP1 is the only baseline scenario that resulted in radiative forcing close to the RCP 4.5 level, and was judged to be the only SSP that could plausibly link with RCP 4.5 for RPA Assessment purposes. Combining any of the remaining SSPs with RCP 4.5 would require varying levels of technology or policy assumptions that are beyond the scope of RPA Assessment analyses except when the RPA framework is used specifically for policy analysis. Combining SSP5 and RCP 8.5 is plausible according to the baseline results. The remaining SSPs, SSP2 and SSP3, produced forcing levels between RCP 6.0 and RCP 8.5. Pairing these SSPs with RCP 8.5-based climate projections could overstate climate influence in RPA resource models. In summary, pairing SSPs and RCPs and assessing the mutual consistency of their assumptions is an inexact science, and various choices are probably equally justified in a scenario-driven assessment such as the RPA Assessment.

Therefore, four RCP–SSP combinations were chosen as plausible to underpin 2020 RPA Assessment analyses of resource effects without significant policy changes (fig. 8). Only one RCP–SSP combination is based on RCP 4.5. Rather than focusing on future outcomes that equally consider the full range of scientific uncertainty, we are focusing more attention on outcomes with higher societal risk from changing socioeconomic and climate conditions. Low probability, high impact outcomes tend to carry the greatest societal risk. Those risks are highest under scenarios of the greatest climate change, such as those associated with RCP 8.5. Decisionmakers are likely to be most interested in understanding higher impact futures so that they can plan for the most extreme outcomes (Weaver et al. 2017).

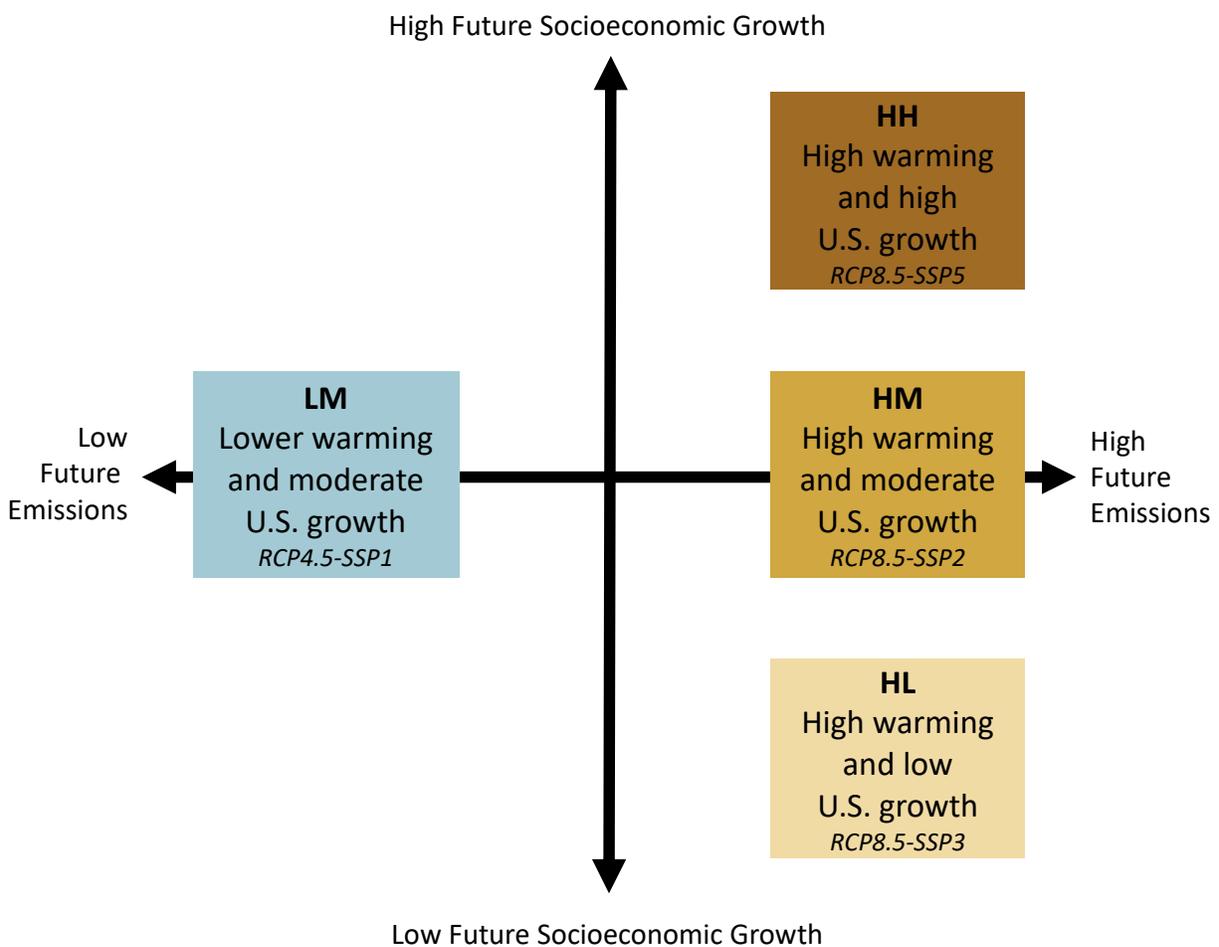


Figure 8—Characterization of global warming and U.S. socioeconomic growth characteristics of the four Representative Concentration Pathway (RCP)–Shared Socioeconomic Pathway (SSP) combinations underpinning the 2020 RPA Assessment scenarios.

The range of changes in global and U.S. characteristics is similar between the 2010 and 2020 RPA Assessment scenarios. The four 2020 RPA Assessment scenarios encompass most of the projected range of climate change from the RCPs and projected quantitative and qualitative range of socioeconomic change from the SSPs, resulting in four distinct futures (table 3). The scenario “short names” are linked to their global radiative forcing levels and U.S. socioeconomic growth characteristics, as described in the first line of table 3. We have described RCP 4.5 as “lower warming” and RCP 8.5 as “high warming.” For the United States, economic and population growth trends initially move in the same direction across scenarios (with population growth turning to shrinkage under SSP3 for the U.S. after 2040), whereas globally, economic and population growth diverge in three of the four scenarios. These quantitative trends and narratives provide a unifying framework that organizes the RPA Assessment natural resource sector analyses around a consistent set of possible world views.

Table 3—Characteristics of the four 2020 RPA Assessment scenarios.^a

| Characteristic | Scenario LM | Scenario HL | Scenario HM | Scenario HH |
|--|--|----------------------------------|---------------------------------------|-----------------------------------|
| Global warming and U.S. socioeconomic growth | Lower warming and moderate U.S. growth | High warming and low U.S. growth | High warming and moderate U.S. growth | High warming and high U.S. growth |
| Global real GDP ^b growth, 2020–2070 | Medium (4.9X) | Low (3.2X) | Medium (4.6X) | High (6.9X) |
| Global population growth, 2020–2070 | Low ^c (1.2X) | High (1.6X) | Medium (1.4X) | Low (1.2X) |
| U.S. real GDP growth, 2020–2070 | Medium (3.0X) | Low (1.9X) | Medium (2.8X) | High (4.7X) |
| U.S. population growth, 2020–2070 | Medium (1.5X) | Low (1.0X) | Medium (1.4X) | High (1.9X) |
| Global emissions | Lower | High | High | High |
| Global scenario links | RCP4.5-SSP1 | RCP8.5-SSP3 | RCP8.5-SSP2 | RCP8.5-SSP5 |

^a Numbers in parentheses are the factors of change in the projection period. For example, U.S. real gross domestic product increases by a factor of 3.0 between 2020 and 2070 in Scenario LM.

^b GDP = gross domestic product (based on estimates by the International Institute for Applied Systems Analysis 2018).

^c Note: Low population involves initial increase with declines in the latter decades of the projection period.

Linking 2020 RPA Assessment Scenarios to Natural Resource Sectors

Defining the 2020 RPA Assessment scenarios is the beginning of the RPA analysis process. The RPA scientists determine how to use the scenario data and assumptions in their resource sector analyses. Each analysis uses different combinations of the scenario variables and resource-specific variables to evaluate future resource outcomes. Examples of connections between components of the 2020 RPA Assessment scenarios and RPA Assessment resource analyses (fig. 9) illustrate the numerous routes through which the scenario variables can influence resource analyses. In some cases, both socioeconomic and climate projections are direct inputs to resource analyses, including outdoor recreation demand, water vulnerability, and forest product supply and demand. In other cases only the climate variables are direct inputs to the analyses, for example, in projections of rangeland productivity and stress on terrestrial habitats.

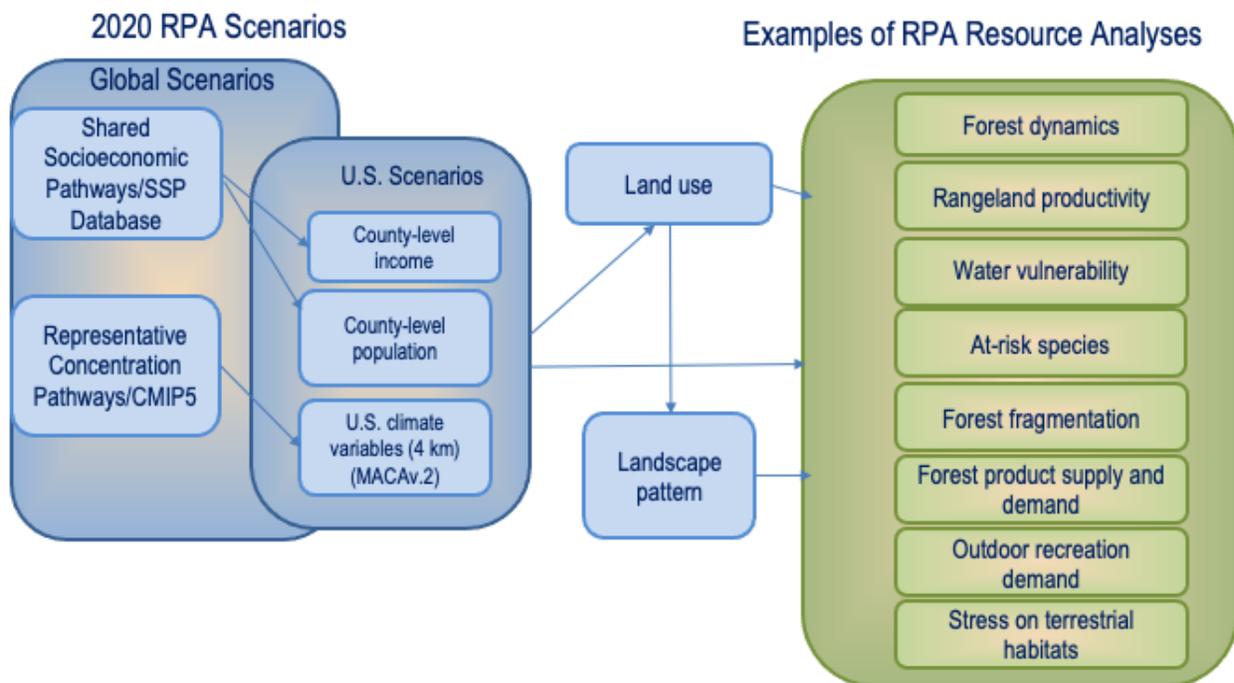


Figure 9—Scenarios for the 2020 RPA Assessment and examples of links to resource analyses.

Land use and landscape pattern projections are often the intermediary between the scenarios and resource-specific effects (fig. 9). The land use projections incorporate the U.S. climate and socioeconomic projections. In turn, the landscape pattern projections are based on the land use projections. Land use projections are strongly influenced by population and economic drivers; changes are more rapid and more extensive in futures of higher populations or more rapid economic growth (or both).

Analyses that rely on the land use or landscape patterns incorporate the scenario variables indirectly. For example, the forest dynamics model uses land use projections to adjust projected future forest land area. The landscape pattern projections support projections of forest fragmentation and future hotspots for at-risk species. Patterns such as the degree of forest fragmentation influence the feasibility of land management options, the availability of land resources to support uses such as outdoor recreation, and the ability of ecosystems to support biological diversity.

The examples shown in figure 9 are only a subset of the connections across the resource sectors. Daigneault et al. (2019) provide an example of building on the SSPs to develop potential future pathways for the global forest sector. They use differences in scenario components such as technology adoption and energy use and translate them into assumptions about harvest rates, biomass demands, and the productivity of forest plantations.

The following narratives provide a broad overview of the four 2020 RPA Assessment scenarios, focusing on how the climate and socioeconomic projections and qualitative aspects of each scenario may affect natural resource conditions and trends. It is premature to predict the direction of change in resource conditions before the analyses have been completed because underlying drivers may interact in unexpected ways.

Scenario LM (RCP 4.5–SSP1): Lower Global Warming and Moderate U.S. Socioeconomic Growth

Scenario LM (RCP 4.5–SSP1) has a lower level of global warming and a moderate level of economic growth globally and in the United States, implying shifts from historical trends in development patterns, commodity demand, technology, trade, and energy use. The emphasis on sustainability is consistent with maintaining natural environments, including forests and rangelands. Under this scenario, the United States will face continued pressure for development in response to continued population growth. More compact development will reduce pressure on natural landscapes compared to historical patterns of extensive development in the wildland-urban interface.

Growing incomes will increase demand for both natural resource commodities and amenities. Growth in U.S. demand for housing will be moderate, in line with population and income growth; increased interest in wood as a building material, combined with new wood-based technologies

could create demand for new wood product construction. Demand for agricultural commodities usually increases with rising incomes, but population-driven demand will be moderate. As world populations shrink, the demand for cropland may decline, reducing pressure on other natural land covers. Demand for livestock generally increases with rising incomes, possibly increasing demand for livestock grazing on rangelands, or creating pressure to convert rangelands to more productive pasture. With lower levels of global warming, effects on water will be less pronounced than under high warming scenarios, but water availability is still likely to be a constraint in some regions of the United States, affecting choices in agricultural production. Competition between irrigation and high-valued urban uses will continue, although continued efficiencies in water use in combination with water pricing could ameliorate some of the competition. Energy portfolios shift to sources with lower greenhouse gas emissions. The role of forests in producing biomass energy is likely to increase. Highly productive energy crops may affect uses of agricultural lands and create competition between energy and food crops. Improvements in technology and livestock and crop breeding may ease some of these constraints.

Global forest land is likely to expand, as will forest area in the United States. The composition of U.S. forests will change in response to shifting forest market demand and climatic changes, which will interact with natural disturbance events. Increases in biomass for energy could increase plantation forest area, possibly at the expense of natural forest cover. Increasing demand for resource amenities, such as outdoor recreation and biodiversity, indicates rising pressures on public lands to provide these services. Climate effects on public land resources are likely to change recreation opportunities and affect habitats, which will, in turn, influence the diversity of fauna and flora.

Scenario HL (RCP 8.5–SSP3): High Global Warming and Low U.S. Socioeconomic Growth

Scenario HL (RCP 8.5–SSP3) portends larger and faster rates of climate change, rapid global but low U.S. population growth, and slow economic growth domestically and globally. World population more than triples by 2070, although U.S. population increases slowly to 2070 and then declines. Domestic population pressures on natural resources will be lower compared to other scenarios, particularly in concert with low economic growth. For example, there will be less demand for development, reducing conversion of natural landscapes. Though high global population growth could be a source of increased demand for exports of agricultural commodities and forest products from the United States, low global economic growth combined with high trade barriers will constrain such trade. The combination of trade barriers and limited technological innovation will reduce the rate of conversion to renewable energy resources and also increase reliance on domestic energy sources. If biomass becomes a more important domestic energy source, demand for forest and agricultural energy biomass could increase, affecting the extent and use of forest and agricultural lands.

Forest land is projected to decline globally, as global population pressure and limited agricultural productivity and technological innovation combine to result in expansion of cropland. Urban expansion is also likely to continue at the expense of natural land covers such as forest land. Forest area for the United States will depend on factors that could move in opposite directions: Increased demand for crop exports could increase cropland; increased use of forest biomass for energy could expand forest land in plantations. Lack of export demand for crops or forest products would reduce economic incentives for either. Global warming will exacerbate water shortages in the United States. The limited population pressure in the United States changes the domestic dynamics compared to the dynamics elsewhere in the world where populations will be increasing rapidly and economic growth is higher.

Resource amenities and biodiversity are likely to be negatively affected by the combination of global climate shifts and low economic growth that will limit growth in demand for these services. Environmental protection tends to suffer when countries face the types of financial challenges envisioned by this scenario. In the United States, lower to negative population growth could lead to increased provision of natural amenities because of the limited pressures for expanded development, but maintaining existing environmental protections will also be critical to achieving such a result.

Scenario HM (RCP 8.5–SSP2): High Global Warming and Moderate U.S. Socioeconomic Growth

Scenario HM (RCP 8.5–SSP2) has a low to moderate level of global population growth and moderate global economic growth. U.S. population growth is higher than the global average and economic growth is lower. These trajectories are combined with high global warming. This scenario assumes that globalization norms of the early decades of this century are maintained, indicating international trade continues at levels that are lower than in scenarios LM and HH (discussed next), but higher than in HL. The level of global cooperation generally reflects the status quo of the early 2000s in both environmental and market governance.

Development patterns of the United States and globally will reflect the wide variation currently seen in land use regulation and zoning across and within countries. Technological improvements will continue at historical rates, which could support technologies and energy use portfolios that limit greenhouse gas emissions. The change in energy use toward reducing greenhouse gas emissions will be relatively slow, but biomass use will increase in some global regions, including the United States. Therefore, there could be potential expansion of forest land and forest biomass exports. If demand for forest biomass for energy increases, there could be additional conversion of natural forest to plantations; overall forest land area is likely to decline in the United States in the long run.

Population growth is likely to increase demand for cropland, putting additional pressure on natural landscapes for conversion. Agricultural productivity improvements could lessen these impacts, but the effects of global warming on agriculture are also expected to influence both the location and extent of cropland. As with all high warming scenarios, water availability will be constrained, particularly in areas of the United States already experiencing water supply issues. Water shortages will also impact aquatic biodiversity as there may be pressure to reduce environmental protections such as in-stream flow levels.

High warming will impact recreation opportunities, particularly those related to water and snow activities. Biodiversity will be affected in various ways; some species will be at greater risk of becoming endangered.

Scenario HH (RCP 8.5–SSP5): High Global Warming and High U.S. Socioeconomic Growth

Scenario HH (RCP 8.5–SSP5) has the highest level of global warming and the highest economic growth globally and in the United States. World population increases slowly through 2070 and then declines, while in the United States population grows at the fastest rate of all the scenarios. As with other scenarios where the global and U.S. trends diverge, the resource consequences may also diverge. In the United States there will be a larger population with increased income to fuel increased demand for natural resource commodities and amenities. Worldwide there will be income-fueled increased demand, but the effects will be offset to some extent by the slowing population trend.

This scenario includes a strong reliance on markets, with open markets that encourage trade. Economic globalization implies, in this case, that economic growth is prioritized over environmental objectives that are perceived as negatively affecting economic growth; less emphasis is placed on global governance standards and global environmental cooperation. Rapid technological innovation is likely to enhance productivity in agricultural and forest product commodities. Growing income is generally consistent with high demand for resource amenities such as natural areas and biodiversity. While this scenario should reflect such demand, the substantial population and economic growth is highly likely to reduce natural land cover to meet development for housing and associated infrastructure. There is no assumption of constraints on development in this scenario, so the pattern of development could range from intensive to extensive, and is likely to vary according to variations in State and local land use ordinances.

With high levels of global warming, impacts on natural resources are also expected to be substantial. The implicit assumption in this scenario is that economic growth and technological innovation will be able to overcome some of the biophysical constraints imposed by climate change. Continued reliance on fossil fuels indicates a lesser role for agricultural or forest biomass for energy than other scenarios, but some expansion is likely. Effects

of global warming on water will increase supply and demand imbalances across the United States; improved technology for water use will ease some of the demand increases, but there will still be pressure to reduce high consumptive uses such as irrigation so that supplies can be diverted to urban uses. The interaction of warming effects on agriculture and associated demand for irrigation will make these tradeoffs challenging.

High economic growth indicates increasing demand for outdoor recreation, but opportunities are likely to be shifted or constrained (or a combination thereof) from both global warming and recreational use levels that exceed environmental capacities. Technology has often improved access for some recreation; technology could also create substitutes for outdoor recreation that ameliorate some demand pressures. Demand for biodiversity may be high in this scenario, reflecting increases in income, but the market-driven growth in commodity use is likely to reduce the extent of natural environments critical to maintaining aquatic and terrestrial species. Coupled with warming effects, this contraction of the natural landscape is likely to put species at greater risk of becoming endangered.

CONCLUSIONS

The Resources Planning Act (RPA) Assessment scenarios provide the context for the resource analyses that meet the legislative mandate of the RPA. The global Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) are critical to providing global context and coherence to the national-scale scenarios that are described in this document. The future of global and domestic natural resources could differ substantially across the four scenarios. These scenarios will be used in the RPA Assessment modeling framework, but they could also be used by other modeling systems to allow comparisons of results. As the 2020 RPA Assessment analyses are completed, the projection of resource effects associated with the underlying drivers of change will allow us to provide more resource-specific narratives of how the different scenario drivers and assumptions interact.

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