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The parameterized model was then applied to the entire Pacific Northwest of the United States, using appropriate climatological and soil input data. Existing agricultural patterns were used to estimate regional water availability for irrigation, and for nonirrigated regions, land cover features including ownership, slope , soil salinity and water table depth where used to limit predictions to areas with a real potential to support a SRWC plantation.

Results can be integrated with other models that allow for optimizing the crop selection and biorefinery site selection. Important findings from the model include; validation of the 3PG model for coppiced SRWC plantings, estimates of biomass feedstock yields under different irrigation patterns and weather conditions, and annual estimates for feedstock availability when combined with crop adoption scenarios.

Highlights (for review)

+ A poplar growth model was applied to the Pacific Northwest of the US
+ We included a coppicing module to the exsiting 3PG growth model
+ We investigated growth under irrigated and non-irrigated conditions
+ We developed Geospatial yield estimates
+ We discuss changes in yield from climate change

Modeling Poplar Growth as a Short Rotation Woody Crop for Biofuels in the Pacific Northwest

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Abstract

Predicting the economic viability and environmental sustainability of a biofuels industry based on this feedstock requires spatial predictions of the growth and yield of short rotation woody crops (SRWC) under various environmental conditions and throughout large regions. The Physiological Principles in Predicting Growth (3PG) model was modified for modeling SRWC, particularly for poplar plantation methodologies. This included developing a sub-model which takes into account the coppicing strategy for harvesting poplar that allows a monthly growth contribution from an existing root mass.

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Results can be integrated with other models that allow for optimizing the crop selection and biorefinery site selection. Important findings from the model include; validation of the 3PG model for coppiced SRWC plantings, estimates of biomass feedstock yields under different irrigation patterns and weather conditions, and annual estimates for feedstock availability when combined with crop adoption scenarios.

Keywords: Short rotation woody crops, Poplar, 3PG, Yield estimations, Pacific Northwest, USA.

1. Introduction

The Advanced Hardwood Biofuels Northwest (AHB-PNW) is a consortium of university and industry partners investigating the development of a sustainable hardwood biofuels industry in Washington, Oregon, Northern California and Western Idaho in the U.S. Inspired in part by the U.S. Energy Independence and Security Act 2022 targets for renewable fuel, AHB-PNW is carrying out research and development to support a system for growing and converting hardwoods, such as hybrid poplars, into liquid biofuels that are fully compatible with existing infrastructure.

To support economic and environmental models for a biofuels industry, spatial predictions of the growth and yield of short rotation woody crops (SRWC) under various environmental conditions and throughout the entire Pacific Northwest (PNW), the Physiological Principles in Predicting Growth (3PG) model was utilized. The model was modified for SRWC, particularly for poplar plantation methodologies.

A physiological growth model such as 3PG is advantageous because it allows variation of growth parameters and assumptions regarding management practices for poplar species. In addition to biomass growth and yield estimations, because it is a canopy carbon balance model, allocations for both above and below ground biomass can be tracked for life-cycle analysis of the product fuels.

The original 3PG model does not include coppicing as a management practice, which is problematic as it cannot reasonably account for post-coppicing regrowth. The extended model includes coppicing with a general model that allows a monthly growth contribution from an existing root mass. The model specifies a relatively small contribution of aboveground growth from the accumulated root mass after coppicing in order to initiate the next cycle of production.

The 3PG model was validated against a number of field studies related to the growth of poplar as a SRWC biofuel feedstock. The parameterized model was then applied to the entire Pacific Northwest region, using appropriate climatology and soil input data. Climate data included both historical patterns as well as predicted patterns from simulations predicting climate change. These inputs produce poplar yield prediction maps and expected bounds on the variation of these yields useful for determining when it becomes economically feasible for poplar to be grown within the study area.

This yield model is overlaid with surface and land cover parameters to predict yields for potential plantation locations. Yield maps are the results of running the 3PG model for the entire AHB-PNW region.

With appropriate input information, the 3PG model can predict yields for the entire Pacific Northwest study region, under various irrigation scenarios.

When linked with models of crop adoption, annual feedstock estimates are possible.

2. Methods and Calculation

The main goal of this study was to create spatially explicit poplar growth potential for the PNW that can inform our participants and subsequent modeling efforts on the predicted yields from SRWC plantations.

The study area, the Pacific Northwest of the United States, incorporates Washington, Oregon, Northern California, and Western Idaho. This definition of the PNW is somewhat inclusive in the South, including the northern part of California (Figure 1).

A regular grid partitions the region. The individual pixel size is relatively coarse 8192×8192 $(m\hat{2})$, and designed to reduce some of the complexity of subsequent regional optimization models. The projection is an Albers equal area projection with standard longitude 120° West, and parallels at latitudes 41° and 47° North [1]. This projection insures the pixels maintain a constant area, while maintaining good conformity for transportation networks. The pixel edge length, $8192 = 2^{13}$ (m) is defined as a binary factor to allow easy scaling up and down of the data to different resolutions while maintaining common edges. For example, the National Land Cover Dataset (NLCD) dataset, used in this study, was originally imported and projected to 2^5 (m), and aggregated upwards to determine percentages of each landcover type for each pixel (Figure 7).

Data processing was carried out within a postgresql database, with the postgis geospatial extensions [2, 3, 4]. Specialized calculations were im-

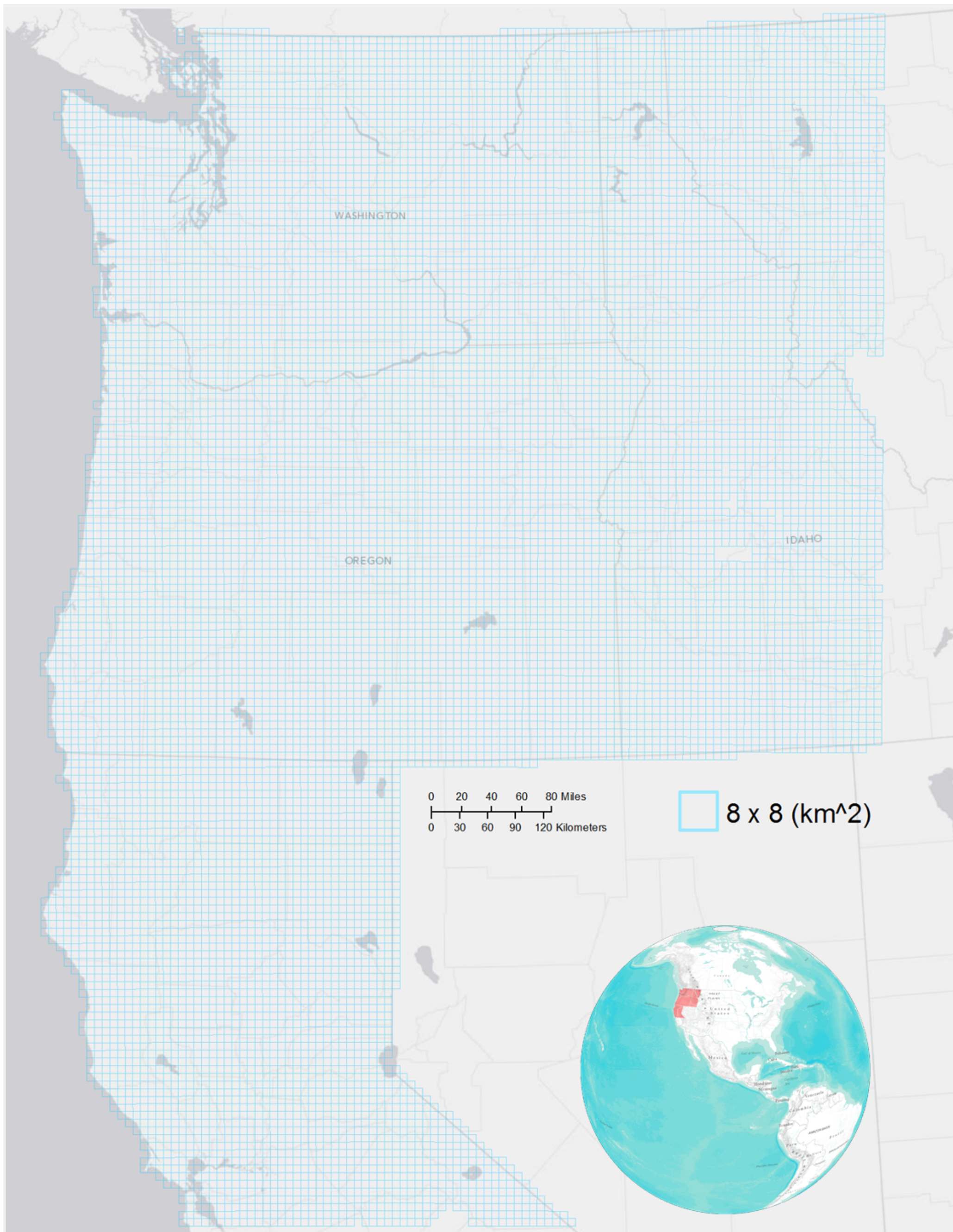

Figure 1: Location of the study area, with grid layer overlaid.

plemented as postgresql functions, using various scripting languages; SQL, PLSQL, Javascript, and R.

2.1. 3PG *Model Formulation*

The Physiological Principles in Predicting Growth (3PG) model [5, 6, 7] is the primary tool used for the SRWC yield estimations, and takes as inputs weather data, soil parameters, site factors, including soil parameters, initial stocking conditions, management practices, and species definitions (Figure 2). The 3PG model is run at a monthly timestep. At each step the physiological parameters are calculated and carried forward to the next month. These incremental physiological parameters can be compared to model predictions with field results at multiple stages in the plantation's history.

The original 3PG model allocates production from transpiration into the creation of new roots, stems and foliage. After coppicing however, the model has no mechanism to increase start of re-growth from the root. A simple coppicing model has been developed to add an additional production from the root system after coppicing [8]. When a SRWC is coppiced, there is a surfeit of root mass when compared to the aboveground biomass. This surfeit is allowed to contribute some of this surfeit as an additional production at each monthly timestep, along with the Net Primary Productivity (NPP) of the original model. The seasonal timing of any root contribution is moderated by comparing the actual NPP to a potential NPP the tree would have a specified target Leaf Area Index (LAI). This difference serves as a maximum limit for the root contribution. Using a potential NPP from a target LAI serves two purposes. First, it allows root contributions up to, but not beyond a certain foliage amount, as specified by the LAI. More importantly, since

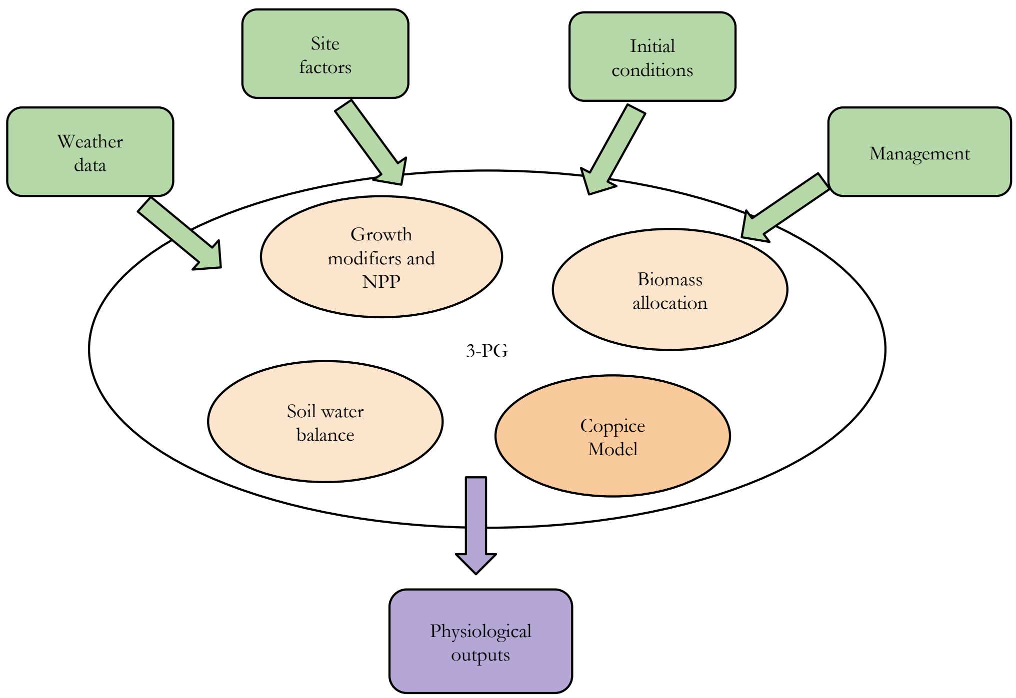

Figure 2: The 3PG model's main inputs. Running at a monthly timestep, with appropriate input parameters, the model predicts tree growth and a number of other parameters.

the root contribution is tied to a potential NPP, the method times regrowth with climatic conditions that are favorable for growth, and does not initiate growth when conditions are not favorable. A maximum allowable monthly root contribution fraction limits the total contribution for any one month, and affects the length of time for the contribution to be made. In poplar plantations, where plantings are initiated with bare cuttings as propagation, the initial growth is modeled the same way, however with different parameters to model initial root dynamics.

Hart et al. [8] validated a set of 3PG tree parameters, primarily following a poplar parameterization of Headlee et al. [9] that reasonably model a generic poplar species. In addition, a~~nd~~ set of 6 additional variations on these parameters were derived to match reported field study results. These sets of parameters were used as an ensemble of inputs to the yield predictions below.

2.1.1. Climatic and Radiation Data

The Pacific Northwest weather patterns are influenced primarily by the Pacific storm track, which brings in the bulk of precipitation in the months of October through March, and the location and size of the mountain ranges, which moderate both the precipitation, and the temperatures throughout the year.

In order to predict temperatures and precipitation on the near term, the Parameter-elevation Relationships on Independent Slopes Model (PRISM) dataset was used [10]. PRISM extrapolates station data spatially to a uniform grid using weights derived from the physiographic similarity of the station to the grid cell. These similarity measures include location, elevation, coastal proximity, topographic facet orientation, vertical atmospheric layer, topographic position, and orographic effectiveness of the terrain. PRISM data is available on a 2.5 minute geographic grid.

16 years of PRISM data were interpolated (cubic spline) to the AHB-PNW grid averaged to determine a representative weather pattern used near term modeling for the AHB-PNW yield predictions. Figure 3 shows annual mean temperature and total precipitation variation of the region. Isolines show the standard deviation between annual mean temperature to the monthly mean temperature. Similarly isolines shown on the precipitation map show the maximum monthly contribution of preciptation.

In order to determine incoming monthly solar radiation, monthly National Renewable Energy Laboratory (NREL) global incident radiation data were utilized [11, 12]. The incident radiation data product provides monthly average and annual average daily total solar resource averaged over surface cells of 0.1 degrees. Hourly radiance images from geostationary weather satellites, daily snow cover data, and monthly averages of atmospheric water vapor, trace gases, aerosols are used to calculate the hourly total direct and diffuse insolation falling on a horizontal surface. Existing ground measurement stations validate the data where available.

The incident radiation data is available on a gridded format with a scale similar to this project and is interpolated (cubic-spline) onto the AHB-PNW grid for use.

2.1.2. Soil Parameters

3PG uses a single layer soil model that maintains an estimate of the amount of water available at any timestep in the model. In addition, 3PG

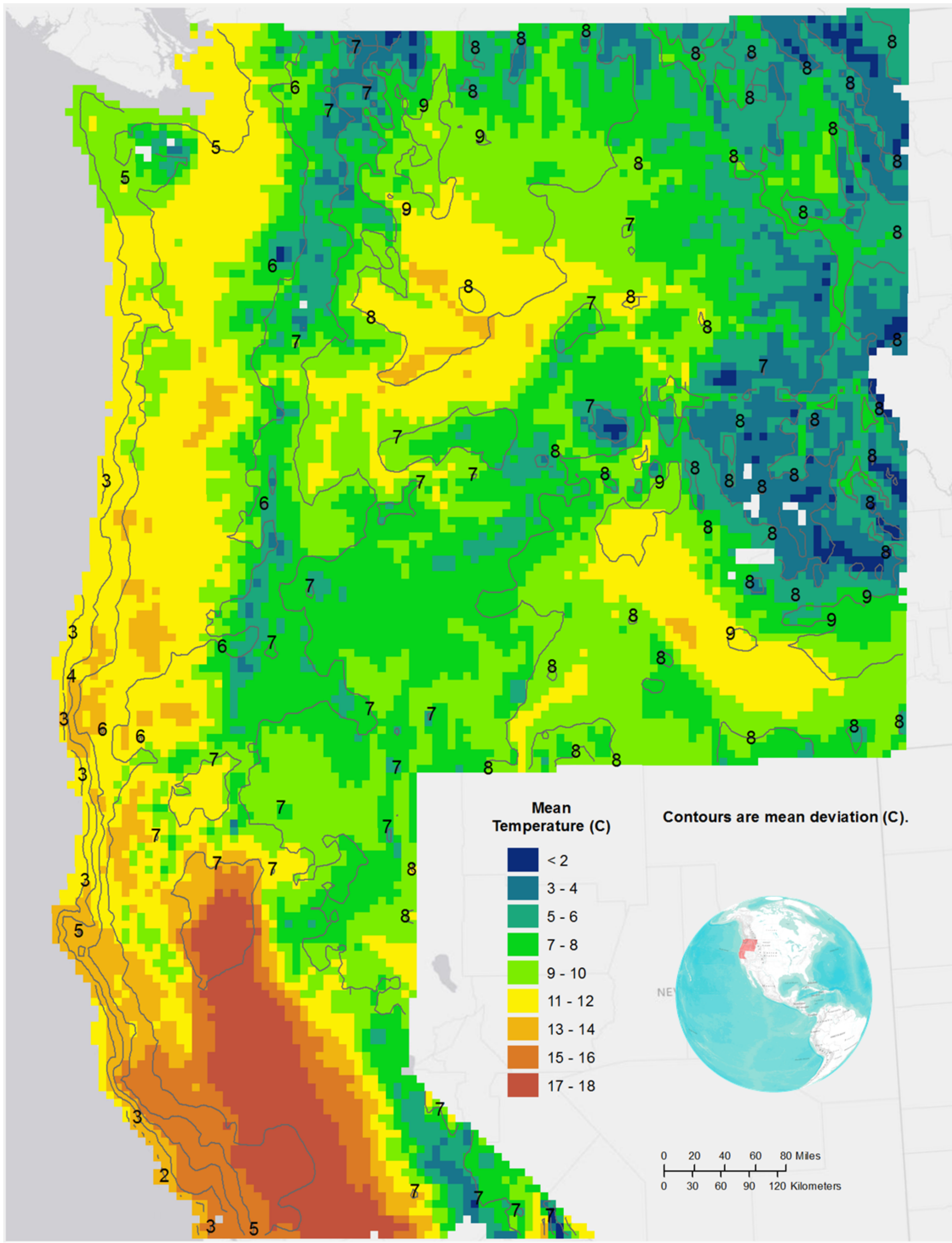

Figure 3: Mean annual Temperature, with isolines showing the standard deviation in monthly temperature.

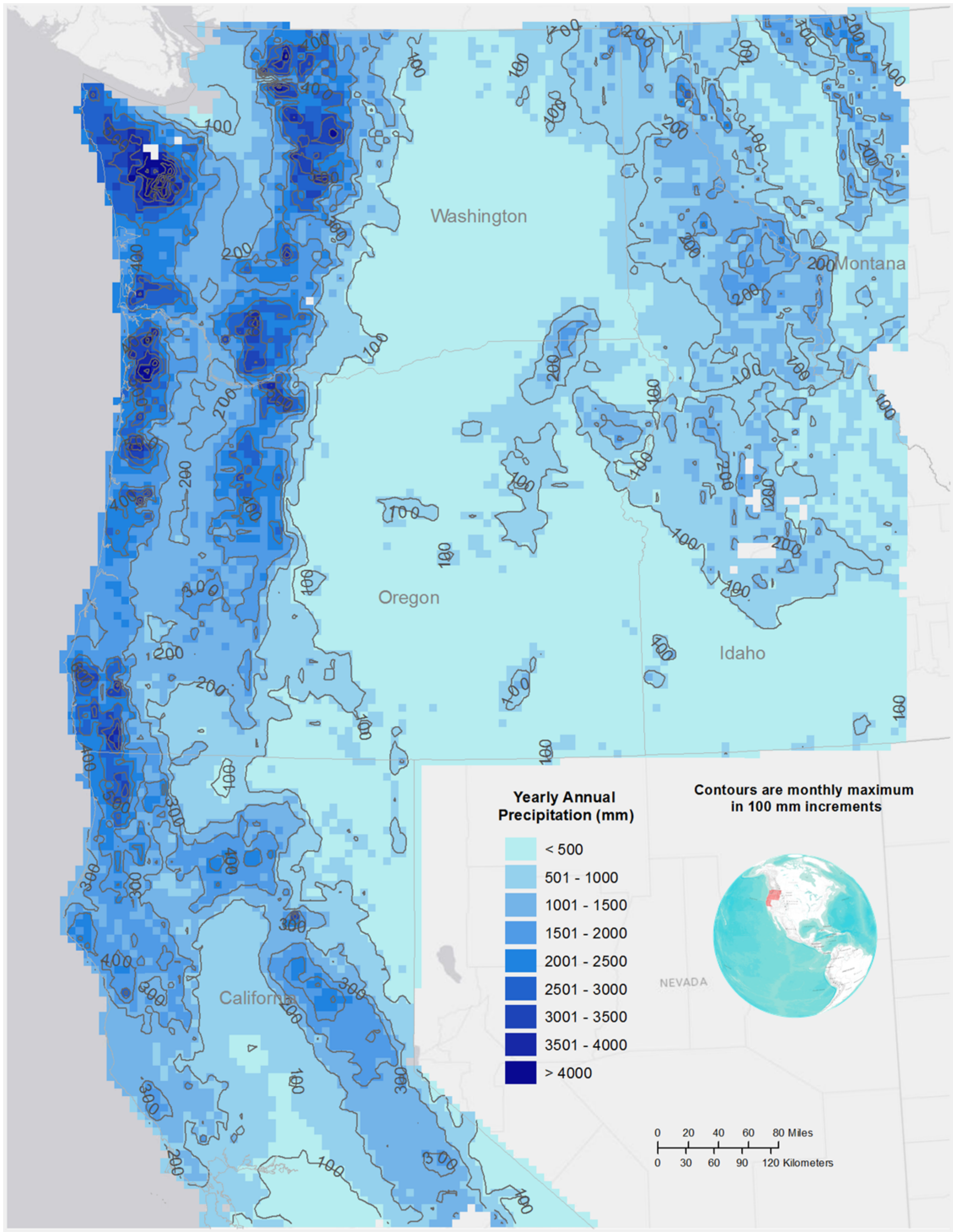

Figure 4: Total annual rainfall, with iso lines showing the maximum monthly rainfall.

includes a growth limiter related to the available water in the soil, and the soil type. These require a number of soil parameters.

These parameters are all determined using the State Soil Geographic (STATSGO) database [13]. STATSGO is a national soil database, distributed by the Natural Resources Conservation Service, Department of Agriculture (NRCS). STATSGO maps are designed for regional studies, and the soil inventories are typically generalized from more detailed surveys, or from a combination of ancillary datasets. Individual STATSGO areas can contain multiple soil components, and the map units are linked to attributes the soil data base which gives the proportionate extent of the component soils and their associated properties. The Minimum mapping unit (mmu) is about 625 (ha). For each pixel in the modeling grid, intersecting map units are averaged for the estimated pixel values. 1887 different soil were used, contributing anywhere from 144 to 1.3M (ha).

Maximum Available soil water (S_x) defines the maximum holding capacity of the soil. S_x is directly taken from the STATSGO database which determines the maximum water holding capacity through the complete horizon over the topmost 1 (m) of soil (Figure 5).

The limiter Soil Water Modifier (f_Θ) is parameterized with two values, f_Θ Power (Θ_P) and f_Θ Constant (Θ_c) are functions of the soil type (Figure 6). The soil type is determined from STATSGO report percentages of silt sand and clay within each soil component.

2.2. Land Classification and Irrigation

Available climatic data makes it possible to make estimations for poplar growth throughout the PNW region. This may provide interesting compar-

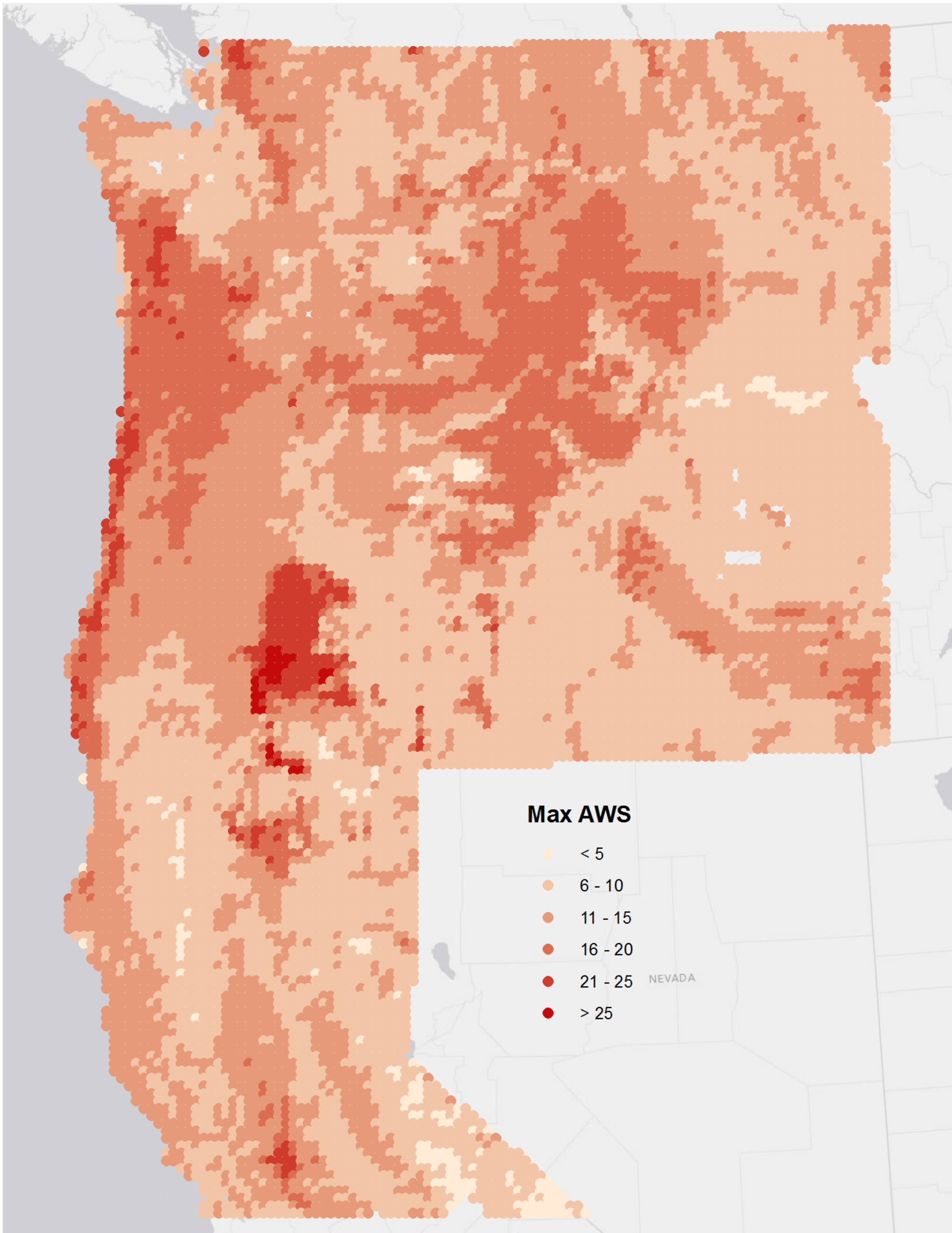

Figure 5: STATSGO derived maximum available water estimates.

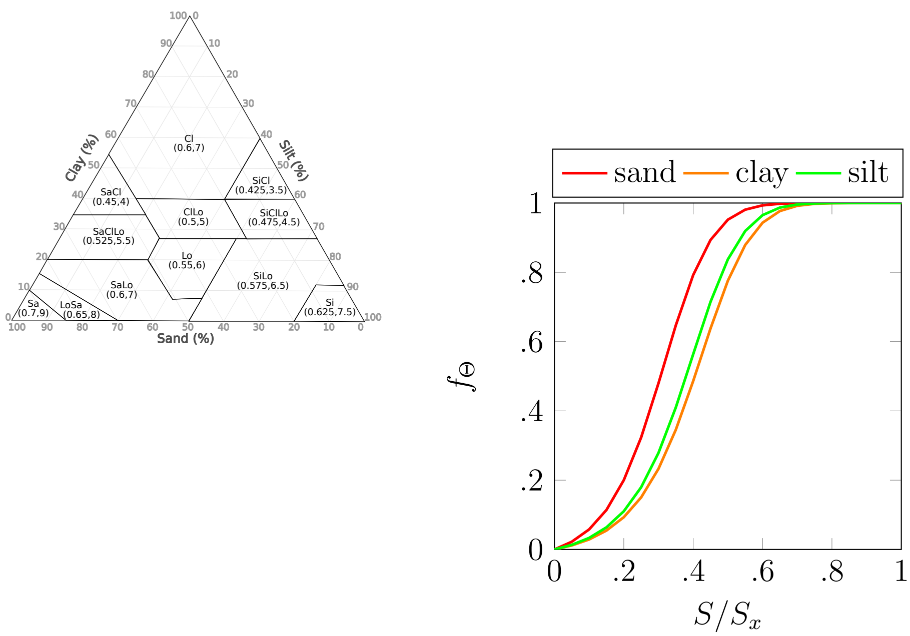

Figure 6: Θ_c and Θ_P as determined by soil composition. Included is a graph for the function $f_\Theta = \frac{1-(1-S/S_x)^{\Theta_P}}{1+((1-S/S_x)/\Theta_c)^{\Theta_P}}$ for sand,silt and clay.

isons of changes in yield, but is not very suitable for determining regional trends, as not all lands are equally likely to be available for poplar plantations. Variables like land ownership, topography and salinity, influence the technical capability of growing poplar.

In addition, the ability to irrigate a poplar plantation can have large effects on the predicted yields of poplar. Determining which areas in the PNW region are liable to be available for irrigation can significantly influence regional polar harvest estimations.

In order to limit the areas within the AHB-PNW region to areas that are technically suitable to poplar plantations, a set of masks were used, derived from a suitability analysis for potential plantation locations [14]. Permanently non-suitable land was identified for removal from consideration. Lands under Federal ownership [15] and currently developed land [16] were excluded from consideration. Physical features including slopes greater than 15% [17], and soil salinity greater than 4 (dS / m) were also excluded (Figure 10).

The land suitability study included other factors for poplar suitability; nine variables considered important for poplar growth were identified: growing season precipitation, temperature, and length; soil texture and drainage, pH, salinity, and depth; water table depth; and slope. Most of these parameters are included more explicitly in the 3PG model, and directly affect yield predictions. Soil salinity and pH have not yet been integrated into the 3PG model.

Available water for irrigation is a difficult question when dealing with crops in the PNW. Irrigation is a combination of availability and rights, that is hard to track on a regional scale. However, one aspect of irrigation is that if it's available it is likely being used currently. Therefore, for determining irrigated yield predictions for poplar, a mask of existing irrigated agricultural areas was used. These locations were determined in two steps. First, the a cropland data layer was used to spatially locate agricultural crops in the region. The USDA, NASS Cropland Data Layer (CDL) is a nationally available raster of crop specific land cover data layer with a ground resolution of 30 meters. The CDL is produced using satellite imagery with a classification emphasis on agricultural land cover [18]. The CDL was projected unto the AHB-PNW region as a scale of 2^5. Individual pixels from the CDL were then aggregated within the larger model's 2^{13} size pixels to determine fractional composition of each large pixel (Figure 7). An additional step was used to adjust the total area in each county to the values of hectares reported to the National Agricultural Statistics Service (NASS). NASS publishes U.S., State and County agricultural statistics for many commodities [19]. Later modeling efforts rely on the NASS reported hectares of the various commodities harvested. This was accomplished by uniformly adjusting the CDL derived pixel fractions, (the AHB-PNW 8192 edge length pixels) so that sum of pixel fractions over nay county in the AHB-PNW region match the reported number of hectares harvested for that county and commodity. This method allows the spatial patterns of the CDL to be retained with fractions that add to the NASS reported values.

2.3. Climate Change

To demonstrate the effect of potential climate change on yield predictions in the near future, the A1B climate change scenario was used as an example for predicting yields with a plantation initially planted in 2040.

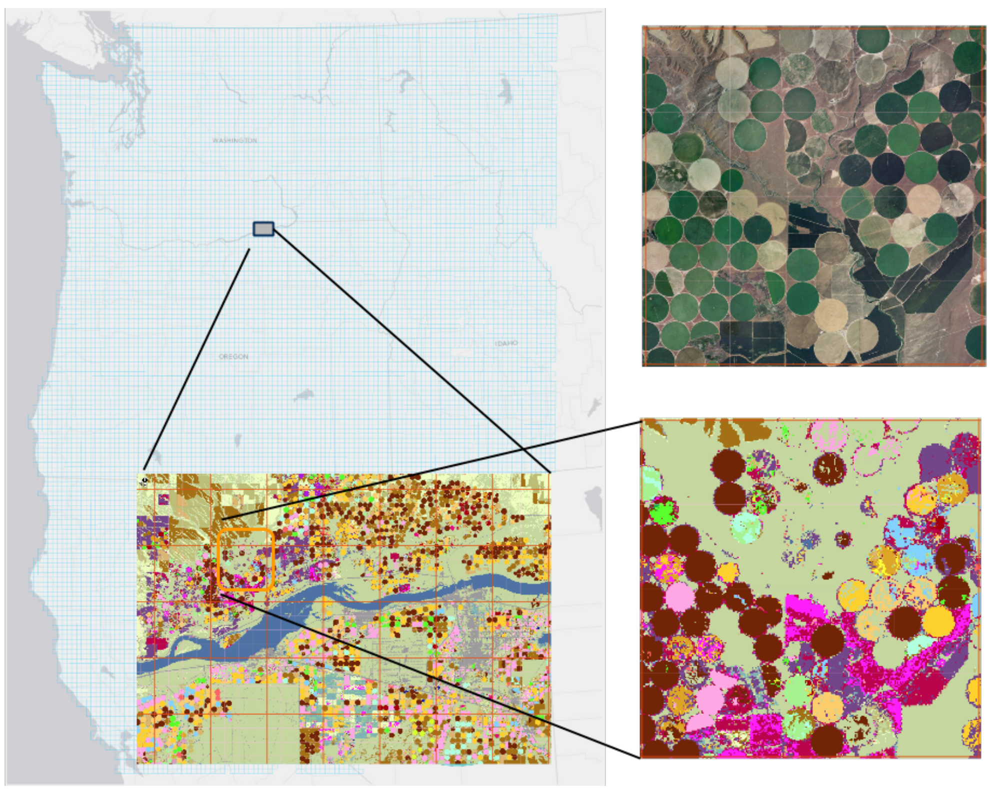

Figure 7: Agricultural Land Classification. Each AHB-PNW pixel is made up of many remotely sensed derived CDL crop classifications. This are aggregated to determine fractional amount of coverage for each AHB-PNW pixel.

The A1B scenario predicts a balanced utilization of available energy sources, with similar improvement rates applied to all energy supply and end-use. The future is one of rapid economic growth, global population that peaks in mid-century and declines thereafter, and a rapid introduction of new and more efficient technologies [20, 21].

Estimations of the expected change in temperature and precipitation were derived from the Community Climate System Model version 3 (CCSM3). The CCSM3 is a climate model with components including the atmosphere, ocean, sea ice, and land surface. CCSM3 is designed to produce realistic simulations over a wide range of spatial and spatial resolutions. CCSM3 predictions are available at 0.5 degree grid cells. Estimations of change in the next fifty years were used in these climate change estimations.

The CCSM3 estimations cannot be used directly, especially comparatively to the current estimations using the PRISM data. This is because when comparing the CCSM3's somewhat coarse scale estimations to the more detailed PRISM estimations the current (2000-2014) predictions exhibit bias. Therefore, the CCSM3 estimations were used to determine the predicted change in temperature and precipitation for the AHB-PNW region, and these changes were then applied to the current PRISM estimations. For example, the 40 year change in temperature, and precipitation for the A1B scenario shows a mean increase in temperature of about 1° Celsius, with larger changes in the South and West. Mean annual precipitation decreases by about 100 (mm) throughout the region with larger changes in along the coast (Figure 8).

3. Results and Discussion

The 3PG model was run with seven representative poplar parameterizations were run over the AHB-PNW region, using both a model that included irrigation and one that was nonirrigated. The results were averaged over the set of species parameters. The runs were over an 18 total lifetime, with a 2.5 year initial coppicing event followed by 5 additional events on a three year cycle. Initial planting was in March, with all coppicing events occurring in November. The 6 total harvest events were annualized over the 18 year time span to report predicted yields on a per year basis.

Finally, the layer of current croplands was used to mask the yield maps to include only those areas where irrigation is likely, to determine an overall predicted irrigated yield. The results show an average yield over the entire region of 19.7 (Mg/ha). 3.8 (Mha) were included in the estimate. Yields were highest in the central valley of California, a rich agricultural center, with similar yields along the temperate western parts of Oregon and Washington. Yields decreased in the Northern plains, reaching lows in the Northeastern section of the study region (Figure 9).

Similarly, the nonirrigated yield predictions were masked with the areas excluded in the land suitability study to include those areas likely to support nonirrigated poplar plantations. Results for the nonirrigated lands predict a yield of 6.6 (Mg/ha) over an area under consideration of 5.7 (Mha). In the case of nonirrigated yields, the highest yields were along the Pacific coast where precipitation is most plentiful, and more uniform in the inland areas of the AHB-PNW region (Figure 10).

To assess the predicted change in yields from the A1B example study, the model was rerun with the same parameters as the previously, but with the predicted changes in temperature and precipitation. The results were averaged and summarized as above to determine annualized yields. The yields were then compared to the current yield estimates to determine the difference in predicted yields under that one example climate change scenario.

Under irrigated conditions, the higher predicted temperatures generally improve yields through most of the region, with the exception of California, where high temperatures often limit monthly growth. Changes in yield are modest in the areas with the highest yields and more significant in the colder Northern and central regions (Figure 9).

For nonirrigated plantations, the predicted decrease in precipitation decreases yields along the areas with the current highest yields, along the wet Pacific coast. Higher temperatures continue to increase yields in most of the inland areas (Figure 12)

These change estimations can inform both the individual farmer in terms of predicting long term viability of poplar plantations as a SRWC feedstock, as well as regional estimations on the mid-term ability of such a feedstock to provide an expected harvest, and therefore an expected level of biofuel production. Not only changes in expected overall yields, but changes in the spatial distribution of the yields can have impacts on economic analysis of a SRWC based biofuel industry in the PNW.

These example climate change yield change predictions are illustrative, but the mean change in yields are not necessarily the most robust estimation of changes in yield predictions. First, the CCSM3 models are not tuned to the relatively short time frame of looking forward 25-50 years. In addition, while temperature increases are consistently predicted, the change in precipitation is less uniformly predicted among different models and scenarios.

With appropriate input information, the 3PG model can predict yields for the entire PNW study region, under various irrigation scenarios. When linked with models of crop adoption and biorefinery models the economic viability of poplar as a biofuel feedstock can be examined.

For example, in the AHB-PNW project, a companion model, the Bioenergy Crop Adoption Model (BCAM), predicts price levels where poplar competes with existing crops in about 35 different general cropping regions in the PNW. The spatially distributed yield predictions inform the BCAM model. For irrigated land, current yields are input into a BCAM model where they compete with existing crops to determine their economic viability. The yield predictions also include predictions in required water, and the BCAM model manages water availability by balancing any water needs from the poplar with water saved from crops taken out of the agricultural system. Outputs of the BCAM model show at what farm gate price ($/Mg) poplar becomes an economically viable product.

For non-irrigated land, marginal and under utilized lands can be added into the overall agricultural economy as newly utilized lands. For nonirrigated plantations, crop budgets can give estimates of farm gate costs ($/Mg) which are affected by the predicted yields.

Both the irrigated and nonirrigated regions, total amount of available feedstock for a particular farm gate price can then be estimated. These are also spatially distributed. Another AHB-PNW model, the Geospatial Bioenergy Systems Model (GBSM) takes as inputs these spatially distributed price curves, and use them in coordination with feedstock transport and refinery costs, to optimize the size and location of a set of refineries, to most efficiently process the poplar into a biofuel. The results from the GBSM model include both the predicted refinery system as well as an anticipated cost of fuel itself. The current resolution of the AHB-PNW grid is designed to provide a workable input for the solver of the GBSM model. Subsequent model runs at a finer scale can test the best scales for application of these models.

4. Conclusions

With the addition of the coppicing model, the 3PG model can be used to predict poplar yields for the PNW region. The model can include irrigation which increases yields from most areas in the region.

With additional layers showing current croplands, areas the can be irrigated are identified. Poplar suitability maps limit consideration on nonirrigated plantations to regions that are amenable to such management.

Spatially distributed yield predictions inform regional models as to the expected costs of producing a poplar biofuel feedstock and the price at which that commodity becomes economically viable.

5. Acknowledgements

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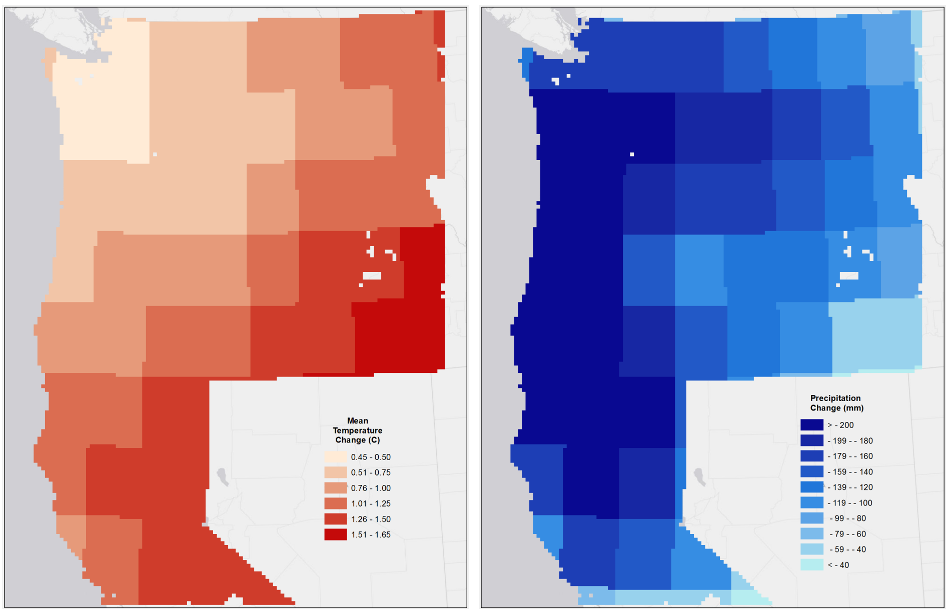

Figure 8: Predicted changes in temperature and precipitation under CCSM3 scenario A1B for plantation planted in 2040.

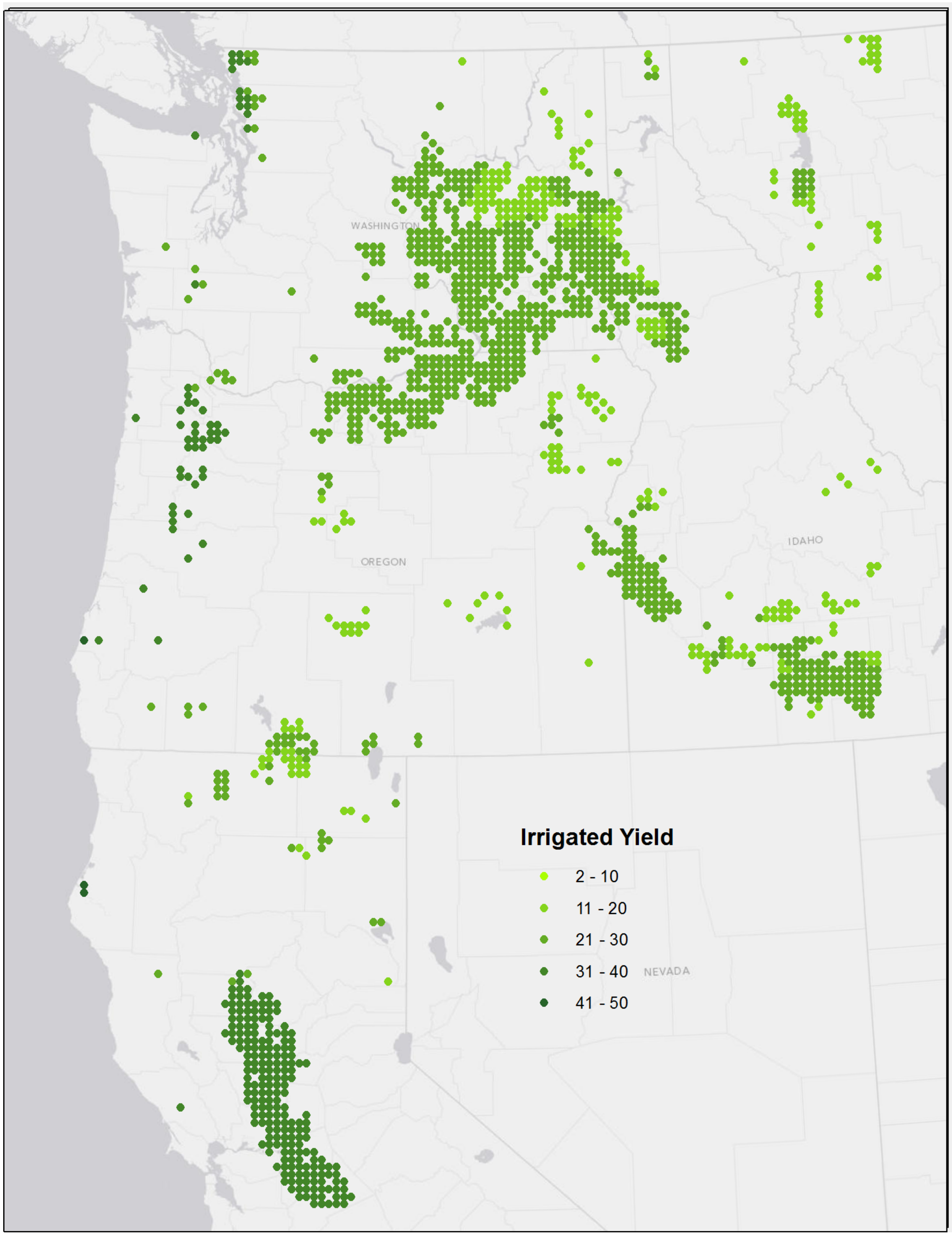

Figure 9: Predicted annual irrigated yields for a 18 year 5 coppice plantation cycle for areas in the PNW currently under agricultural practice. The image only includes pixels with more that %20 area identified as cropland. The isolines on the maps describe the standard deviation over the 7 parameterizations.

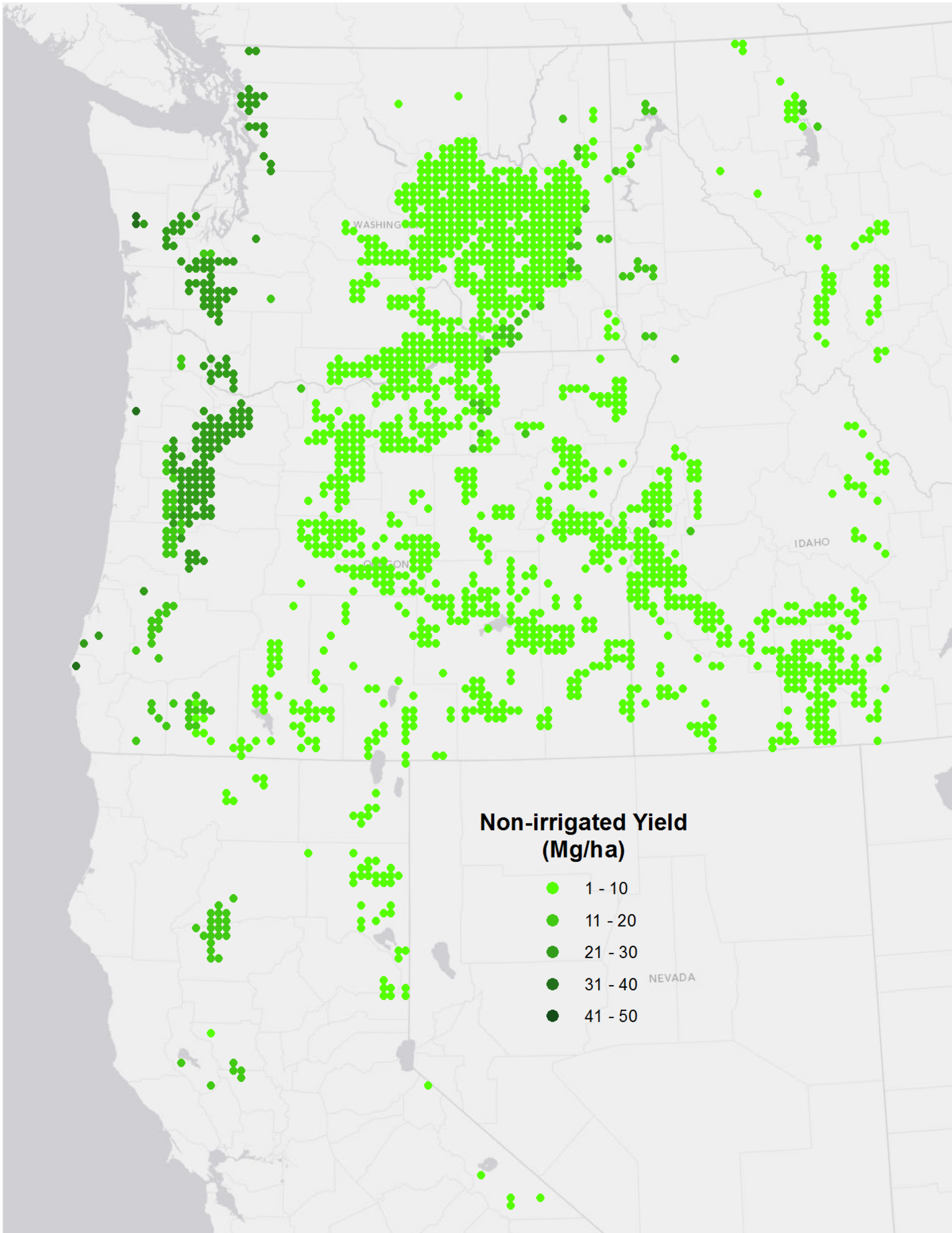

Figure 10: Predicted annual nonirrigated yields for a 18 year 5 coppice plantation cycle for areas in the PNW identified as rangeland or marginal land. The image only includes pixels with more than %20 area identified as marginal or rangeland. The isolines on the maps describe the standard deviation over the 7 parameterizations.

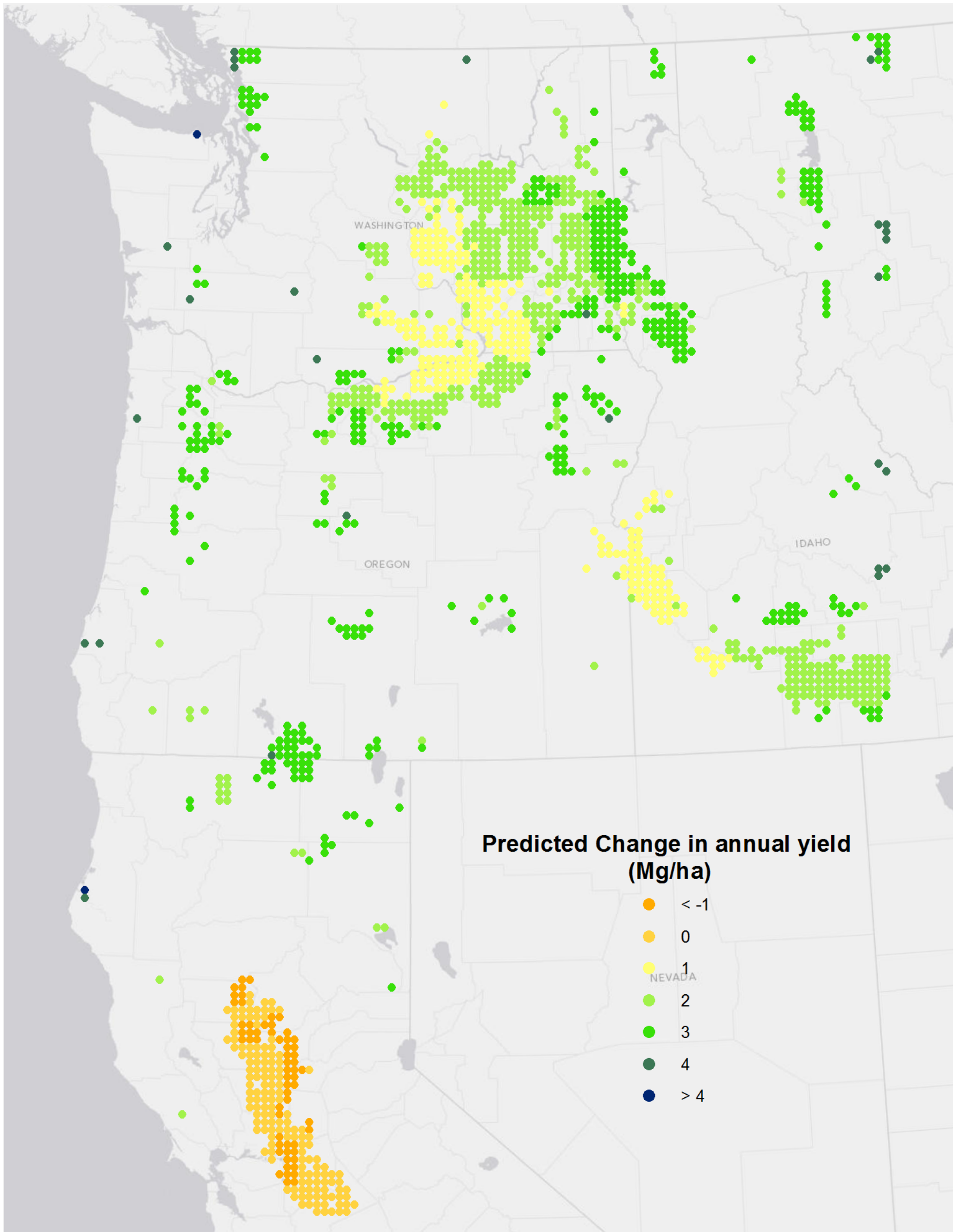

Figure 11: Changes in predicted irrigated yield for CCSM3 scenario A1B for a plantation planting in 2040-2058.

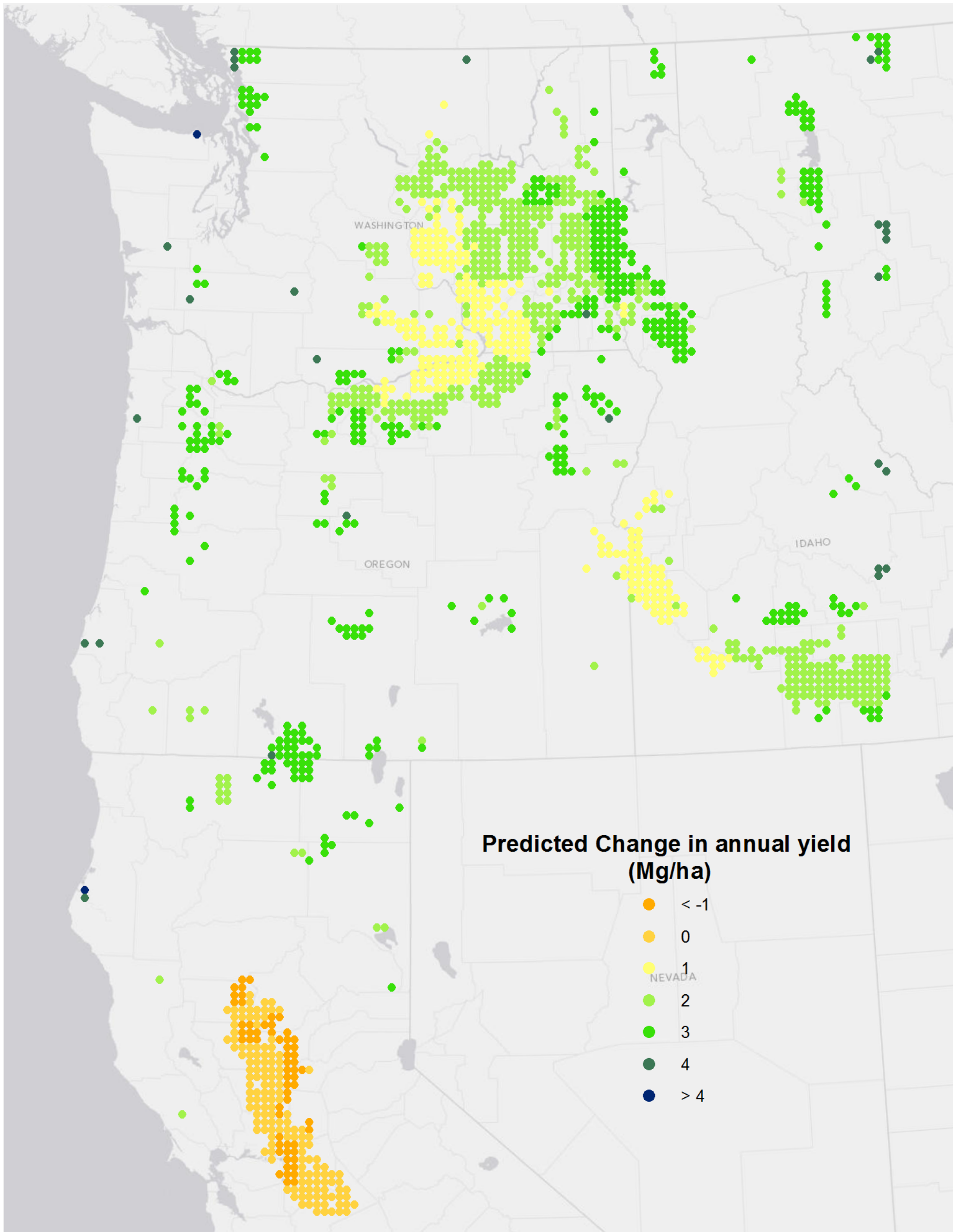

Figure 12: Changes in predicted nonirrigated yield for IPCC scenario A1B for a plantation planting in 2040-2058.