1 Modeling Poplar Growth as a Short Rotation Woody 2 Crop for Biofuels in the Pacific Northwest

3 Q. J. Hart^{a,*}, P.W. Tittmann^b, V. Bandaru^c, B. M. Jenkins^c

4 ^a*Dept. of Land, Air, and Water, University of California, Davis, USA*

5 ^b*Center for Forestry, University of California, Berkeley, USA*

6 ^c*Dept. of Biological and Agricultural Engineering, University of California, Davis, USA*

7 **Abstract**

8 Predicting the economic viability and environmental sustainability of a bio-
9 fuels industry based on intensively cultivated short rotation woody crops
10 (SRWC) requires spatial predictions of growth and yield under various envi-
11 ronmental conditions and across large regions. The Physiological Principles
12 in Predicting Growth (3PG) model was modified to evaluate the growth and
13 yield of coppiced poplar (*Populus spp*). This included an additional biomass
14 partitioning method and developing a sub-model which takes into account the
15 impact of coppicing on post harvest regeneration, extending the applicability
16 of the 3PG model to coppice management regimes.

17 The parameterized model was applied to the entire Pacific Northwest of
18 the United States, using appropriate climate and soil input data. Results
19 predict the yield of poplar cultivation at a spatial resolution of $\approx 64 \text{ km}^2$
20 throughout the $\approx 8,000,000 \text{ km}^2$ of the study region. Existing agricultural
21 cultivation patterns were used to estimate regional water availability for irri-
22 gation, and for non-irrigated regions, land cover features including ownership,
23 slope, soil salinity and water table depth were used to select areas with a
24 real potential to support a SRWC plantation.

Preprint submitted to Biomass & Bioenergy

April 29, 2015

Phone: 530-675-4278

Email address: qjhart@ucdavis.edu (Q. J. Hart)

25 Results can be integrated with other models that allow for optimizing
26 crop selection and biorefinery site selection. Important results include; an
27 updated 3PG model for coppiced SRWC plantings, estimates of biomass
28 feedstock yields under different irrigation patterns and weather conditions,
29 and estimates for feedstock availability when combined with crop adoption
30 scenarios.

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

33 1. Introduction

34 The Advanced Hardwood Biofuels Northwest (AHB-PNW) is a consor-
35 tium of university and industry partners investigating the development of
36 a sustainable hardwood biofuels industry in Washington, Oregon, northern
37 California, Idaho, and western Montana in the United States. Inspired in
38 part by the U.S. Energy Independence and Security Act 2022 targets for
39 renewable fuel, AHB-PNW is carrying out research and development to sup-
40 port a system for growing and converting hardwoods, such as hybrid poplars,
41 into liquid biofuels. This research and development initiative has focused on
42 fuels fully compatible with existing liquid transportation fuel infrastructure.

43 To support economic and environmental models for a biofuels industry,
44 spatial predictions of yield for short rotation woody crops (SRWC) under
45 various environmental conditions are required throughout the entire Pa-
46 cific Northwest (PNW) region. The Physiological Principles in Predicting
47 Growth (3PG) [1, 2, 3] model was utilized for this purpose. Empirically
48 based growth and yield models for hybrid poplar have been used with some

49 success in the region [4], however the samples used to develop allometric rela-
50 tionships did not include coppice management. Stand to Ecosystem CaRbon
51 and EvapoTranspiration Simulator (SECRETS) [5] is another process based
52 model, differing from 3PG in a number of ways, including biomass produc-
53 tion and aboveground partitioning [6].

54 The 3PG model was modified for SRWC, particularly for poplar plan-
55 tation methodologies. The motivation for the use of spatially resolved yield
56 estimates is two-fold:

57 **Biofuels production system optimization** Substantial investment is re-
58 quired to construct facilities capable of producing drop-in fuels [7].
59 Capitalization of these facilities will depend upon a demonstrated con-
60 sistent supply of feedstock. While spot or commodity markets may
61 emerge to supply the demand for these facilities via bulk rail or ma-
62 rine supply chains, first mover facilities will likely depend on contracts
63 with regional producers to supply a substantial percent of the facility
64 demand. This analysis helps identify locations likely to have access to
65 substantial local supply.

66 **Land use** The potential for displacement of food crops from agricultural
67 lands is a possible outcome of expanding biofuel markets. The impacts
68 associated with an increase in food prices on global food security raises
69 ethical issues that relatively developed and food-secure societies must
70 consider [8]. This exercise helps identify land not currently in food
71 production that is potentially viable for SRWC production.

72

73 3PG predicts total carbon based on photosynthetically active radiation
74 and is parameterized by variables relating to the tree, soil (water availability)
75 and weather data. It produces monthly estimates of foliage stem and root
76 biomass. In this analysis 3PG is run for each pixel within a grid of the
77 PNW. Each pixel is modeled as a stand with input parameters that vary with
78 geography (soil, weather) are used to parameterize the model. Modifications
79 to the original 3PG model include changes to the biomass partitioning, and
80 the inclusion of a root contribution to regrowth after coppicing.

81 A physiological growth model such as 3PG is advantageous because it
82 allows variation of growth parameters and assumptions regarding manage-
83 ment practices for poplar species. In addition to biomass growth and yield
84 estimations, allocations for both above and below ground biomass can be
85 tracked for more complete life-cycle analysis of the carbon budget related to
86 the fuels.

87 The 3PG model has been used previously to model SRWC production.
88 One [9] used the 3PG to predict growth of the Walker poplar hybrid (*Pop-*
89 *ulus deltoides* x *Populus nigra*) in Saskatchewan, Canada. This analysis
90 did not investigate the growth dynamics related to coppicing. In a sepa-
91 rate study [10] the SECRETS model was modified and evaluated for coppice
92 poplar production from two varieties under a range of soil fertility conditions.
93 The SECRETS coppice modified partitioning fractions with the presence of
94 a large root mass, one of the outcomes of the coppicing model described here
95 for 3PG.

96 The 3PG model [11] has been deployed across several states in the north-
97 ern Midwest United States to predict growth and yield of hybrid poplar but

98 did not evaluate the impact of coppice management. To date, the use of
99 physiological growth models such as the 3PG to evaluate spatial variability
100 in yields of coppiced SRWC at the scale and extent of the results presented
101 here has not been attempted.

102 The original 3PG model does not include coppicing as a management
103 practice, which is problematic as it cannot reasonably account for post-
104 coppicing regrowth. Coppicing of SRWC has been widely demonstrated to
105 increase growth rates post-coppice in comparison to un-coppiced stands [12,
106 13, 14]. The extensions presented in this paper include coppicing with a gen-
107 eral sub-model that allows a monthly growth contribution from an existing
108 root mass. The model specifies a relatively small contribution of aboveground
109 growth from the accumulated root mass after coppicing in order to initiate
110 the next cycle of production [10].

111 With appropriate input information, the 3PG model can predict yields for
112 the entire Pacific Northwest study region, under various irrigation scenarios.
113 When linked with models of crop adoption, biofuel feedstock estimates are
114 possible.

115 **2. Methods and Calculation**

116 The main goal of this study was to create spatially explicit poplar growth
117 potential for the PNW that can reliably predict yield from SRWC plantations
118 in the region.

119 The study area, the Pacific Northwest of the United States, includes
120 Washington, Oregon, northern California, Idaho, and western Montana. A
121 regular grid partitions the region. The individual pixel size is relatively

coarse 8192 m $\times$ 8192 m. The spatial aggregation will necessarily result in yield estimates that do not capture local variability. However, the intent of the study is to identify areas of high productivity within the study region. A coarse geographic unit was selected to strike a balance between geographic specificity and complexity of subsequent modeling steps not covered in this paper. Another similar study [11] used 32 km² spatial resolution.

An Albers equal area projection with reference longitude 120° W, latitude 44° N and parallels at 41° N and 47° N was utilized [15]. Other input datasets (eg. climate, soils) were scaled to match the base pixel size and raster projection. For example, the National Land Cover Dataset (NLCD) dataset used in this study, was originally imported and projected at a much finer scale, 32 $\times$ 32 m, then aggregated upwards and used to determine proportion of landcover types within each 64 km² unit. Section 2.2 provides additional exemplary detail.

Data processing was carried out within a postgresql database, with the postgis geospatial extensions [16, 17, 18]. The 3PG model was implemented directly in the postgresql database via user-defined functions adapted from the spreadsheet model procured from the University of British Columbia 3PG support website [19]. The functions were implemented in JavaScript[™], so that a single library could support this database (PostgreSQL), and an online application documented in [20].

2.1. 3PG Model Formulation

The 3PG model takes as inputs weather data, soil parameters, site factors, initial stocking conditions, management practices, and species definitions [1, 2, 3]. 3PG runs at a monthly timestep. At each step the physiolog-

ical 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.

A few studies have specifically modeled poplar using the 3PG model [9, 11, 21]. Headlee [11] in particular, developed parameters from a review of laboratory and field studies to represent the growth of a representative hybrid poplar. Alternatively, there have been several reported field tests on coppiced poplar plantations [22, 23, 24, 13] that show large variations in above ground biomass production among different poplar species. To represent this variability, a base input parameter set was modified on a per variety basis to match field reported production, resulting in seven separate parameter sets. All sets were run over the region and the average yield across all species is reported.

The *Base* parameter set used to model poplar in 3PG was altered for each of five species. Parameters were estimated from Pontailier [24, 25, 26], a field test that described biomass measurements over 5 two year coppicing events for five different poplar species, grown in Orsay, France from 1987 through 1997. The clones studied included fast growing, interspecific Interamerican (*Populus trichocarpa* $\times$ *P. deltoides*) hybrid clones (Parameter sets *Beaupre* and *Raspalje*), a native American *P. trichocarpa* (*Fritzi Pauley*) and one Euroamerican reference clone *P. deltoides* $\times$ *P. nigra*, cv., (*Robusta*).

3PG was modified in two ways to allow modeling of SRWC; a modification to the allocation of biomass among roots, foliage and stem, and the inclusion of a coppicing model.

An important component of 3PG is the allocation of Net Primary Pro-

ductivity (NPP) to Root biomass (W_R), Stem biomass (W_S), and Foliage biomass (W_F). This is controlled primarily with the foliage to stem allocation fraction (p_{FS}), a function of W_S which helps determine the aboveground allocations. The parameter p_{FS} is in turn calculated from a pair of allometric relations. In 3PG, p_{FS} is obtained in a two step process, first obtaining an estimate of Diameter at Breast Height (dbh) from the current W_S , and then using dbh to determine p_{FS} through an empirical relationship. These relations are typically determined from comparisons of more mature trees, for example, Headlee's estimates are based on poplars with a range in dbh of about 3.5 - 25 cm [11]

For SRWC, Pontauiller et al. [25] proposed a set of parameterizations based on Volume Index (VI) where $VI = HD^2$, H is height m, and D is tree diameter m at 22cm. They described power relationships between VI and both above ground dry matter and leaf area per stem. These can be used in a similar manner to define p_{FS} , where W_S is used to estimate VI with Stems per stump (n_{stems}) specified and VI then used to predict Leaf Area per stem (LA), which along with Specific Leaf Area (SLA), predicts W_F and p_{FS} . As these relationships were defined for the poplar in the field tests, 3PG was modified to calculate p_{FS} using these relationships. Table 1 describes these inputs. The parameter set *Base*, is the 3PG default parameter set for poplar.

[Table 1 about here.]

Two additional parameter sets *HW1* and *HW2* used the original p_{FS} formulation; $DM = n_{stems}(C_{stem}dbh^{P_{stem}})$, and $p_{FS} = C_{pfs}dbh^{P_{pfs}}$, with $n_{stems} =$

196 2.8, $C_{stem} = 0.18$, $P_{stem} = 2.4$, $C_{pfs} = 1.92$, $P_{pfs} = -1.162$ for *HW1* and
 197 $n_{stems} = 1$, $C_{stem} = 0.08$, $P_{stem} = 2.46$, $C_{pfs} = 1.2$, $P_{pfs} = -0.77$ for *HW2*
 198 with a maximum allowable $p_{FS} = 2$, when the coppiced trees are small.

199 In 3PG, foliage is required for growth. After coppicing however, with no
 200 foliage, there is no mechanism for initial regrowth. A simple coppicing model
 201 was developed to transfer biomass from the root system to the regenerating
 202 foliage after coppicing. When a SRWC is coppiced there is no foliage, but
 203 there is a large root mass. In the coppice sub-model, a small portion of this
 204 mass is allowed to contribute as Root Productivity (RP) at each monthly
 205 timestep. The seasonal timing of any root contribution is moderated by
 206 comparing a monthly NPP to a Target Productivity (NPP_T), corresponding
 207 to a specified Target Leaf Area Index (LAI_T). $NPP_T - NPP$ serves as a limit
 208 on the root contribution. Using a potential NPP_T serves two purposes. First,
 209 it allows root contributions up to, but not beyond a certain foliage amount, as
 210 specified by LAI_T . More importantly, since the root contribution is regulated
 211 by NPP , RP is timed with conditions that are favorable for plant regrowth.

212 In addition to foliage, 3PG modeling requires available root mass for
 213 . 3PG specifies a maximum root fraction (x_{pR}), and any mass above this
 214 fractional amount, $W_R(W_R/W - x_{pR})$, is considered available. A monthly
 215 root contribution (R_Δ) value limits the contribution of this excess to the
 216 small fraction that can be used for regrowth. R_Δ affects both the amount
 217 and the timeliness where contributions are made. In poplar, starch and
 218 sugar can comprise 15% the total dry matter of coarse roots, though this
 219 varies seasonally [27].

220 We are thus able to effectively model post-coppice regrowth using an

221 additional root conversion efficiency (e_R) for transfer from root to above
222 ground biomass, per-month $RP = W_R(W_R/W - x_{pR})R_\Delta * e_R$, subject to the
223 constraint that $RP \leq NPP_T - NPP$.

224 In poplar plantations initiated with bare cuttings as propagation, the
225 initial growth is modeled the same way, however with different parameters to
226 model initial root dynamics. Table 2 shows the values used for the coppicing
227 calculations for both the initial cuttings and the coppiced trees. These values
228 are constant for all parameter sets.

229 [Table 2 about here.]

230 Even with changes in the p_{FS} calculations and the coppice model, contri-
231 butions to the root mass are a fraction of NPP ranging from a minimum to
232 maximum as determined by the plant stress and nutrition, as in the original
233 3PG model. These values, along with root turnover and litterfall are shown
234 in table 3.

235 [Table 3 about here.]

236 Figure 1 shows the five parameter set variations used to match reported
237 variation in the five poplar types. The lines indicate the 3PG model predic-
238 tions, with the black line being the *base* parameter set. The dots indicate
239 reported stem biomass at each coppice event.

240 [Figure 1 about here.]

241 The remaining 3PG parameters used for the seven parameter sets are
242 shown in Tables 4 and 5.

[Table 4 about here.]

Each parameter sets was applied to the entire Pacific Northwest region. 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.

The predictions are overlaid with surface and land cover parameters to predict yields only for potential plantation locations. Yield maps show the average yield from the seven parameter sets over the entire AHB-PNW region.

Predictions were made for both irrigated and non-irrigated conditions over a 17.5 year period. Coppicing was modeled with an initial harvest at 2.5 years followed by 5 additional events on a three year cycle. Initial planting was in March, with coppicing in November.

A 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. Non-irrigated plantations were limited to areas with potentially usable marginal land.

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

267 year.

268 To predict current temperatures and precipitation the Parameter-elevation
269 Relationships on Independent Slopes Model (PRISM) dataset was used [28].
270 PRISM extrapolates station data spatially to a uniform grid using weights
271 derived from the physiographic similarity of the station to the grid cell.
272 These similarity measures include location, elevation, coastal proximity, to-
273 pographic facet orientation, vertical atmospheric layer, topographic position,
274 and orographic effectiveness of the terrain. PRISM data is available on a 2.5
275 minute geographic grid.

276 16 years of PRISM data were interpolated (cubic spline) to the AHB-PNW
277 grid and averaged to determine a representative weather pattern used for
278 yield predictions. Annual mean temperature is shown in figure 2. Iso-
279 lines show the standard deviation between annual mean temperature to the
280 monthly mean temperature. Total precipitation is shown in figure 3. Isolines
281 on the precipitation map show the maximum monthly contribution.

282 [Figure 2 about here.]

283 [Figure 3 about here.]

284 In order to determine incoming monthly solar radiation, monthly National
285 Renewable Energy Laboratory (NREL) global incident radiation data were
286 utilized [29]. The incident radiation data product provides monthly average
287 and annual average daily total solar resource averaged over surface cells of
288 0.1 degrees. Hourly radiance images from geostationary weather satellites,
289 daily snow cover data, and monthly averages of atmospheric water vapor,
290 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. Where no existing ground weather stations exist, the model is assumed to be the best estimate.

The incident radiation data is available as a grid with a scale similar to this project and is interpolated (cubic-spline) onto the AHB-PNW pixels.

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 includes a growth limiter related to the available water in the soil, and the soil type.

These soil parameters are determined with the State Soil Geographic (STATSGO) database [30]. 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 delineations were used, contributing anywhere from 144 to 1.3M ha.

Maximum available soil water (S_x) defines the 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

316 topmost 1 m of soil (Figure 4).

317 [Figure 4 about here.]

318 The soil water limiter (f_{Θ}) is parameterized with a power Θ_P and a
319 constant Θ_c , both functions of the soil type (Figure 5). The soil type is
320 determined from STATSGO report percentages of silt, sand, and clay within
321 each soil component.

322 [Figure 5 about here.]

323 2.2. Land Classification and Irrigation

324 Available climatic data makes it possible to make estimations for poplar
325 growth throughout the PNW region. This may provide interesting com-
326 parisons of changes in yield, but is not suitable for determining regional
327 estimations, as not all lands are equally likely to be available for poplar plan-
328 tations. Variables like land ownership, topography and salinity, influence the
329 technical capability of growing poplar.

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

334 To limit the areas within the PNW region to areas that are technically
335 suitable to poplar plantations, a set of masks were used. Permanently non-
336 suitable land was removed from consideration. Lands under Federal own-
337 ership [31] and currently developed land were excluded from consideration.
338 Physical features including slopes greater than 15% [32], and soil salinity
339 greater than 4 dS m⁻¹ were also excluded.

340 Available water for irrigation is an important question when dealing with
 341 crops in the PNW. Irrigation is a combination of availability and rights,
 342 that is hard to track on a regional scale. However, one aspect of irrigation
 343 is that if it's available it is likely being used. Therefore, for determining ir-
 344 rigated yield predictions for poplar, a mask of existing irrigated agricultural
 345 areas was used. These locations were determined in two steps. First, the
 346 a cropland data layer was used to spatially locate agricultural crops in the
 347 region. The USDA, National Agricultural Statistics Service (NASS) Crop-
 348 land Data Layer (CDL) is a nationally available raster of crop specific land
 349 cover data layer with a ground resolution of 30 meters. The CDL is pro-
 350 duced using satellite imagery with a classification emphasis on agricultural
 351 land cover [33]. The CDL was projected unto the AHB-PNW region. Indi-
 352 vidual pixels from the CDL were then aggregated within the larger model's
 353 pixels to determine fractional composition of each pixel (Figure 6). An ad-
 354 ditional step was used to adjust the total area in each county to the values
 355 of hectares reported to the NASS. NASS publishes U.S., State and County
 356 agricultural statistics for many commodities [34]. Later modeling efforts rely
 357 on the NASS reported hectares of the various commodities harvested. This
 358 was accomplished by uniformly adjusting the CDL derived pixel fractions, so
 359 that sum of pixel fractions over any county in the AHB-PNW region match
 360 the reported number of hectares harvested for that county and commodity.
 361 This method allows the spatial patterns of the CDL to be retained with
 362 fractions that add to the NASS reported values.

363 All images were scaled to match the $\approx 64 \text{ km}^2$ project pixel resolution.
 364 Scaled pixels reflect the area weighted average of any smaller pixels.

[Figure 6 about here.]

2.3. Climate Change

The A1B climate change scenario articulated in the Intergovernmental Panel on Climate Change (IPCC) 2007 Summary for Policymakers is plausible, somewhat optimistic scenario for climate change [35, 36]. 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.

We used expected conditions based on the A1B scenario to demonstrate the effect of potential climate change on yield predictions in the near future. Yields were predicted based A1B scenario outcomes on a plantation initiated in 2040.

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 temporal 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. There-

fore, 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 274.15° K, 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 7).

[Figure 7 about here.]

3. Results and Discussion

Results show an average coppice yield for irrigated poplar over the entire region of 19.7 Mg ha⁻¹. 38000 km² 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 eastern Washington, reaching lows in the Northeastern section of the study region (Figure 8).

[Figure 8 about here.]

Similarly, the non-irrigated yield predictions were masked with the areas excluded in the land suitability study to include those areas likely to support non-irrigated poplar plantations. Results for the non-irrigated lands predict an average coppice yield of 6.6 (Mg ha⁻¹) over an area under consideration of 57000 km². In the case of non-irrigated 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 9).

413 [Figure 9 about here.]

414 To assess the predicted change in yields from the A1B example study, the
415 model was rerun with the predicted changes in temperature and precipitation.
416 The results were averaged and summarized as above to predict yields. The
417 yields were then compared to the current yield estimates to determine the
418 difference in predicted yields under that one example climate change scenario.

419 Under irrigated conditions, the higher predicted temperatures generally
420 improve yields through most of the region, with the exception of California,
421 where high temperatures often limit monthly growth. Changes in yield are
422 modest in the areas with the highest yields and more significant in the colder
423 northern and central regions (Figure 10).

424 [Figure 10 about here.]

425 For non-irrigated plantations, the predicted decrease in precipitation de-
426 creases yields along the areas with the current highest yields, along the wet
427 Pacific coast. Higher temperatures continue to increase yields in most of the
428 inland areas (Figure 11)

429 [Figure 11 about here.]

430 These change estimations can inform both the individual farmer in terms
431 of predicting long term viability of poplar plantations as a SRWC feedstock,
432 as well as regional estimations on the mid-term ability of such a feedstock
433 to provide an expected harvest, and therefore an expected level of biofuel
434 production. Not only changes in expected overall yields, but changes in the

435 spatial distribution of the yields can have impacts on economic analysis of a
436 SRWC based biofuel industry in the PNW.

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

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

447 For example, in the AHB-PNW project, a companion model, the Bioen-
448 ergy Crop Adoption Model (BCAM), predicts price levels where poplar com-
449 petes with existing crops in about 35 different general cropping regions in the
450 PNW. The spatially distributed yield predictions inform the BCAM model.
451 For irrigated land, current yields are input into a BCAM model where they
452 compete with existing crops to determine their economic viability. The yield
453 predictions also include predictions in required water, and the BCAM model
454 manages water availability by balancing any water needs from the poplar
455 with water saved from crops taken out of the agricultural system. Outputs
456 of the BCAM model show at what farm gate price (\$ Mg⁻¹) poplar becomes
457 an economically viable product.

458 For non-irrigated land, marginal and under utilized lands can be added
459 into the overall agricultural economy as newly utilized lands. For non-

460 irrigated plantations, crop budgets can give estimates of farm gate costs
461 (\$ Mg⁻¹) which are affected by the predicted yields.

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

474 The production of bioenergy feedstocks from lands not used in agricul-
475 tural production can ensure that prime agricultural lands continue to produce
476 food crops. We interpreted the results of this modeling exercise to assess the
477 potential production of hybrid poplar SRWC as biofuel feedstock with mini-
478 mal impact on agricultural land use. To accomplish this we used the CDL
479 to identify landcover types associated with grazing/pastureland and grass-
480 lands. Table 6 shows production from this land base by state within the
481 study area. States for which the data in Table 6 include the entire area
482 of the state are Washington, Oregon, and Idaho. Total annual growth on
483 marginal lands in the study area is estimated to be approximately 260 Pg
484 y⁻¹. Further economic filters must be applied to assess the cost for produc-

485 ing fuel from SRWC, however this analysis shows that feedstock produced
486 from lands with little or no impact on agricultural markets can contribute
487 substantially to meeting transportation energy needs for the region.

488 [Table 5 about here.]

489 **4. Conclusions**

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

493 With additional layers showing current croplands, areas the can be ir-
494 rigated are identified. Poplar suitability maps limit consideration on non-
495 irrigated plantations to regions that are amenable to such management.

496 Limitations of the model presented here are primarily related to reliability
497 of the predicted yield at the local scale. As the spatial unit of measure is
498 a 64 km² land area, variability in growth and yield at a local scale may be
499 great.

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

503 **5. Acknowledgments**

504 This work is supported by an Agriculture and Food Research Initiative
505 Competitive Grant no. 2011-68005-30407 from the USDA National Institute
506 of Food and Agriculture (NIFA).

- 507 [1] Landsberg JJ, Sands P. Physiological ecology of forest production: prin-
508 ciples, processes and models. vol. 4. Academic Press; 2011.
- 509 [2] Landsberg JJ, Waring RH. A generalised model of forest productivity
510 using simplified concepts of radiation-use efficiency, carbon balance and
511 partitioning. *For Ecol Manage.* 1997 Aug;95(3):209–228.
- 512 [3] Sands P. 3PG PJS - a user-friendly interface to 3-PG , the Landsberg
513 and Waring model of forest productivity. Hobart: Cooperative Research
514 Centre for Sustainable Production Forestry; 2004. 14.
- 515 [4] Clendenen GW. Use of harmonized equations to estimate above-ground
516 woody biomass for two hybrid poplar clones in the Pacific Northwest.
517 *Biomass Bioenergy.* 1996 Jan;11(6):475–482.
- 518 [5] Sampson DA, Janssens IA, Ceulemans R. Simulated soil CO₂ efflux and
519 net ecosystem exchange in a 70-year-old belgian Scots pine stand using
520 the process model SECRETS. *Ann For Sci.* 2001;58(1):31–46.
- 521 [6] Surendran Nair S, Kang S, Zhang X, Miguez FE, Izaurralde RC, Post
522 WM, et al. Bioenergy crop models: Descriptions, data requirements,
523 and future challenges. *GCB Bioenergy.* 2012;4(6):620–633.
- 524 [7] Parker N, Tittmann P, Hart Q, Nelson R, Skog K, Schmidt A, et al. De-
525 velopment of a biorefinery optimized biofuel supply curve for the West-
526 ern United States. *Biomass Bioenergy.* 2010 Nov;34(11):1597–1607.
- 527 [8] Pimentel D, Marklein A, Toth MA, Karpoff M, Paul GS, McCormack R,
528 et al. Biofuel Impacts on World Food Supply: Use of Fossil Fuel, Land
529 and Water Resources. *Energies (Basel, Switz).* 2008 Sep;1(2):41–78.

- 530 [9] Amichev BY, Johnston M, Van Rees KCJ. Hybrid poplar growth
531 in bioenergy production systems: Biomass prediction with a simple
532 process-based model (3PG). *Biomass Bioenergy*. 2010 May;34(5):687–
533 702.
- 534 [10] Deckmyn G, Laureysens I, Garcia J, Muys B, Ceulemans R. Poplar
535 growth and yield in short rotation coppice: model simulations using the
536 process model SECRETS. *Biomass Bioenergy*. 2004 Mar;26(3):221–227.
- 537 [11] Headlee WL, Zalesny RS, Donner DM, Hall RB. Using a Process-Based
538 Model (3-PG) to Predict and Map Hybrid Poplar Biomass Productivity
539 in Minnesota and Wisconsin, USA. *BioEnergy Res*. 2012 Sep;6(1):196–
540 210.
- 541 [12] Verwijst T. Cyclic and progressive changes in short-rotation willow cop-
542 pice systems. *Biomass Bioenergy*. 1996;(11):161–165.
- 543 [13] Afas NA, Marron N, Van Dongen S, Laureysens I, Ceulemans R. Dy-
544 namics of biomass production in a poplar coppice culture over three
545 rotations (11 years). *For Ecol Manage*. 2008 Apr;255(5-6):1883–1891.
- 546 [14] Sennerby-Forsse L, Ferm A, Kauppi A. Coppicing ability and sustain-
547 ability. In: Mitchell CP, Ford-Robertson JB, Hinckley TM, Sennerby-
548 Forsse L, editors. *Ecophysiology of Short Rotation Forest Crop*. Oxford:
549 Elsevier Applied Science; 1992. p. 146–184.
- 550 [15] NAD83 / US Pacific Northwest Albers [homepage on the Internet]. Spa-
551 tial Reference;

- 552 [16] PostgreSQL 9.4.1 Documentation [software manual on the Internet]. The
553 PostgreSQL Global Development Group; 2015 [cited 2015 Apr 23]. Avail-
554 able from: <http://www.postgresql.org>.
- 555 [17] Holl S, Plum H. PostGIS. GeoInformatics. 2009 Apr;03/2009:34–36.
- 556 [18] PostGIS 2.0 Manual [software manual on the Internet]. PostGIS Project;
557 2015 [cited 2015 Apr 23]. Available from: <http://postgis.net>.
- 558 [19] 3-PG Forest Growth Model [homepage on the Internet]. Vancouver,
559 British Columbia: University of British Columbia;.
- 560 [20] Prilepova O, Hart Q, Merz J, Parker N, Bandaru V, Jenkins B. Design of
561 a GIS-Based Web Application for Simulating Biofuel Feedstock Yields.
562 ISPRS Int J Geoinf. 2014 Jul;3(3):929–941.
- 563 [21] Zalesny RS, Donner DM, Coyle DR, Headlee WL. An approach for
564 siting poplar energy production systems to increase productivity and
565 associated ecosystem services. For Ecol Manage. 2012 Nov;284:45–58.
- 566 [22] Proe MF, Gri JH, Craig J. Effects of spacing , species and coppicing
567 on leaf area , light interception and photosynthesis in short rotation
568 forestry. Biomass Bioenergy. 2002;23:315–326.
- 569 [23] Proe MF, Craig J, Gri J, Wilson A, Reid E. Comparison of biomass
570 production in coppice and single stem woodland management systems on
571 an imperfectly drained gley soil in central Scotland. Biomass Bioenergy.
572 1999;17:141–151.

- 573 [24] Pontailler JY, Ceulemans R, Guittet J. Biomass yield of poplar after
574 five 2-year coppice rotations. *Forestry*. 1999;72(2):157–163.
- 575 [25] Pontailler J, Ceulemans R, Guittet J, Mau F. Linear and non-linear
576 functions of volume index to estimate woody biomass in high density
577 young poplar stands. *Ann For Sci*. 1997;54(4):335–345.
- 578 [26] Ceulemans R, Pontailler JY, Mau F, Guittet J. Leaf allometry in young
579 poplar stands: Reliability of leaf area index estimation, site and clone
580 effects. *Biomass Bioenergy*. 1993 Jan;4(5):315–321.
- 581 [27] Regier N, Streb S, Zeeman SC, Frey B. Seasonal changes in starch and
582 sugar content of poplar (*Populus deltoides* x *nigra* cv. Dorskamp) and
583 the impact of stem girdling on carbohydrate allocation to roots. *Tree*
584 *physiology*. 2010 Aug;30(8):979–87.
- 585 [28] Daly C, Halbleib M, Smith JI, Gibson WP, Doggett MK, Taylor GH,
586 et al. Physiographically sensitive mapping of climatological temperature
587 and precipitation across the conterminous United States. *Int J Climatol*.
588 2008 Dec;28(15):2031–2064.
- 589 [29] Perez R, Ineichen P, Moore K, Kmiecik M, Chain C, George R, et al. A
590 new operational model for satellite-derived irradiances: description and
591 validation. *Sol Energy*. 2002 Nov;73(5):307–317.
- 592 [30] Soil Survey Staff. U.S. General Soil Map (STATSGO2). Natural Re-
593 sources Conservation Service, United States Department of Agriculture;.
594 Available from: <http://sdmdataaccess.nrcs.usda.gov/>.

- 595 [31] National Atlas of the United States. Federal Lands and Indian Lands;
596 2013.
- 597 [32] Gesch DB. The National Elevation Dataset, in Maune, D., ed., Digital
598 Elevation Model Technologies and Applications: The DEM Users Man-
599 ual, 2nd Edition:. American Society for Photogrammetry and Remote
600 Sensing. 2007;p. 99–118.
- 601 [33] Boryan C, Yang Z, Mueller R, Craig M. Monitoring US agriculture: the
602 US Department of Agriculture, National Agricultural Statistics Service,
603 Cropland Data Layer Program. *Geocarto Int.* 2011 Aug;26(5):341–358.
- 604 [34] Quick Stats [homepage on the Internet]. USDA National Agricultural
605 Statistics Service; 2015 [cited 2015 Apr 23]. Available from: [http:
606 //www.nass.usda.gov/Quick_Stats/](http://www.nass.usda.gov/Quick_Stats/).
- 607 [35] IPCC. IPCC Fourth Assessment Report (AR4). IPCC. 2007;1:976.
- 608 [36] Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE.
609 IPCC, 2007: Summary for Policymakers. New York: Cambridge Uni-
610 versity Press; 2007.

637 **List of Tables**

638	1	Volume Index (<i>VI</i>) parameter variations of 3PG among pa-	
639		rameter sets.	31
640	2	3PG Coppicing Parameters	32
641	3	Root allocation and litterfall	33
642	4	Additional 3PG model parameters	34
643	5	3PG Parameter set variation	35
644	6	Poplar growth and yield on marginal lands in the Pacific	
645		Northwest.	36

TABLES

Table 1

Parameter	<i>Beaupre</i>	<i>Fritzi Pauley</i>	<i>Raspalje</i>	<i>Robusta</i>	<i>Base</i>
γ_{DM}	0.854	0.863	0.887	0.838	0.887
β_{DM}	166.0	157.6	161.5	162	161.5
γ_{LA}	0.428	0.481	0.495	0.496	0.495
β_{LA}	$e^{-0.161}$	$e^{-0.198}$	$e^{-0.287}$	$e^{-0.273}$	$e^{-0.287}$
n_{stems}	4	3.5	2.8	5	2.8

$DM = n_{stems}(\beta_{DM}VI^{\gamma_{DM}})$, and $LA = \beta_{LA}VI^{\gamma_{LA}}$ [25].

Table 2

Parameter	Description	Cutting	Coppiced
R_{Δ}	Monthly root contribution	0.01	0.1
LAI_T	Target Leaf Area Index (LAI_T)	1	1
e_R	Root conversion efficiency	0.6	0.75

Table 3

Parameter	Description	HW1	All Others
n_{pR}	Minimum Root allocation (p_R)	0.25	0.17
x_{pR}	Maximum p_R	0.34	0.7
0_{pR}	Dependence of p_R on f_{nutr}	0	0.5
	Monthly root turnover rate.	0.005	0.02
$f0_{lf}$	Litter fall (lf) at initial time step	0.0015	0.0015
$f1_{lf}$	lf infinite time step	0.03	0.03
tm_{lf} (yr)	Where value is the average of $f0$ and $f1$	2	2
n_{lf}	Rate of change around tm	2.5	2.5

For coppicing, when $W_R/W > x_{pR}$ root allocation is further decreased by $(x_{pR}/(W_R/Plantbiomass(W)))^2$

Table 4

Parameter	Source	HW1	Others
y	Assimilation use efficiency	0.47	0.47
BL_{cond} (m-1)	Boundary layer conductance	0.2	0.04
$f0_{SLA}$	SLA at initial time	10.8	19
$f1_{SLA}$	SLA at infinite time step	10.8	10.8
tm_{SLA} (y)	When average of $f0$ and $f1$	1	5
n_{SLA}	Rate of change around tm	2	2
k	Radiation Extinction Coefficient	0.5	0.5
$n_{Intcptn}$	Minimum rainfall interception, when $LAI = 0$	0	0
$x_{Intcptn}$	Maximum rain	0.24	0.24
$lai_{Intcptn}$ (m ² m ⁻²)	LAI where parameter reaches a maximum value.	7.3	7.3
n_{Cond}	Minimum canopy conductance	0.0001	0.0001
x_{Cond}	Maximum canopy conductance	0.033	varies
lai_{Cond} (m ² m ⁻²)	LAI for maximum	3.33	2.6
kG (kg Pa ⁻¹)	Response of the canopy conduc- tance to the vapor pressure deficit	0.85	varies
$CanopyAge$ (y)	When tree reaches full Canopy Cover	1.5	varies
$alpha$ (kg mol ⁻¹)	Canopy quantum efficiency.	0.08	varies
$f0_{nutr}$	Minimum nutritional lim- iter (f_{nutr})	1	varies
n_{f_T} (°C)	Minimum respiration tempera- ture	5	0
opt_{f_T} (°C)	Optimum respiration temperature	20	20
x_{f_T} (°C)	Maximum respiration tempera- ture	40	varies
$f0_{f_{age}}$	age growth limiter (f_{age}) at initial time	1	1
$f1_{f_{age}}$	f_{age} at infinite time	0	0
$tm_{f_{age}}$ [y]	When average of $f0$ and $f1$	47.5	varies
$n_{f_{age}}$	Rate of change around tm	3.5	varies

Table 5

Parameter	<i>HW2</i>	<i>Base</i>	<i>Raspalje</i>	<i>Beaupre</i>	<i>Fritzi</i>	<i>Robusta</i>
x_{Cond}	0.02	0.02	0.04	0.03	0.04	0.03
kG (kg Pa-1)	0.5	0.5	0.4	0.3	0.5	0.5
$Canopyage$ (y)	1.5	0.6	0.5	0.7	0.9	1.2
$alpha$ (kg mol-1)	0.08	0.08	0.11	0.09	0.08	0.06
$f0_{nutr}$	0.26	0.26	1	0.8	0.3	1
x_{f_T}	50	50	60	60	50	50
$tm_{f_{age}}$ [y]	47.5	47.5	12	47.5	25	25
$n_{f_{age}}$	3.5	3.5	5	3.5	3.5	3.5

Table 6

State	Annual growth (Pg y ⁻¹)	Average yield (Mg ha ⁻¹)	Marginal land area (km ²)
Oregon	117.59	9.60	2,141,559
Washington	96.33	7.18	2,346,141
Idaho	29.56	4.68	1,104,391
California	13.60	7.97	297,156
Montana	4.25	5.77	128,560
Nevada	0.12	2.45	8,805
Utah	0.06	4.96	2,134

610 **List of Figures**

611	1	Fitted parameters to measurement comparisons for yearly growth over five coppicing events.	19
612			
613	2	Mean annual temperature, with isolines showing the standard deviation in monthly temperature.	20
614			
615	3	Total annual precipitation, with isolines showing the maximum monthly precipitation.	21
616			
617	4	STATSGO derived maximum water holding capacity.	22
618	5	(Θ_c, Θ_P) pairs 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.	23
619			
620			
621	6	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.	24
622			
623			
624			
625	7	Predicted changes in temperature and precipitation under CCSM3 scenario A1B for plantation planted in 2040.	25
626			
627	8	Predicted irrigated yield of a 3 year coppice harvest for areas under agricultural practice. The image only includes pixels with more that %20 area identified as cropland.	26
628			
629			
630	9	Predicted non-irrigated yields of a 3 year coppice harvest for areas identified as rangeland or marginal land. The image only includes pixels with areas more than %20.	27
631			
632			
633	10	Changes in predicted irrigated yield for CCSM3 scenario A1B for a plantation planting in 2040-2058.	28
634			
635	11	Changes in predicted non-irrigated yield for IPCC scenario A1B for a plantation planting in 2040-2058.	29
636			

FIGURES

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11