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Impacts of Supplyshed-Level Differences in Productivity and Land Costs on the Economics of Hybrid Poplar Production in Minnesota, USA

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Abstract The joint effects of poplar biomass productivity and land costs on poplar production economics were compared for 12 Minnesota counties and two genetic groups, using a process-based model (3-PG) to estimate aboveground biomass productivity. The counties represent three levels of productivity which, due to spatial stratification, were analogous to three biomass supplysheds. An optimal rotation age (ORA) was calculated that minimizes the annualized, discounted per-dry megagrams biomass cost for each county, genetic group and land cover, and for two discount rates (5 and 10 %). The ORA for the lowest-cost county (Todd) with specialist genotypes and a 5 % discount rate is 14 years and the breakeven price at that age is US$71 dry Mg^{-1}, while for the highest-cost county (McLeod), the generalist genotype and a 10 % discount rate, the ORA is 10 years and the breakeven price at that age is US$175 dry Mg^{-1}. Planting after a previous poplar stand increased breakeven prices and increased the ORAs by 1 to 2 years relative to planting after a previous annual crop. An ANOVA analysis showed a significant genetic group effect and significant productivity class × land rent interactions. All other factors being equal, an increase in the discount rate from 5 to 10 % is expected to reduce ORAs by 2 to 3 years. High-productivity supplysheds can also be expected to have ORAs that are 2 to 3 years shorter than low-productivity ones. Land costs were not as closely correlated to productivity as we expected.

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Introduction

Uncertain profitability across the landscape is a concern that hinders broad-scale deployment of short-rotation woody crops such as species and hybrids within the genus *Populus* (e.g., hybrid poplars; hereafter referred to as poplars). However, there may be specific locations throughout the USA where these purpose-grown trees are the best crop choice because of unique soil, climatic, or market conditions that limit the alternatives [1], thereby creating opportunities for inclusion of these woody feedstocks into national bioenergy portfolios. The Physiological Principles Predicting Growth (3-PG) process-based model was recently used to predict poplar biomass productivity for Minnesota and Wisconsin, USA and to evaluate areas that are most suitable for poplar production within these states [2, 1]. Physical productivity is not the only determinant of landowners' decisions to grow a given crop, however. Costs and markets are also key factors. Escalating prices for corn, soybeans, and other agronomic crops in particular have increased the demand for land capable of growing those crops. That demand has translated into sharply increasing land purchase prices and rental rates. Cropland rental rates in Minnesota increased at an average annual rate of 10.8 % between 2008 and 2012, with rates increasing 17.8 % between 2011 and 2012 alone [3, 4]. The ethanol blend wall and a more competitive corn export market suggest that US corn prices may retrench over the next few years, which may stabilize or reduce land rents [5].

Given that land costs vary widely across space, the main purpose of this study was to estimate how the profitability of poplar production would be affected by the joint effects of productivity and land cost differences in Minnesota. Hachfeld et al. [3] showed that county average annual rental rates in Minnesota in 2011 varied from US$91 ha^{-1} in Kanabec County in the east-central part of the state, to US$534 ha^{-1} in Freeborn County on the Iowa border. That data is from rents actually paid by farmers participating in the Minnesota State Colleges and Universities (MnSCU) Farm Business Management program and the Southwestern Minnesota Farm Business Management Association, and summarized in the Finbin database [6].[1] As such, rental rates are only reported for counties with a minimum of ten farms participating in those programs. The counties in the northeastern and east-central parts of the state do not have farms in those programs, so are not represented in that dataset. The USDA National Agricultural Statistics Service (NASS) also does a land rent survey, and that data tends to align closely with the Finbin data. The 2011 NASS survey showed a low of US$25 ha^{-1} in Carlton County, just north of Kanabec County. The high in that survey was US$489 ha^{-1} in Faribault County, just west of Freeborn County.

The Finbin rental rates are based on acres of all row crops, small grains, canning crops, and other annual crops. Not included in that analysis were acres allocated to pasture, aftermath grazing, hay and haylage, exiting Conservation Reserve Program (CRP) land,[2] fallow, or prevented planted acres. Given that, we also sought to determine where poplar might best compete with annual crops around the state. Our working hypothesis was that poplar might have a competitive advantage in the counties with more marginal land, as indicated by lower rental rates. Our additional objectives were to evaluate: (1) the impact of properly matching poplar genotypes to varying site conditions (referred to here as “specialist” genotypes) versus using those that produce less biomass but can be grown across a greater range of sites (i.e., “generalists”) on profitability [1], and (2) the economic impact of planting into different types of previous land cover (i.e., annual row crops or poplar). As such economic information is lacking in the region, the results are important for producers making decisions on whether poplars warrant the aforementioned broad-scale deployment for bioenergy, biofuels, and/or bioproducts.

[1] The Finbin database consists of individual farm data calculated using a component of the Finpack farm financial planning and analysis software package. See http://www.cffm.umn.edu/FINPACK/ for more details.

[2] CRP is a land conservation program administered by the USDA Farm Service Agency. In exchange for an annual rental payment, farmers remove land from production and plant species that will improve environmental quality for 10–15 years based on a conservation plan that is agreed to in advance. Planting a tree crop such as hybrid poplar on land currently in the CRP program and planted to grasses and legumes is a possibility if the tree crop enhances the site’s environmental benefits [7] and would not be harvested until after the end of the CRP contract, but this would require approval of the local USDA-FSA committee and the NRCS. The CRP payment could then offset the land cost for the poplar planting. The impact of having a CRP payment offset the land rent is discussed in a brief note in the Results section of this paper.

Materials and Methods

Site Preparation, Planting, Maintenance, and Harvesting Practices and Costs

The costs presented here are organized into per-hectare enterprise budgets that are intended to represent typical poplar production. The practices for site preparation, planting, maintenance, and harvesting are based on information from experts with three companies currently operating poplar plantings in the USA and Europe, a poplar researcher at Michigan State University, and a review of two publications that contain a certain amount of detail such as planting equipment and labor costs, and fertilization timing and rates [8, 9]. As such, these costs represent the best information available at the time our analyses were conducted, and are subject to change over time as alternative practices evolve and new information becomes available. Additional information on best practices for the wide-spacing, long rotation production mode for poplar are summarized in two publications by van Oosten, and in Isebrands [10–12].

Costs of site preparation, planting, and early crop maintenance were estimated for two land cover scenarios: (1) an annual crop such as corn, and (2) a previous poplar planting. The corn scenario was considered based on field reconnaissance that identified variations in the amount of vegetative cover which would likely affect poplar establishment and maintenance practices and costs, as discussed in Zalesny et al. [1]. The previous poplar scenario was chosen because some poplar plantings are being harvested at present and questions are being raised about the best way to re-establish them for future production. A third scenario of planting into pasture or CRP land was also considered. However, the site preparation cost difference between corn and pasture, when averaged over the overall stand life, was small compared to the land rent differences. Previous field reconnaissance showed that annual crops such as corn were more common than pasture or CRP on the sites considered [1]. Therefore, in the interest of conserving space, only the detailed results for corn and previous poplar scenarios are presented in this paper. The third pasture/CRP scenario is then discussed in a brief note.

The chemical applications and machinery operations assumed here through the early maintenance years for the three scenarios are listed in Table 1. Planting year practices assumed here when following corn are two passes with a tandem disk, an application of Fusilade and 2,4-D herbicides and three row cultivations, in addition to the planting operations. Practices in the first maintenance year after planting assumed here include applications of Fusilade and Sevin. A rotary mower pass is substituted in the planting and first maintenance year for the cultivations when following poplar.

A site preparation year is included before the planting year when following poplar, but not after corn. Two herbicide

Table 1 Machinery operations and chemical applications for early years of hybrid poplar production, by previous land cover

Previous land cover and year	Chemical applications	Machinery operations
Corn or other annual agronomic crop		
Planting year	Fusilade and 2,4-D	Disk 2x; plant; row cultivation 3x
Maintenance year 1	Fusilade and Sevin	Row cultivation 2x
Maintenance year 2	None	Row cultivation 1x
Poplar		
Site preparation year	Glyphosate and 2,4-D	None
Planting year	Glyphosate, 2,4-D and Fusilade	Rototill; plant; mow
Maintenance year 1	Fusilade and Sevin	Replant; mow

applications are made during that site preparation year—an application of glyphosate for total vegetation kill, followed by a 2,4-D application for selective broadleaf control. Ugarte et al. [8] included a pass with a forestry disk and a glyphosate application in that year, and there have been reports of harvested willow plantings in Minnesota that have been prepared by using heavy equipment such as disks to pulverize the old stumps [13]. In contrast, Brad Bender at Michigan State University reported that judicious use of herbicides and mowing over the stumps have allowed for successful new plantings without the use of such heavy equipment, so the detailed results here omit that step which saves several hundred dollars per hectare. The planting year operations then consist of another herbicide application, mowing over the stumps to remove shoots, and planting the new cuttings in the row between the old stumps. He also used a tractor-drawn rototiller to control weeds, which is included here. The poplar stand life is assumed to be ten years without considering that site preparation year, so that extra year of no poplar growth increases the overall rotation length to 11 years and reduces the average annual growth and revenue compared to the corn scenario that is planted in the first year of the rotation. The impact of adding a disking operation to the scenarios reflected in the main results is then discussed in a brief note.

Fertilization practices also varied in the publications and reports from the company experts, from no fertilization at all to fertilization in three different years. One application of 34 kg N, 9 kg P_2O_5, and 16 kg K_2O per hectare is assumed in the fourth year after planting. The N rate and timing is based on Ugarte et al. (2000), while the P_2O_5 and K_2O rates and timing are based on the experts' information.

Prices and cost rates for the inputs and machinery operations are shown in Table 2. Poplar cuttings are priced at US $0.29 each, based on a price quote from a commercial nursery (Segal Ranch Hybrid Poplars; http://www.hybridpoplar.com). This is higher than the $0.09 cutting^{-1} listed by Perlack and Stokes [9]. One justification for using the higher price here is that the growth rates assumed in the 3-PG model used for the present study assumes high-quality planting stock that may be more likely to be achieved when the cuttings are obtained from a commercial nursery than when propagated under less tightly controlled conditions. Costs for planting and harvesting are based on Perlack and Stokes [9]. The chemicals and fertilizer are assumed to be custom-applied while the plowing, row cultivation, and mowing costs are based on 2012 cost estimates for Minnesota [14, 15]. Labor directly involved in operating the machinery is included with the machinery cost rates in Table 2. However, labor is also likely to be required for non-machinery-related tasks such as vegetation management, supervisory tasks, and inspecting for diseases, insects, and nutrient deficiencies. No source is available on non-machinery labor requirements for poplar production, but farms with intensively-managed pastureland in Minnesota averaged somewhat more than 2.47 hrs ha^{-1} yr^{-1}, based on labor disappearance estimates [6]. Labor of 2.47 hrs ha^{-1} yr^{-1} is included here for non-machinery labor based on that information, and valued at US$20 hr^{-1}.

The costs presented here are intended to include delivery to the final processing plant, so transportation costs and storage losses are considered. The wood is assumed to be stored temporarily near the field and then chipped and transported by truck to final processing. A one-way hauling distance of 40 km and a speed of 80 km hr^{-1} are included from the New York Eco-willow spreadsheet [16]. Load size is a critical variable, but is highly speculative at this point given that large-volume biomass logistics systems are still under development. The maximum load size may be constrained by either weight or volume, depending on the density of the material. The load weight is assumed here to be 23.6 Mg [17]. A US $0.31 km^{-1} truck cost for non-fuel expenses and a fuel consumption rate of 3 km L^{-1} are from the Eco-willow spreadsheet. Other assumptions are a loading and unloading time of 20 min per load, a driver labor cost of US$20 hr^{-1}, and a diesel fuel price for on-road use of US$1.08 L^{-1}.

A loss in dry matter during harvest, storage, and transport of 5 % is assumed, based on Swedish research showing that wood residue stored in bundles experienced dry matter losses of 6 % after 5 months and 12 % after 8 months [18], and that wood chip dry matter losses were 5 % with ventilation or 13 % without ventilation after 62 days of storage [19].

Table 2 Prices (US$) per unit for cuttings, chemicals, fertilizer, machinery operations, and miscellaneous labor

Item			Price per unit (US$)
Cuttings, each			0.29
Plant and replant, per cutting			0.09
Chemicals:			
Glyphosate, per L			1.24
2,4-D, per L			2.57
Fusilade, per L			3.71
Sevin, per L			3.04
Apply chemicals, per ha			17.30
Fertilizer ingredients:			
N, per kg			1.19
P2O5, per kg			1.15
K20, per kg			0.88
Apply fertilizer, per ha			24.71
Machinery operations	Year of poplar stand after corn	Year of poplar stand after poplar	
Disk, per ha per pass	Year 1–2x		23.89
Plant or replant, per cutting	Year 1	Year 2	0.09
Row cultivation, per ha per pass	Year 1–3x, Year 2–2x, Year 3–1x		17.17
Rototill, per ha		Year 2	106.16
Mow (rotary mower), per ha		Year 3	29.53
Harvest, per Mg	Varies	Varies	22.05
Misc labor other than for machinery operations, per ha			49.42
Transport to processing			
One-way hauling distance, km			40
Travel speed, km hr^{-1}			80
Load weight, Mg			23.6
Fuel consumption rate, km L^{-1}			3
Loading and unloading time, minutes per load			20
Non-fuel cost, km^{-1}			$0.31
Diesel fuel price for on-road travel, L^{-1}			$1.08
Driver labor cost, hr^{-1}			$20

Study Design

Factorial Structure

The study was designed to evaluate the economics of poplar plantations with respect to the following factors: previous land cover, productivity, land costs, and genotype. As stated above, while three previous land covers were considered (annual crops, pasture, and poplar), the annual crop and poplar scenarios are presented here. Three levels of productivity were also analyzed (low, medium, high), along with two levels of land rent (low, high) each represented by two counties. Because land rent data are available at the county-level, this resolution was also used to generate the productivity estimates described below. Two genetic groups (generalist, specialist) were also evaluated. Thus, a total of 48 unique combinations of factors were assessed (2 previous land covers×3 site productivity classes×2 land rent categories×2 counties×2 genetic groups).

County Selection

Based on previous studies with 3-PG in the region [2, 1], an initial categorization of counties by productivity class was conducted. Specifically, area-weighted averages of productivity (dry Mg ha^{-1} yr^{-1} at age 10) were calculated for each county, and the range of values was then divided into thirds such that the three productivity classes for the counties were: low=5.0 to 7.5 dry Mg ha^{-1} yr^{-1}; medium=7.5 to 10.0 dry Mg ha^{-1} yr^{-1}; and high=10.0 to 12.5 dry Mg ha^{-1} yr^{-1}. In addition to these productivity estimates, which are based on generalist clones that perform relatively consistently across sites [2], county-level productivity estimates were likewise generated for specialist genotypes, similar to Zalesny et al.

[1] While productivity was consistently higher in the specialist scenario than the generalist scenario, the spatial trends for productivity are similar in both (Fig. 1).

Within each of the productivity classes described above, counties lacking Finbin land rent data and/or shown by Zalesny et al. [1] to be largely unsuitable for hybrid poplar production were eliminated from consideration. Due to strong spatial patterns in productivity among the counties, completely randomized sampling for each productivity class was not practical, and instead counties were systematically selected

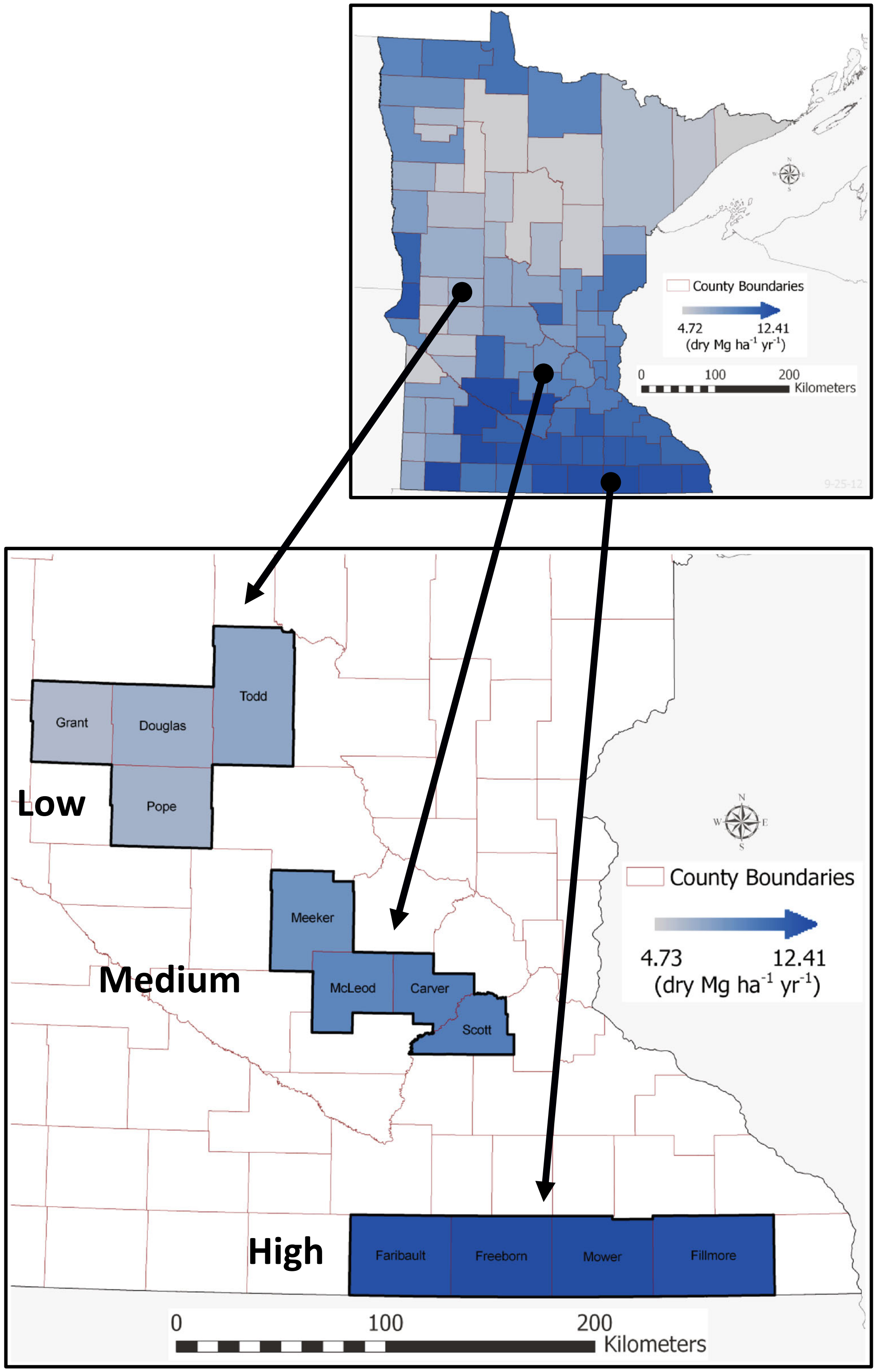

Fig. 1 Modeled yields ranging from 4.72 to 12.41 dry Mg ha^{-1} yr^{-1} for counties within Minnesota, USA comprising three woody biomass supplysheds for generalist genotypes, according to low, medium, and high site productivity classes (each represented by four counties). Note that yields for specialist genotypes exhibited similar trends that ranged from 5.34 to 13.84 dry Mg ha^{-1} yr^{-1}

from the observed spatial strata. Specifically, four contiguous counties having a wide range in land costs were selected within each productivity class, with the two counties having the lowest land rent classified as “low rent” and the two having the highest land rent classified as “high rent” (Table 3). Thus, the site productivity classes are analogous to woody biomass supplysheds (and are hereafter referred to as such), and the county-level data reflect the variability in predicted productivity and land rent within each supplyshed.

Modeling Methods

Climate and Soils Data

The monthly climate inputs required by 3-PG were obtained from existing long-term averages of weather station data. Specifically, 30-year averages (1981 to 2010) of mean monthly temperatures and precipitation were obtained for weather stations in or near each county [20]; these data are summarized in Table 4. For solar radiation data, 20-year averages (1991 to 2010) of mean monthly downward solar radiation were used [21]. Because only one county per supplyshed (i.e. Douglas, Freeborn, and Meeker) had solar radiation data available, and the counties within the supplysheds were adjacent to one another, the same solar radiation data was assigned to all counties within a supplyshed (data not shown). Similar to Headlee et al. [2], soils data were obtained from the Natural Resources Conservation Service STATSGO soil data layers [22] and area-weighted averages of minimum depth to water table and maximum available soil water in the top meter of soil were calculated for each 3-PG soil class in each county (summarized in Table 4). For a description of 3-PG soil classes and procedures for calculating minimum available soil water in the top meter of soil, see Headlee et al. [2].

Model Settings and Biomass Estimates

The 3-PG model has been calibrated for poplar biomass productivity in the region [2], based on a network of plantations for which biomass yields of clonal blocks planted at 2.4×2.4 m spacing and measured from 3 to 11 years (along with growth and disease ratings of mixed clonal trials from ages 7 to 12 years) were previously reported [23]. Three of these biomass plantations were recently harvested at age 20 for another study [24], allowing reconstruction of annual diameter at breast height (DBH) growth from tree ring measurements. These data, along with mortality estimates recorded during site assessments for the three plantations, were used to refine the model calibration to accurately predict growth and mortality out to 20 years of age (Fig. 2) and thus allow for a more thorough analysis of potential rotation lengths. The resulting parameter values are presented in Table 5 along with the previous parameter values they replace; all other parameters and settings (e.g., planting density of 1,736 trees ha^{-1}) are the same as those described by Headlee et al. [2]. We confirmed that the productivity class assignments indicated by the final model agreed with those produced by the initial model (see Table 3), albeit with slight shifts in the ranges of biomass estimates for the productivity classes (low=6.1 to 7.7 Mg ha^{-1} yr^{-1}, medium=7.8 to 8.9 Mg ha^{-1} yr^{-1}, high=9.0 to 10.1 Mg ha^{-1} yr^{-1}). Thus, the initial productivity class assignments were carried forward with the final model. We

Table 3 Counties selected for comparison according to productivity class, land rent category, and land rental rate. Initial biomass estimates (representing generalist clones at age 10) were generated prior to adjustment of model parameters; these estimates were used to preliminarily assign counties to productivity classes

County	Productivity class	Land rent category	Land rental rate (US$ ha^{-1} yr^{-1})	Initial model (dry mg ha^{-1})	Final model (dry mg ha^{-1})
Todd	Low	Low	128	71.2	76.1
Douglas	Low	Low	210	65.7	72.0
Pope	Low	High	255	65.2	61.9
Grant	Low	High	326	63.8	65.5
Meeker	Medium	Low	371	80.9	85.5
Scott	Medium	Low	395	87.4	86.7
McLeod	Medium	High	457	84.3	78.4
Carver	Medium	High	442	87.3	88.0
Fillmore	High	Low	489	115.0	90.3
Faribault	High	Low	479	115.2	92.8
Mower	High	High	497	118.1	99.4
Freeborn	High	High	534	115.9	100.4

Final biomass estimates (also representing generalist clones at age 10) were generated after adjusting model parameters to fit the long-term growth data; based on their agreement with the previous groupings, the initial assignments to productivity classes were maintained

Table 4 Summary of county data including latitude (Lat), weather station identification (ID) number, mean daily maximum (T_{max}), and minimum (T_{min}) air temperature during the growing season (April to October), mean annual precipitation (Precip), depth to water table (D_w), and maximum (ASW_{max}) and minimum (ASW_{min}) available soil water

County	Lat (°N)	ID[a]	T_{max} (°C)[a]	T_{min} (°C)[a]	Precip (mm yr^{-1})[a]	D_w (cm)[b]	ASW_{max} (mm)[b]	ASW_{min} (mm)[c]
Carver	44.8	211468	21.8	9.2	831	>100	206	0
Douglas	45.9	14910	20.3	9.0	638	>100	163	0
Faribault	43.7	219046	22.2	9.8	831	73	184	50
Fillmore	43.7	216654	21.9	8.9	904	>100	188	0
Freeborn	43.7	210075	21.6	9.8	865	>100	195	0
Grant	45.9	211245	21.3	8.0	650	>100	171	0
McLeod	44.8	213962	21.9	9.3	721	68	195	63
Meeker	45.1	214778	20.9	9.3	744	98	175	3
Mower	43.7	210355	21.1	9.5	878	55	185	84
Pope	45.6	213174	22.4	8.1	653	>100	148	0
Scott	44.7	214176	21.2	9.1	786	>100	188	0
Todd	46.1	214861	20.1	7.6	771	80	151	30

[a] Based on 30-year (1981 to 2010) monthly climate normals from the nearest weather station. Obtained from the National Oceanic and Atmospheric Administration (*NOAA*) National Climatic Data Center [20]

[b] Area-weighted average soil properties. Calculated from STATSGO soils data obtained from the Natural Resources Conservation Service [22]

[c] ASW_{min} estimated from ASW_{max} and D_w as described by Headlee et al. (2013a)

did not evaluate coppice systems consisting of narrower spacings and shorter rotations because past research has demonstrated that wider spacings and longer rotations result in superior productivity and/or economic considerations for hybrid poplars in the USA [25, 26]; also, the lack of yield data in the literature for such systems in this region over the last 20 years precludes us from calibrating and validating the model for these narrower spacings and shorter rotations.

Using the final model, aboveground biomass (dry Mg ha^{-1}) was estimated for each soil class in each county from ages 1 to 20 years. County-level estimates were generated by calculating average biomass (weighted by soil class area) by year for each county. These county-level biomass estimates were then

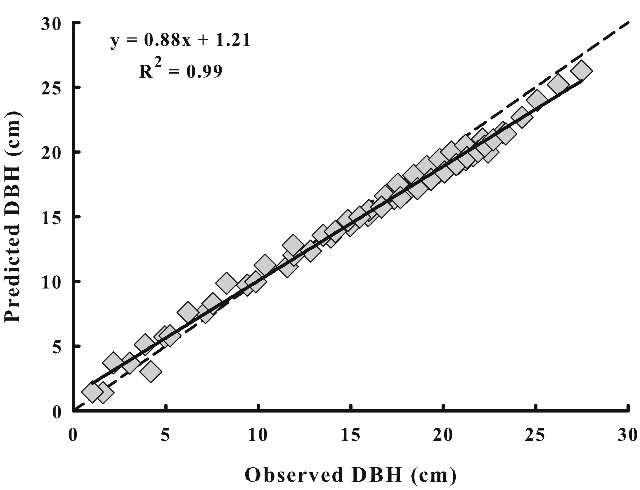

Fig. 2 Observed versus predicted mean diameter at breast height (*DBH*) from three, 20-year-old hybrid poplar plantations in Minnesota, USA modeled using 3-PG. *Dashed line* represents perfect 1:1 relationship

used to determine optimal rotation length, mean annual increments, and breakeven prices for each county under generalist and specialist scenarios. Similar to Zalesny et al. [1], the specialist genetic group was simulated by setting the optimal temperature for photosynthesis (T_{opt}) equal to the mean temperature for June through August, to demonstrate the potential of matching clones to prevailing environmental conditions.

Data Analysis

Economic Analyses

An optimal rotation age (ORA) was calculated for each county and for both genetic groups and discount rates by minimizing the annualized, discounted per-dry megagrams biomass costs that would result from an infinite series of like rotations. The formulation is similar to a discrete form of the Land Expectation Value (LEV) or Faustmann formula [27], converted to an Equal Annual Equivalent (EAE) by multiplying by the discount rate [28, 29]:

$$\mathrm{NPV} = \sum_{t=0}^{N} \frac{B_t - C_t}{(1+r)^t}$$

$$\mathrm{LEV} = \frac{\text{Net value in year } N}{\left[(1+r)^N - 1\right]} = \mathrm{NPV}\frac{(1+r)^N}{\left[(1+r)^N - 1\right]}$$

$$\mathrm{EAE} = r\ \mathrm{LEV} = \mathrm{NPV}\frac{r(1+r)^N}{\left[(1+r)^N - 1\right]}$$

Table 5 Updated 3-PG parameter values for poplars based on observed diameter growth and mortality at three 20-year-old plantations in Minnesota, USA

Parameter (units)	3-PG Name	Previous value (Headlee et al. 2013a)	Updated value (20-year data)
Ratio of NPP to GPP (unitless)	Y	0.43	0.47[a]
Max stem mass per tree at 1,000 stems ha^{-1} (kg tree^{-1})	wSx1000	500	300[a]
Power in self-thinning rule (unitless)	thinPower	1.45	1.32
Optimum temperature for growth (°C)	Topt	30	26
Fertility rating (unitless)	FR	1.00	0.70

All other parameter values are the same as those used by Headlee et al. (2013a)

[a] Default 3-PG parameter values [37]

where

B_t revenues in year t
C_t costs in year t
r discount rate, and
N rotation age, in years

Since we compared counties with different land rental rates, we included the land rental rate for each county as part of cost C_t rather than omitting land costs and calculating the value of bare land as in the usual Faustmann formulation [27]. The 2011 rental rates from Hachfeld et al.'s 2012 report [3] are used in this analysis rather than the higher 2012 rates listed in the 2013 report, based on the expectation that land rents may stabilize or decrease as US corn prices retrench due to the ethanol blend wall and a more competitive corn export market [5].

The economic analyses were carried out by first tabulating costs per hectare for each year of the rotation, as shown in Table 6 for the lowest-cost scenario (Todd County, specialist genetic group, and a 5 % discount rate) and the highest-cost scenario (McLeod County, generalist genetic group, and a 10 % discount rate). The intended use of the wood from expanded poplar plantings in Minnesota is for energy, but market prices for the wood are uncertain at this time due to the slow development of bioenergy processing plants. Rather than assuming an arbitrary market price, the approach taken here was to calculate a breakeven price per Mg of poplar wood by using the above discounting and annualization formulas to:

1. discount each year's costs back to a present value by dividing by $(1+r)^t$ and adding them up for a net present value (NPV) over the rotation,
2. annualize the NPV to arrive at EAE by multiplying the NPV by $[r\,(1+r)^N]/[(1+r)^N-1]$,
3. convert the physical wood yield harvested in year t to a present value basis equivalent to the EAE (referred to here as EAE_w) by applying the formulas as we used on the financial numbers to the physical wood yield; that is, dividing the physical wood yield in harvest year t by $(1+r)^t$ and then multiplying by $[r\,(1+r)^N]/[(1+r)^N-1]$, and finally
4. calculate the breakeven price per-dry Mg by dividing the EAE by EAE_w.

By definition, substituting the breakeven wood price into the budget results in an LEV and an EAE of zero—no profit or loss results from the enterprise. We arrive at the ORA by calculating the breakeven prices for a range of rotation ages, and selecting the age that minimizes the breakeven price.

Analyses of Variance

Land rental rate data were analyzed using PROC GLM in SAS (SAS Institute, Inc., Cary, NC) as a completely random, 2-way factorial design assuming three productivity classes (low, medium, high) and two land rent categories (low, high), with replication coming from counties as described above. A third factor, genetic group (generalist, specialist), was added to similar 3-way analyses of variance for mean annual increment (MAI) at 10 years after planting as well as the following parameters, which were each evaluated independently at 5 and 10 % discount rates: (1) ORA, (2) MAI at ORA, and (3) breakeven price at ORA. Fisher's protected least significant difference (LSD) was used to compare significant main effects and interactions at $P<0.05$. Significant main effects were not evaluated when comprising significant interactions.

Results

Calculated Enterprise Budgets, ORAs, and Breakeven Prices

Table 6 provides a breakdown of enterprise budgets for combinations of the lowest- and highest-cost counties with genetic group and discount rate scenarios, assuming planting into a previous annual crop such as corn. The ORA for Todd County with specialist genotypes and a 5 % discount rate is 14 years and the breakeven price at that age is US\$71 dry Mg^{-1}, while for McLeod County with the generalist genotype and a 10 % discount rate, the ORA is 10 years and the breakeven price at

Table 6 Annual cash flow summaries for a poplar planting after a previous annual crop, such as corn, for the lowest-cost and highest-cost combinations of site, genetic group, rotation age, and discount rate

Cost item	Annual cost (US$ ha^{-1}), by year(s)						NPV (US$ ha^{-1})	NPV_A (US$ ha^{-1} yr^{-1})	Breakeven price (US$ Mg^{-1})
	1	2	3	5	4; 6 to 13	14			
Lowest-cost: Todd County, specialist, 14 years, 5 %									
Yield net of 5 % storage loss						141 Mg	71 Mg	7.2 Mg	
Cuttings	487						465	47	7
Fertilizer				185			146	15	2
Crop chemicals	77	82					146	15	2
Machinery with labor	250	35	17			3,291	1,947	198	27
Transport to processing						1,067	539	54	8
Non-machine labor and mgmt	49	49	49	49	49	49	489	49	7
Land rent	128	128	128	128	128	128	1,273	128	18
Interest on variable expenses	27	5	2	7		116	94	10	1
Total listed costs	1,021	297	195	371	178	4,653	5,098	514	71
	Annual cost (US$ ha^{-1}), by year(s)								
Cost item	1	2	3	5	4; 6 to 9	10	NPV (US$ ha^{-1})	NPV_A (US$ ha^{-1} yr^{-1})	Breakeven Price (US$ Mg^{-1})
Highest-cost: McLeod County, generalist, 10 years, 10 %									
Yield net of 5 % storage loss						74 Mg	29 Mg	4.6 Mg	
Cuttings	487						445	72	15
Fertilizer				185			116	20	4
Crop chemicals	77	82					136	22	5
Machinery with labor	250	35	17			1,732	937	153	33
Transport to processing						563	217	35	8
Non-machine labor and mgmt	49	49	49	49	49	49	304	49	11
Land rent	457	457	457	457	457	457	2,810	457	98
Interest on variable expenses	30	5	0	7		62	57	10	2
Total listed costs	1,349	625	524	699	507	2,861	5,019	815	175

NPV net present value; NPV_A annualized net present value that age is US$175 dry Mg^{-1} (Table 6). At any other rotation age, the enterprise would operate at a loss. The rotation age that minimizes the breakeven price is also the rotation age that maximizes the LEV and EAE at that price, since at any other rotation age a loss would result at that price because the breakeven prices are higher at the other ages considered.

Table 7 compares the ORAs, yields, and breakeven prices for the 12 counties, for the scenario of planting into corn. The four panels of the table show how the genetic group and discount rate affect those results. As previously indicated in Table 6, Todd County has the lowest breakeven price while McLeod County has the highest. The higher 10 % discount rate reduced the value of the yield, in present value terms, compared to the 5 % rate. The effect was to reduce the benefit of prolonging the rotation, so the ORA was reduced by two to three years. The higher discount rate also increased the breakeven price by around 25 to 30 %. The specialist genotypes increased the yields, making it optimal to prolong the rotations and reduce the breakeven prices.

The third scenario considered, that of planting into a previous pasture or CRP field, is assumed to require a moldboard plowing operation costing US$55 ha^{-1} in addition to the other operations shown in Table 2 for planting into a previous corn crop. The impact of that additional cost on the breakeven prices will vary with rotation age, yield, and discount rate. For Todd County with generalist genotypes and a 5 % discount rate, the increase would be US$1 Mg^{-1} compared to the US$85 Mg-1 shown in Table 7. As noted earlier, another scenario would be to plant hybrid poplars on land under an existing CRP contract, which would be allowable if it can be demonstrated to enhance environmental benefits compared to

Table 7 Optimal rotation ages (yrs) and breakeven prices (Mg^{-1}) at those ages required to cover annualized costs over the life of the stand, comparing generalist and specialist genetic groups in different Minnesota counties, planting into a previous annual crop such as corn, 5 or 10 % discount rate

County	Land rental rate	5 % Discount rate			10 % Discount rate		
	(US$ ha^{-1} yr^{-1})	Optimal rotation age (yrs)	Yield at optimal age[a] (Mg ha^{-1})	Breakeven price (US$ Mg^{-1})	Optimal rotation age (yrs)	Yield at optimal age[a] (Mg ha^{-1})	Breakeven price (US$ Mg^{-1})
Generalist genetic group							
Todd	128	12	89	85	10	72	107
Douglas	210	14	107	99	11	79	129
Meeker	371	12	103	115	10	81	146
Scott	395	12	103	119	10	82	149
Pope	255	13	84	119	11	68	157
Mower	497	11	106	123	9	83	150
Carver	442	11	94	125	9	72	156
Faribault	479	12	110	126	10	88	157
Freeborn	534	11	107	126	9	83	155
Grant	326	13	89	129	11	72	168
Fillmore	489	11	96	131	9	75	160
McLeod	457	13	105	136	10	75	175
Specialist genetic group							
Todd	128	14	142	71	11	106	89
Douglas	210	16	157	86	12	106	114
Meeker	371	14	150	101	11	110	129
Scott	395	13	142	102	10	100	129
Mower	497	11	133	104	10	118	127
Pope	255	15	122	104	12	89	140
Carver	442	12	126	109	10	100	136
Freeborn	534	12	141	111	10	113	137
Grant	326	15	130	111	12	95	149
Fillmore	489	11	119	111	10	106	137
Faribault	479	12	130	111	10	102	140
McLeod	457	14	137	119	11	99	155

[a] The yields shown here are the modeled yields minus a 5 % storage loss

a previous grass cover. Such a situation may be unusual, but could be cost-effective where it is possible. Looking again at Todd County with generalist genotypes and a 5 % discount rate as an example, suppose it were possible to plant poplars on land that has six more years remaining on a CRP contract that pays enough to offset the $128 ha-1 yr-1 land rental cost in that county. Having the CRP payment offset the land cost for the first 6 years of the 12-year rotation would reduce the breakeven cost by US$12 Mg^{-1} compared to the US$85 Mg-1 shown in Table 7.

Table 8 shows the same information for the more-costly scenario of planting into a previous poplar stand. A higher price was required to break even as a result of the higher establishment costs. These higher prices also increased the ORAs by 1 to 2 years, relative to the scenario of planting into a previous annual crop, as higher yields were needed to offset the added establishment costs. Similar as for the annual crop scenario, the 10 % discount rate resulted in higher breakeven prices and shorter ORAs than the discount rate of 5 %, and the higher yields of the specialist genotypes resulted in lower breakeven prices and slightly longer rotations than the generalist genotypes.

The impact on the breakeven prices of adding a disking or other heavy equipment operation to remove stumps in the site preparation year rather than relying on chemicals will again vary with rotation age, yield, and discount rate. For Todd County with generalist genotypes and a 5 % discount rate, the increase would be US$2.02 Mg^{-1} for each US$100 ha-1

Table 8 Optimal rotation ages (yrs) and breakeven prices (Mg^{-1}) at those ages required to cover annualized costs over the life of the stand, comparing generalist and specialist genetic groups in different Minnesota counties, planting into a previous poplar stand, 5 or 10 % discount rate

County	Land rental rate	5 % Discount rate			10 % Discount rate		
	(US$ ha^{-1} yr^{-1})	Optimal rotation age (yrs)	Yield at optimal age[a] (Mg ha^{-1})	Breakeven price (US$ Mg^{-1})	Optimal rotation age (yrs)	Yield at optimal age[a] (Mg ha^{-1})	Breakeven price (US$ Mg^{-1})
Generalist genetic group							
Todd	128	13	89	91	11	72	117
Douglas	210	15	107	106	12	79	142
Meeker	371	14	113	124	11	81	163
Pope	255	15	92	129	12	68	174
Scott	395	13	103	129	11	82	167
Mower	497	12	106	133	10	83	169
Carver	442	13	104	136	11	84	175
Faribault	479	13	110	136	11	88	176
Freeborn	534	12	107	138	10	83	175
Grant	326	15	97	140	12	72	188
Fillmore	489	12	96	143	10	75	181
McLeod	457	14	105	148	12	85	196
Specialist genetic group							
Todd	128	15	142	75	12	106	97
Douglas	210	17	157	91	14	119	125
Meeker	371	15	150	108	12	110	143
Scott	395	15	155	109	12	114	143
Pope	255	17	132	111	13	89	155
Mower	497	13	148	112	11	118	141
Carver	442	14	139	117	11	100	152
Grant	326	17	141	119	13	95	165
Freeborn	534	13	141	120	11	113	153
Faribault	479	14	142	120	11	102	156
Fillmore	489	13	132	120	11	106	153
McLeod	457	15	137	128	12	99	173

The rotation age for the scenarios where planting into a previous poplar stand includes a soil preparation year before planting in year 2, while the scenarios planting into corn assume planting in year 1. Consequently, the yield at a 13-year ORA in Todd County following poplar (89 Mg ha^{-1}) in Table 8 is the same as the 12-year yield following corn shown in Table 7

[a] The yields shown here are the modeled yields minus a 5 % storage loss

spent on the stump removal operation compared to the US \$91 Mg^{-1} shown in Table 8.

ANOVA for Land Rent and MAI at Age 10

A significant genetic group effect was observed for MAI at age 10 years (P=<0.0001), with the specialist genetic group predictably having a higher MAI (9.9 Mg ha^{-1} yr^{-1}) than the generalist group (8.3 Mg ha^{-1} yr^{-1}). In addition, significant productivity class×land rent interactions were observed for rental rate (P=0.0158) and MAI at age 10 years (P=0.0021). Rental rates tended to vary more widely in the low-productivity supplyshed (US\$169 to US\$290 ha^{-1}) than high-productivity supplyshed (US\$484 to US\$515 ha^{-1}), with the low-rent and high-rent counties being significantly different in the low-productivity supplyshed but not in the high-productivity supplyshed (Fig. 3). For the high-productivity supplyshed, MAIs at age 10 years (Fig. 4) were significantly higher for high-rent counties (10.0 to 12.2 Mg ha^{-1} yr^{-1}) than for low-rent counties (9.2 to 10.9 Mg ha^{-1} yr^{-1}). In contrast, for the low-productivity supplyshed, the MAIs at age 10 years were significantly higher for low-rent counties (7.4 to 9.0 Mg ha^{-1} yr^{-1}) than for high-rent counties (6.4 to 7.3 Mg ha^{-1} yr^{-1}). The medium-productivity supplyshed was intermediate, with high- and low-rent counties not differing significantly (8.3 to 10.3 Mg ha^{-1} yr^{-1}).

ANOVA for ORA and Associated Values of MAI and Breakeven Prices at ORA

The main effect of productivity class was found to have a statistically significant (P<0.05) impact on ORA for all iterations of prior land use and discount rate (Table 9). Similarly, the main effect of genetic group was significant for ORA, MAI at ORA, and breakeven prices at ORA for all prior land uses and discount rates. In addition, productivity class×land rent interactions were observed for MAI and breakeven prices for both prior land uses and discount rates, and when applicable are described below in lieu of significant main effects for productivity class and/or land rent. The high-productivity supplyshed was associated with significantly lower ORAs than the low-productivity supplyshed for both prior land uses at a discount rate of 5 % (i.e., 2.6 to 2.7 years earlier), and for the prior land use of annual crops at a rate of 10 % (i.e., 1.7 to 1.8 years earlier). Similarly, the medium-productivity supplyshed had significantly lower ORAs than the low-productivity supplyshed across the board. The high-productivity supplyshed had significantly lower ORAs then the medium-productivity supplyshed for both prior land uses at the 5 % discount rate (i.e., 1.2 to 1.3 years earlier) and for prior poplar land use at the 10 % discount rate (i.e., 0.9 years earlier), but was not significantly different for prior annual crops at the 10 % discount rate (Table 10).

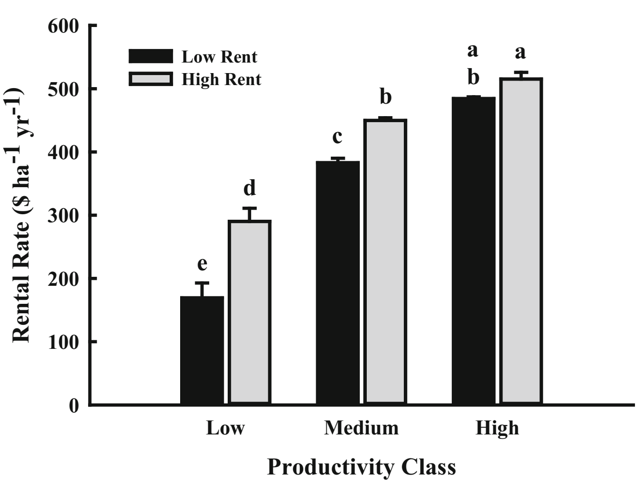

Fig. 3 Land rental rate (US\$ ha^{-1} yr^{-1}) for each combination of productivity class and land rent category. Means (±one standard error) with *different letters above bars* were different at P<0.05

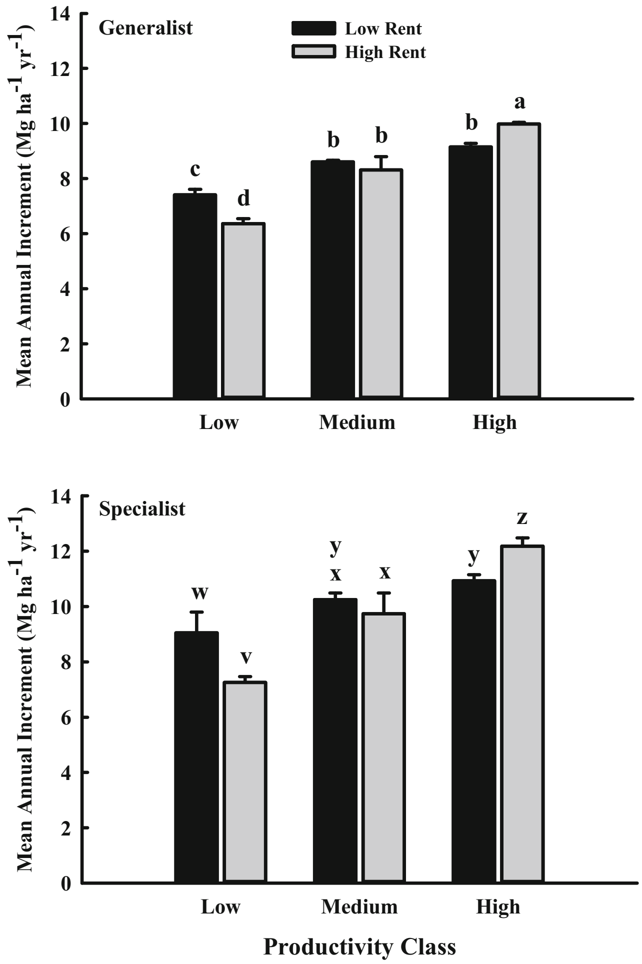

Fig. 4 Mean annual increment (Mg ha^{-1} yr^{-1}) at 10 years after planting for each combination of productivity class and land rent category for generalist and specialist genetic groups. Means (±one standard error) with *different letters above bars* within genetic groups were different at P<0.05

Table 9 Probability values from analyses of variance testing the effects of genetic groups (G; generalists, specialists), productivity classes (P; low, medium, high), and land rent categories (L; low, high) on optimal rotation age (ORA), mean annual increment (MAI), and breakeven prices (PRICE) at 5 and 10 % discount rates, assuming planting into previous annual crops or poplars

Source	$ORA_{5\%}$	$MAI_{ORA5\%}$	$PRICE_{ORA5\%}$	$ORA_{10\%}$	$MAI_{ORA10\%}$	$PRICE_{ORA10\%}$
	Annual crop					
G	**0.0087**	**<0.0001**	**<0.0001**	**0.0015**	**<0.0001**	**0.0004**
P	**0.0004**	**<0.0001**	**0.0002**	**<0.0001**	**<0.0001**	**0.0135**
G×P	0.1994	0.9758	0.9579	0.8484	0.5180	0.9446
L	0.6627	**0.0471**	**0.0002**	1.0000	0.1113	**0.0005**
G×L	1.0000	0.3370	0.7799	0.4301	0.8373	0.8764
P×L	0.9514	**<0.0001**	**0.0004**	0.2621	**0.0003**	**0.0007**
G×P×L	0.8623	0.1496	0.9680	0.8484	0.2652	0.9960
	Poplar					
G	**0.0005**	**<0.0001**	**<0.0001**	**0.0041**	**<0.0001**	**0.0003**
P	**<0.0001**	**<0.0001**	**0.0001**	**0.0002**	**<0.0001**	**0.0079**
G×P	0.3966	0.8781	0.9495	0.4418	0.5295	0.9286
L	0.7862	0.1096	**0.0001**	1.0000	0.0826	**0.0004**
G×L	0.7862	0.3909	0.7643	0.4930	0.3193	0.8619
P×L	0.1343	**0.0001**	**0.0004**	0.6951	**0.0001**	**0.0007**
G×P×L	0.9264	0.3057	0.9628	0.4418	0.1381	0.9952

Significant values are in bold

The specialist genetic group showed significantly higher MAIs (i.e., 1.8 to 2.1 Mg ha^{-1} yr^{-1} greater than the generalist group) and significantly lower breakeven prices (i.e., US$16 to US$22 Mg^{-1} less than the generalist group) at ORA across prior land uses and discount rates (Table 11). The discount rate of 5 % was associated with slightly higher MAIs (0.4 to 0.6 Mg ha^{-1} yr^{-1} greater than at a rate of 10 %) and lower breakeven prices (US$28 to US$39 Mg^{-1} less than at a rate of 10 %). Thus, the highest MAIs (10.3 to 10.4 Mg ha^{-1} yr^{-1}) and lowest breakeven prices (US$103 to US$111 Mg^{-1}) were associated with the specialist genetic group at a discount rate of 5 %, and the lowest MAIs (7.9 Mg ha^{-1} yr^{-1}) and highest breakeven prices (US$150 to US$169 Mg^{-1}) were associated with the generalist genetic group at a discount rate of 10 %. The specialist genetic group also had significantly higher ORAs (i.e., 0.8 to 1.4 yrs later than the generalist group), as slightly more time was needed for the specialist group to reach its higher growth ceiling.

For MAIs at ORA, the productivity class×land rent interactions (Fig. 5) were similar to that observed for MAIs at age 10, but with higher values of MAI associated with harvesting at ORA. The high-rent counties in the high-productivity supplyshed tended to have higher MAIs (9.7 to 12.0 Mg ha^{-1} yr^{-1}) than the low-rent counties (8.9 to 11.0 Mg ha^{-1} yr^{-1}). Conversely, the low-rent counties in the low-productivity supplyshed tended to have higher MAIs (7.5 to 10.0 Mg ha^{-1} yr^{-1}) than the high-rent counties (6.7 to 8.5 Mg ha^{-1} yr^{-1}). The medium-productivity supplyshed was generally intermediate, with the MAI of high- and low-rent counties rarely differing (8.3 to 10.9 Mg ha^{-1} yr^{-1}).

The aforementioned relationship between MAI and land rent in the high-productivity supplyshed resulted in similar breakeven prices at ORA for high- and low-rent counties (US $107 to US$158 Mg^{-1}; Fig. 6). The medium-productivity supplyshed also generally had similar breakeven prices for high-rent and low-rent counties (US$101 to US$165 Mg^{-1}),

Table 10 Optimal rotation age (years) for each combination of productivity class and discount rate, assuming planting into previous annual crops or poplars

Discount rate	Productivity class					
	Low Annual crop	Medium	High	Low Poplar	Medium	High
5%	14.0±0.5^{a}	12.6±0.4^{b}	11.4±0.2^{c}	15.5±0.5^{a}	14.1±0.3^{b}	12.8±0.3^{c}
10%	11.3±0.3^{a}	10.1±0.2^{b}	9.6±0.2^{b}	12.4±0.3^{a}	11.5±0.2^{b}	10.6±0.2^{c}

Means (±one standard error) with different letters within cropping systems in each row were different at $P<0.05$

Table 11 Optimal rotation age (ORA; years), mean annual increment at ORA (MAI; Mg ha^{-1} yr^{-1}), and breakeven price at ORA (PRICE; US $ Mg^{-1} dry wood) for generalist and specialist genetic groups at 5 and 10 % discount rates, assuming planting into previous annual crops or poplars

	Genetic group			
	Generalist Annual crop	Specialist	Generalist Poplar	Specialist
$ORA_{5\%}$	12.1±0.3^{b}	13.3±0.5^{a}	13.4±0.3^{b}	14.8±0.4^{a}
$MAI_{ORA5\%}$	8.3±0.3^{b}	10.3±0.3^{a}	8.3±0.3^{b}	10.4±0.3^{a}
$PRICE_{ORA5\%}$	119.49±4.13^{a}	103.27±3.78^{b}	129.27±4.61^{a}	110.84±4.21^{b}
$ORA_{10\%}$	9.9±0.2^{b}	10.8±0.3^{a}	11.1±0.2^{b}	11.9±0.3^{a}
$MAI_{ORA10\%}$	7.9±0.3^{b}	9.7±0.4^{a}	7.9±0.3^{b}	9.8±0.4^{a}
$PRICE_{ORA10\%}$	150.62±5.19^{a}	131.73±4.92^{b}	168.54±6.04^{a}	146.32±5.68^{b}

Means (±one standard error) with different letters within genetic groups in each row were different at $P<0.05$

although a few scenarios showed significantly lower breakeven prices for low-rent counties (i.e., generalist scenarios with 5 % discount rate). In contrast, the low-productivity supplyshed had significantly lower breakeven prices in low-rent counties (US$78 to US$118 Mg^{-1}) than in high-rent counties (US$111 to US$158 Mg^{-1}) for all scenarios. Thus, the most cost-effective scenarios for growing hybrid poplars were observed in low-rent counties within the low-productivity supplyshed (i.e., Todd and Douglas counties).

Discussion

In general, both land rent and MAI tended to increase with increasing productivity of the supplyshed (see Figs. 3 and 4). Within supplysheds, however, lower land rents were not always associated with lower MAIs. For example, low- and high-rent counties had similar MAIs within the medium-productivity supplyshed, and low-rent counties had higher MAIs compared to the high-rent counties within the low-productivity supplyshed (see Figs. 4 and 5). This may stem from of a decoupling of land rent and MAI for poplars on marginal lands. For instance, if land rents are primarily driven by commodity crops whose productivity declines more dramatically on marginal land than that of poplars, then land rent will not necessarily correlate well with poplar productivity for counties with large amounts of marginal land. Alternatively, it is possible that a difference in resolution between our productivity estimates and land rents contributed to the observed trend. Specifically, our productivity estimates reflect average conditions in each county, whereas the Finbin land rents (while the best information available) may be more heavily skewed in some counties toward farms on particularly productive or unproductive soils, rather than being evenly distributed over the entire county. Due to the confidential nature of the land rent surveys, however, we are unable to test this hypothesis in the present study. Thus, farm-scale studies which specifically evaluate the link (or lack thereof) between land rent and poplar MAI in low-productivity areas are recommended to shed further light on this trend. In any event, if the land rents are accurate, then the high MAIs in the low-rent counties suggest that those are the counties with the greatest opportunity for profitable poplar production in the future.

In terms of breakeven prices, our results indicate that the higher yields attainable in the high-productivity supplyshed were typically canceled out by higher land rents (see Fig. 6). Breakeven prices were generally similar across productivity classes (approximately US$100 to US$160 Mg^{-1}), with the only consistent opportunity for significantly lower breakeven prices (roughly US$80 to US$120 Mg^{-1}) appearing to come from establishing poplars in low-rent counties within the low-productivity supplyshed, where land rents were low relative to poplar MAIs as previously discussed. The breakeven prices observed in the present study are similar to those recently reported for poplars in Belgium [30], in which breakeven prices were approximately 80 Mg^{-1}€(or approximately US $110 Mg^{-1}). Biomass prices as low as US$60 Mg^{-1} at 5.5 % IRR (compared to US$71 to US$136 Mg^{-1} at 5 % interest in the present study) have been suggested for willow in New York [31], although those lower prices appear to be at least partially attributable to considerably lower land rental rates of US$85 ha^{-1} in that state, compared to our counties in Minnesota which ranged from US$128 to US$534 ha^{-1}. Though poplars produce greater yields than willows in the North-Central region, they also require longer rotations than willow and are typically replanted rather than regenerated from coppice due in part to pathogen concerns [32], both of which may also contribute to the somewhat higher breakeven prices for poplars.

Specialist genotypes which are adapted to local conditions are expected to result in higher biomass productivity [33], which in turn would be expected to improve the economic performance of poplars. Our results indicate that specialist genotypes can be expected to produce about 2 Mg ha^{-1} yr^{-1} more biomass at ORA than generalists (see Fig. 5), with an associated reduction of about US$20 Mg^{-1} in the breakeven

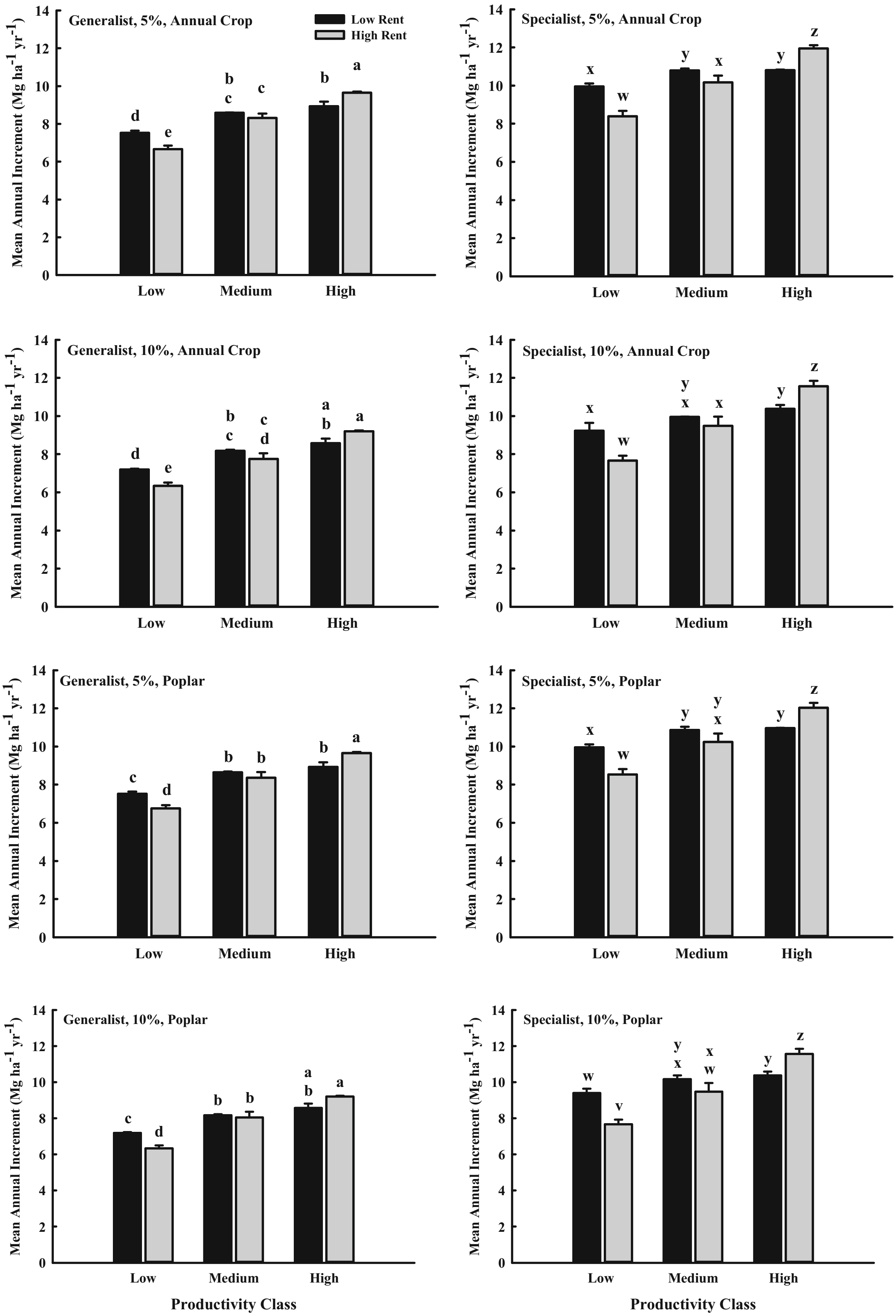

Fig. 5 Mean annual increment (Mg ha^{-1} yr^{-1}) at optimal rotation age for each combination of productivity class and land rent category for generalist and specialist genetic groups at 5 and 10 % discount rates, assuming planting into previous annual crops or poplars. Means (±one standard error) with *different letters above bars* within each graph were different at P<0.05

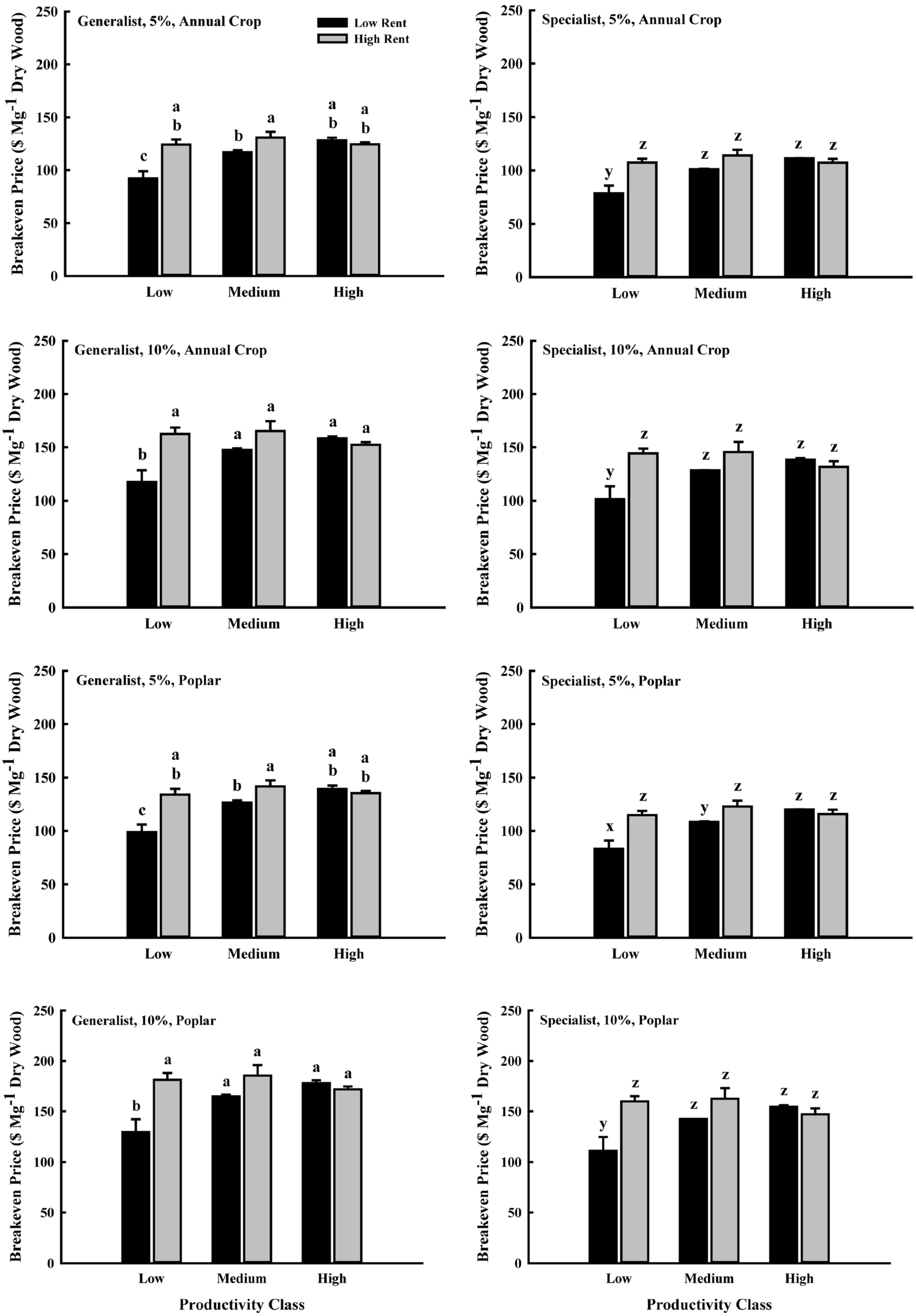

Fig. 6 Breakeven price (US$ Mg^{-1} dry wood) at optimal rotation age for each combination of productivity class and land rent category for generalist and specialist genetic groups at 5 and 10 % discount rates, assuming planting into previous annual crops or poplars. Means (±one standard error) with *different letters above bars* within each graph were different at $P<0.05$

price compared to using generalists (see Fig. 6). Our analysis assumes, however, that specialist and generalist planting stock will be similarly priced. Though we believe this assumption merits further study, we were unable to do so in the present study, as the commercial release of clones in the region to date has been quite limited. Our results also indicate that specialist genotypes may be expected to have higher growth ceilings (in addition to higher growth rates) than generalists, which may result in specialists having slightly higher ORAs (i.e., 0.8 to 1.4 years later) compared to generalists (see Table 11).

All other factors being equal, higher discount rates are expected to result in shorter rotations [34]. Our results support this concept, and demonstrate that for hybrid poplars in Minnesota, an increase in the discount rate from 5 to 10 % can be expected to reduce ORAs by 2 to 3 years (see Table 11). In addition, our results indicate that high-productivity supplysheds can be expected to have shorter ORAs than low-productivity supplysheds by 2 to 3 years (see Table 10). Thus, the high-productivity supplyshed and high discount rate produced the lowest ORAs (9.6 to 10.6 years), while the low-productivity supplyshed and low discount rate produced the highest ORAs (14.0 to 15.5 years). As such, planning harvest operations and the inflow of biomass to a given bioenergy facility should give serious consideration to both the discount rate and the relative productivity of the supplyshed.

Finally, it should be noted that relatively little information is available in the literature regarding best practices and associated costs for replanting into lands previously managed for poplar. The appendix of Ugarte et al. [8] listed tillage practices for poplar and other energy crops into land cover similar to our corn scenario, but did not address replanting into a previous poplar planting. Perlack and Stokes (2011) did not differentiate by previous land cover. As such, the costs reported here for planting into previous poplar cover should be viewed as a first approximation, and are subject to further refinement as additional research becomes available. Furthermore, practices currently being followed by our four experts varied considerably. There were several mentions of practices that had been tried on some sites and not on others, so that it was uncertain what practices and associated costs are really the "typical" ones to include in the budgets. For example, one expert used pre-emergent herbicides that were more expensive than our post-emergent herbicides, but also had access to cheaper planting materials and labor than those described in the current study. Thus, the actual input costs for an individual producer will differ somewhat from those reported here. However, to the extent that such differences in input costs are independent of the factors we evaluated (e.g., land rent class, previous land cover, productivity class), the relative trends should be similar to those observed in the current study (e.g., lowest breakeven costs occurring on low-rent lands previously planted to corn in low-productivity supplysheds).

Conclusions

Our economic analyses illustrated that siting new plantings of purpose-grown poplars should consider the unique soil and climatic conditions of particular landscape locations, which was also corroborated biologically in Minnesota [35] and Iowa [36]. Also, interest rates have been very low in the USA for a number of years, so it is tempting to ignore the role that rates play in many economic decisions. However, these results highlight that interest rates have a large impact on optimal poplar rotation ages and breakeven prices which should be kept in mind if rates rise in the future. It is perhaps not surprising that Todd and Douglas Counties, with the lowest land rental rates in Minnesota, have the lowest poplar breakeven prices. The lack of apparent correlation between land rents and yields within the low-productivity supplyshed is somewhat surprising, but as discussed previously, this may be at least partially due to: (1) the difference in productivity on marginal lands between poplars and commodity crops (the latter of which influence rental rates), and/or (2) the potential difference in resolution between the productivity estimates and the land rent data, which stems from the way the land rent data is collected. Taken together, these results for breakeven prices and land rent effects suggest that additional research with poplars on low-productivity lands in the region is warranted.

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References

1. Zalesny RS Jr, Donner DM, Coyle DR, Headlee WL (2012) An approach for siting poplar energy production systems to increase productivity and associated ecosystem services. For Ecol Manag 284:45–58
2. Headlee WL, Zalesny RS Jr, Donner DM, Hall RB (2013) Using a process-based model (3-PG) to predict and map hybrid poplar biomass productivity in Minnesota and Wisconsin, USA. Bioenerg Res 6:196–210
3. Hachfeld G, Lazarus W, Nordquist D, Loppnow R (2012) Cropland rental rates for Minnesota counties. University of Minnesota Extension, St. Paul
4. Hachfeld G, Lazarus W, Nordquist D (2013) Cropland rental rates for Minnesota Counties. University of Minnesota Extension, St. Paul, MN http://www.cffm.umn.edu/Publications/pubs/FarmMgtTopics/RentalRates.pdf
5. Good D, Irwin S (2013) Is the U.S. corn boom ending? Farmdoc Daily. Department of Agricultural and Consumer Economics, University of Illinois Urbana-Champaign, Urbana, IL http://farmdocdaily.illinois.edu/2013/06/is-us-corn-boom-ending.html

6. Center for Farm Financial Management (2013) FINBIN Farm Financial Database. University of Minnesota. http://www.finbin.umn.edu/. Accessed 7/3/2013
7. USDA Farm Service Agency (2013) Conservation Reserve Program Sign-Up 45 Environmental Benefits Index (EBI). http://www.fsa.usda.gov/Internet/FSA_File/su45ebifactsheet.pdf
8. Ugarte DGDLT, Walsh ME, Shapouri H, Slinsky SP (eds) (2000) The economic impacts of bioenergy crop production on U.S. Agriculture. Agricultural Policy Analysis Center, University of Tennessee and U.S. Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses, Knoxville
9. Perlack RD, Stokes BJ (2011) U.S. Billion-Ton Update: biomass supply for a bioenergy and bioproducts industry, ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, Tennessee
10. van Oosten C (2008) Purpose-grown woody biomass crops: state of knowledge. Saskatchewan Forest Centre
11. van Oosten C (2006) Hybrid poplar crop manual for the Prairie Provinces." Manual. Saskatchewan Forest Centre
12. Isebrands JG (2007) Best management practices poplar manual for Agroforestry applications in Minnesota. Environmental Forestry Consultants, LLC
13. Lazarus W (2008) Energy crop production costs and breakeven prices under Minnesota Conditions, Staff Paper P08-11. Department of Applied Economics, University of Minnesota, St. Paul, MN http://www.apec.umn.edu/faculty/wlazarus/documents/EnergybudStaff_Paper.pdf
14. Lazarus W (2012) Machinery Cost Estimates. Department of Applied Economics, University of Minnesota, St. Paul, MN http://faculty.apec.umn.edu/wlazarus/documents/machdata.pdf
15. Edwards W, Johanns A (2012) Iowa farm custom rate survey. Department of Economics, Iowa State University, Ames
16. SUNY College of Environmental Science and Forestry (2008) EcoWillow v1.1 (Beta) (spreadsheet). http://www.esf.edu/willow/downloads.asp
17. Fruin J, Fortowsky JK (2004) Modal shifts from the Mississippi River & Duluth/Superior to Land Transportation, Staff Paper P04-10. http://ageconsearch.umn.edu/bitstream/14057/1/p04-10.pdf
18. Springer EL (ed) (1979) Should whole-tree chips for fuel be dried before storage? USDA Forest Service, Forest Products Laboratory Research Note FPL-0241
19. de Toro A, Jirjis R, Nilsson D (eds) (1994) Cold air ventilated and sealed storage of wood-chips from willow: laboratory experiments. Rapport - Sveriges lantbruksuniversitet, Institutionen för lantbruksteknik.
20. National Oceanic and Atmospheric Administration (2013) U.S. Department of Commerce NOAA National Climatic Data Center (NCDC) monthly summaries. http://www.ncdc.noaa.gov/oa/ncdc.html. Accessed 20 March 2013 2013
21. National Renewable Energy Lab (2013) U.S. Department of Energy NREL National Solar Radiation Database. http://www.nrel.gov/rredc/solar_data.html. Accessed 20 March 2012 2012
22. Natural Resources Conservation Service (2012) U.S. Department of Agriculture NRCS U.S. General Soil Map (STATSGO2). http://soildatamart.nrcs.usda.gov.
23. Netzer DA, Tolsted DN, Ostry ME, Isebrands JG, Riemenschneider DE, Ward KT (eds) (2002) Growth, yield, and disease resistance of 7- to 12-year-old poplar clones in the North Central United States, General Technical Report GTR-NC-229. U.S. Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN
24. Headlee WL, Zalesny RS Jr, Hall RB, Bauer EO, Bender B, Birr B, Miller RO, Randall JA, Wiese AH (2013) Specific gravity of hybrid poplars in the north-central region, USA: within-tree variability and site × genotype effects. For 4:251–269
25. Strong T, Hansen E (1993) Hybrid poplar spacing/productivity relations in short rotation intensive culture plantations. Biomass Bioenergy 4(4):255–261
26. Debell DS, Clendenenan GW, Zasadat JC (1993) Growing populus biomass: comparison of woodgrass versus wider-spaced short-rotation systems. Biomass Bioenergy 4(5):305–313
27. Langholtz M, Carter DR, Rockwood DL, Alavalapati JRR (2009) The influence of CO2 mitigation incentives on profitability of eucalyptus production on clay settling areas in Florida. Biomass Bioenerg 33:785–792
28. IFAS Extension (2006) Florida Forest Stewardship. University of Florida. http://www.sfrc.ufl.edu/extension/florida_forestry_information/planning_and_assistance/financial_analysis.html. Accessed 7/2/13 2013
29. Measells M, Henderson J (2010) Financial considerations. In: managing the family forest in Mississippi, P2470. Department of Forestry, Mississippi State University,
30. Kasmioui OE, Ceulemans R (2013) Financial analysis of the cultivation of short rotation woody crops for bioenergy in Belgium: barriers and opportunities. Bioenerg Res 6:336–350
31. Buchholz T, Volk TA (2011) Improving the profitability of willow crops—identifying opportunities with a crop budget model. Bioenergy Res 4:85–95
32. Dickmann DI, Stuart KW (1983) The culture of poplars in eastern North America. Michigan State University Publications, East Lansing
33. Zalesny RS Jr, Hall RB, Zalesny JA, McMahon BG, Berguson WE, Stanosz GR (2009) Biomass and genotype × environment interactions of Populus energy crops in the midwestern United States. Bioenergy Res 2:106–122
34. Klemperer WD (1996) Economics of forestland use and even-aged rotations. In: Forest Resource Economics and Finance. McGraw-Hill, New York, pp 202–238
35. Thelemann R, Johnson G, Sheaffer C, Banerjee S, Cai H, Wyse D (2010) The effect of landscape position on biomass crop yield. Agronomy J 102:513–522
36. Headlee WL, Hall RB, Zalesny RSJ (2013) Establishment of alleycropped hybrid aspen "Crandon" in central Iowa, USA: effects of topographic position and fertilizer rate on aboveground biomass production and allocation. Sustainability 5:2874–2886
37. Sands PJ (2004) Adaptation of 3-PG to novel species: guidelines for data collection and parameter assignment. Technical Report 141. Hobart, Australia