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U.S. Woody Biomass Yields at the State and Regional Level

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1.0 Short Rotation Woody Crops

The following tables include yield data for four of the most promising short rotation woody crops in the United States (willow, hybrid poplar, eucalyptus, and loblolly pine) within those regions of the country where each crop is expected to be grown. Experimental yields are reported, as well as the future potential yield in 2050 under each of two crop improvement scenarios, one in which improvements result in an average annual yield (AAY) of 2% and one in which AAY improvement is 4%. These crop improvement scenarios summarize possible yield improvements from improved culturing practices as well as from crop breeding and genetic improvements. For each crop, there are two tables – one summarizing information from trials in which neither fertilization nor irrigation were used, and one in which these more intensive practices were used. Although these four crops are currently receiving the most attention, they are certainly not the only promising woody crop species being studied (Merkle and Cunningham 2011). Citations listed below were largely summarized in two documents, Wright (2010) and Volk et al. (In Press).

Table 1: Current and predicted future yields of willow crops (*Salix* spp.) in the United States. Yield data in ODT ac^{-1} yr^{-1}.

Region	Yield	Yield in 2050 (est. 2% AAY)	Yield in 2050 (est. 4% AAY)	References
Northeast (NY, QC)	3.7-7.5	5.2-10.5	9.6-19.5	a,b

[a] Adegbidi, H.G., R.D. Briggs, T.A. Volk, E.H. White, and L.P. Abrahamson. 2003. Effect of organic amendments and slow-release nitrogen fertilizer on willow biomass production and soil chemical characteristics. Biomass and Bioenergy 22: 449-454.

[b] Labreque, M. and T.I. Teodedorescu. 2005. Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern Quebec (Canada). Biomass and Bioenergy 29:1-5.

Table 2: Current and predicted future yields of intensively managed (fertilized and/or irrigated) willow crops (*Salix* spp.) in the United States. Yield data in ODT ac^{-1} yr^{-1}.

Region	Yield	Yield in 2050 (est. 2% AAY)	Yield in 2050 (est. 4% AAY)	References
Northeast (NY)	4.0-12.3	5.6-17.2	10.4-32.0	a,b,c,d

[a] Adegbidi, H.G., T.A. Volk, E.H. White, L.P. Abrahamson, R.D. Briggs, and D.H. Bickelhaupt. 2001. Biomass and nutrient removal by willow clones in experimental bioenergy plantations in New York State. Biomass and Bioenergy 20:399-411.

[b] Adegbidi, H.G., R.D. Briggs, T.A. Volk, E.H. White, and L.P. Abrahamson. 2003. Effect of organic amendments and slow-release nitrogen fertilizer on willow biomass production and soil chemical characteristics. Biomass and Bioenergy 22: 449-454.

[c] Kopp, R.F., L.P. Abrahamson, E.H. White, K.F. Burns, and C.A. Nowak. 1997. Cutting cycle and spacing effects on biomass production by a willow clone in New York. Biomass and Bioenergy 12:313-319.

[d] Kopp, R.F., L.P. Abrahamson, E.H. White, T.A. Volk, C.A. Nowak, and R.C. Fillhart. 2001. Willow biomass production during ten successive annual harvests. Biomass and Bioenergy 20: 1-7.

Table 3: Current and predicted future yields of hybrid poplar crops (*Populus* spp.) in the United States. Yield data in ODT ac^{-1} yr^{-1}.

Region	Yield	Yield in 2050 (est. 2% AAY)	Yield in 2050 (est. 4% AAY)	References
Northeast (QC)	3.7-8.1	5.2-11.3	9.6-21.1	a,b,c
Midwest/central (IA,KA, SD, MN, ND, WI)	1.8-5.1	2.5-7.1	4.7-13.3	d,e,f
Pacific northwest (WA)	2.5-12.3	3.5-17.2	6.5-32.0	g,h

[a] Bowersox, T.W. and W.W. Ward. 1976. Growth and yield of close-spaced, young hybrid poplars. Forest Science 22: 449-454.

[b] Labreque, M. and T.I. Teodedorescu. 2005. Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern Quebec (Canada). Biomass and Bioenergy 29:1-5.

[c] Strauss, C.H., S.C. Grado, P.R. Blackenhorn, and T.W. Bowersox. 1990. Cost parameters affecting multiple rotation SRIC biomass systems. Applied Biochemistry and Biotechnology 24-25:721-733.

[d] Coyle, D.R., E.R. Hart, J.D. McMillin, L.C. Rule, and R.B. Hall. 2008. Effects of repeated cottonwood leaf beetle defoliation on *Populus* growth and economic value over an 8-yr harvest rotation. Biomass and Bioenergy 225: 3365-3373.

[e] Geyer, W.A. 1981. Growth, yield, and woody biomass characteristics of seven short-rotation hardwoods. Wood Science 13: 209-215.

[f] Netzer, D.A., D.N. Tolsted, M.E. Ostry, J.G. Isebrands, D.E. Riemenschneider, and K.T. Ward. 2002. Growth, Yield, and Disease Resistance of 7-12 Year Old Poplar Clones in the North Central United States. General Technical Report GTR-NC-229. USDA Forest Service. North Central Experiment Station, St. Paul, MN. 33 p.

[g] Heilman, P.E., and X. Fu-Gaung. 1993. Influence of nitrogen on growth and productivity of short-rotation *Populus trichocarpa x Populus deltoides* hybrids. Canadian Journal of Forest Research 23:1863-1869.

[h] Heilman, P.E. and D.V. Peabody, Jr. 1981. Effect of harvest cycle and spacing on productivity of black cottonwood in intensive culture. Canadian Journal of Forest Research 11: 118-123.

Table 4: Current and predicted future yields of intensively managed (fertilized and/or irrigated) hybrid poplar crops (*Populus* spp.) in the United States. Yield data in ODT ac^{-1} yr^{-1}.

Region	Yield	Yield in 2050 (est. 2% AAY)	Yield in 2050 (est. 4% AAY)	References
Northeast (NY, PA)	3.7-5.8	5.2-8.1	9.6-15.1	a,b
Midwest/central (MO, MN, SD, ND, WI, IA)	3.2-9.3	4.5-13.0	8.3-24.2	c,d,e,f,g,h,i
Pacific northwest (WA)	3.2-19.4	4.5-27.2	8.3-50.4	j,k,l,m,n,o,p,q

[a] Kopp, R.F., L.P. Abrahamson, E.H. White, K.F. Burns, and C.A. Nowak. 1997. Cutting cycle and spacing effects on biomass production by a willow clone in New York. Biomass and Bioenergy 12:313-319.

[b] Strauss, C.H., S.C. Grado, P.R. Blackenhorn, and T.W. Bowersox. 1990. Cost parameters affecting multiple rotation SRIC biomass systems. Applied Biochemistry and Biotechnology 24-25:721-733.

[c] Dowell, R.C., D. Gibbins, J.L. Rhoads, and S.G. Pallardy. 2009. Biomass production physiology and soil carbon dynamics in short-rotation-grown *Populus deltoides* and *P. deltoids x P. nigra* hybrids. Forest Ecology and Management 257: 134-142.

[d] Netzer, D.A., D.N. Tolsted, M.E. Ostry, J.G. Isebrands, D.E. Riemenschneider, and K.T. Ward. 2002. Growth, Yield, and Disease Resistance of 7-12 Year Old Poplar Clones in the North Central United States. General Technical Report GTR-NC-229. USDA Forest Service. North Central Experiment Station, St. Paul, MN. 33 p.

[e] Riemenschneider, D.E., W.E. Berguson, D.I. Dickmann, R.B. Hall, J.G. Isebrands, C.A. Mohn, G.R. Stanosz and G.A. Tuskan. 2001. Poplar breeding and testing strategies in the north-central states U.S.: demonstration of potential yield and consideration of future research needs. The Forestry Chronicle 77: 245-253.

[f] Strong, T.F. 1989. Rotation Length and Repeated Harvesting Influence Populus Coppice Production. USDA Forest Service. North Central Forest Experiment Station, Duluth, MN. 4 p.

[g] Strong, T.F. and E.A. Hansen. 1993. Hybrid poplar spacing/productivity relations in short rotation intensive culture plantations. Biomass and Bioenergy 4: 255-261.

[h] Zalesny, R.S., R.B. Hall, J.A. Zalesny, B.G. McMahon, W.E. Berguson, and G.R. Stanoz. 2009. Biomass and genotype x environment interactions of *Populus* energy crops in the Midwestern United States. Bioenergy Research 2:106-122.

[I] Zavitkovski, J., J.G. Isebrands, and D.H. Dawson. 1976. Productivity and utilization potential of short-rotation *Populus* in the Lake States. p. 392-401. In: Thieldges, B.A., and S.B. Land, Jr. (eds.). Proceedings of the Symposium on Eastern Cottonwood and Related Species. Louisiana State University, Baton Rouge, LA.

[j] DeBell, D.S., G.W. Clendenen, C.A. Harrington, and J.C. Zasada. 1996. Tree growth and stand development in short-rotation *Populus* plantings: 7-year results for two clones at three spacings. Biomass and Bioenergy 11:253-269.

[k] DeBell, D.S., G.W. Clendenen, and J.C. Zasada. 1993. Growing *Populus* biomass: comparison of woodgrass versus wider-spaced short-rotation systems. Biomass and Bioenergy 4:305-313.

[l] Heilman, P.E. and D.V. Peabody, Jr. 1981. Effect of harvest cycle and spacing on productivity of black cottonwood in intensive culture. Canadian Journal of Forest Research 11: 118-123.

[m] Heilman, P.E., D.V. Peabody, Jr., D.S. DeBell, and R.F. Strand. 1972. A test of close-spaced, short-rotation culture of black cottonwood. Canadian Journal of Forest Research 2:456-459.

[n] Heilman, P.E., G. Ekuan, and D.B. Fogle. 1994. Above- and below-ground biomass and fine roots of four-year-old hybrids of *Populus trichocarpa x P. deltoides* and parental species in short rotation culture. Canadian Journal of Forest Research 24:1186-1192.

[o] Heilman, P.E. and R.F. Stettler. 1985. Genetic variation and productivity of *Populus trichocarpa* and its hybrids. II, biomass production in a 4-year plantation. Canadian Journal of Forest Research 15:384-388.

[p] Heilman, P.E. and X. Fu-Gaung. 1993. Influence of nitrogen on growth and productivity of short-rotation *Populus trichocarpa x Populus deltoides* hybrids. Canadian Journal of Forest Research 23:1863-1869.

[q] Weber, J.C., R.F. Stettler, and P.E. Heilman. 1985. Genetic variation and productivity of *Populus trichocarpa* and its hybrids. I, morphology and phenology of 50 native clones. Canadian Journal of Forest Research 15:376-383.

Table 5: Current and predicted future yields of eucalyptus crops (*Eucalyptus* spp.) in the United States. Yield data in ODT ac^{-1} yr^{-1}.

Region	Yield	Yield in 2050 (est. 2% AAY)	Yield in 2050 (est. 4% AAY)	References
Southeast (FL)	2.3-11.4	3.2-16.0	6.0-29.6	a

[a] Langholtz, M., D.R. Carter, D.L. Rockwood, and J.R.R. Alavalapati. 2007. The economic feasibility of reclaiming phosphate mined lands with short-rotation woody crops in Florida. Journal of Forest Economics 12: 237-249.

Table 6: Current and predicted future yields of intensively managed (fertilized and/or irrigated) eucalyptus crops (*Eucalyptus* spp.) in the United States. Yield data in ODT ac^{-1} yr^{-1}.

Region	Yield	Yield in 2050 (est. 2% AAY)	Yield in 2050 (est. 4% AAY)	References
Southeast (FL)	6.4-12.4	9.0-17.4	16.6-32.2	a,b

[a] Langholtz, M., D.R. Carter, D.L. Rockwood, and J.R.R. Alavalapati. 2007. The economic feasibility of reclaiming phosphate mined lands with short-rotation woody crops in Florida. Journal of Forest Economics 12: 237-249.

[b] Rockwood, D.L., C.W. Comer, D.R. Dippon, and J.B. Huffman. 1985. Woody Biomass Production Options for Florida. Bulletin. Agricultural Experiment Station Institute of Food and Agriculture Sciences (IFAS), University of Florida, Gainsville, FL. 865 p.

Table 7: Current and predicted future yields of Loblolly pine crops (*Pinus taeda*) in the United States. Yield data in ODT ac^{-1} yr^{-1}.

Region	Yield	Yield in 2050 (est. 2% AAY)	Yield in 2050 (est. 4% AAY)	References
Southeast (GA, FL)	1.5-3.8	2.1-5.3	3.9-9.9	a,b,c,d

[a] Borders, B.E., R.E. Will, D. Markewitz, A. Clark, R. Hendrick, R.O. Teskey, and Y. Zhang. 2004. Effect of complete competition control and annual fertilization on stem growth and canopy relations for a chronosequence of loblolly pine plantations in the lower coastal plain of Georgia. Forest Ecology and Management 192:21-37.

[b] Cobb, W.R., R.E. Will, R.F. Daniels, and M.A. Jacobson. 2008. Aboveground biomass and nitrogen in four short-rotation woody crop species growing with different water and nutrient availabilities. Forest Ecology and Management 255:4032-4039.

[c] Jokela, E.J. and T.A. Martin. 2000. Effects of ontogeny and soil nutrient supply on production, allocation, and leaf area efficiency in loblolly and slash pine stands. Canadian Journal of Forestry Research 30: 1511-1524.

[d] Williams, T.M. and C.A. Gresham. 2006. Biomass accumulation in rapidly growing loblolly pine and sweetgum. Biomass and Bioenergy 30:370-377.

Table 8: Current and predicted future yields of intensively managed (fertilized and/or irrigated) Loblolly pine crops (*Pinus taeda*) in the United States. Yield data in ODT ac^{-1} yr^{-1}.

Region	Yield	Yield in 2050 (est. 2% AAY)	Yield in 2050 (est. 4% AAY)	References
Southeast (GA, FL)	3.6-8.5	5.0-11.9	9.4-22.1	a,b,c,d,e

[a] Borders, B.E., R.E. Will, D. Markewitz, A. Clark, R. Hendrick, R.O. Teskey, and Y. Zhang. 2004. Effect of complete competition control and annual fertilization on stem growth and canopy relations for a chronosequence of loblolly pine plantations in the lower coastal plain of Georgia. Forest Ecology and Management 192:21-37.

[b] Cobb, W.R., R.E. Will, R.F. Daniels, and M.A. Jacobson. 2008. Aboveground biomass and nitrogen in four short-rotation woody crop species growing with different water and nutrient availabilities. Forest Ecology and Management 255:4032-4039.

[c] Ruth, B.E., E.J. Jokela, T.A. Martin, D.A. Huber, and T.L. White. 2007. Genotype x environment interactions in selected loblolly and slash pine plantations in the Southeastern United States. Forest Ecology and Management 238:175-188.

[d] Samuelson, L.J., J. Butnor, C. Maier, T.A. Stokes, K. Johnsen, and M. Kane. 2008. Growth and physiology of loblolly pine in response to long-term resource management: defining growth potential in the southern United States. Canadian Journal of Forest Research 38:721-732.

[e] Williams, T.M. and C.A. Gresham. 2006. Biomass accumulation in rapidly growing loblolly pine and sweetgum. Biomass and Bioenergy 30:370-377.

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Volk, T.A., M.A. Buford, B. Berguson, J.Caputo, J.Eaton, J.H. Perdue, T.G. Rials, D. Riemenschneider, B. Stanton, and J.A. Stanturf. (in press). Woody Feedstocks – Management and Regional Differences. In: Sustainable Alternative Feedstock Opportunities, Challenges and Roadmap for 6 U.S. Regions. Soil and Water Conservation Society.

Biomass from Forest Management

Forest management activities in the United States have the potential to yield significant quantities of biomass for use in energy production. The bulk of forest biomass is expected to come from two sources, logging residues and removals of poor growing stock, low-value trees, and trees from overstocked forest stands. Logging residues consist of tops, limbs, and other non-merchantable material generated during harvesting activities. Although it is important to leave some of this material on site to provide wildlife habitat, and to maintain soil productivity and ecosystem function, it is estimated that up to 70% of material can be safely removed (Minnesota Forest Resources Council 2007, Evans and Perschel 2009). Potential for additional removals can be estimated by subtracting the annual rate of removals from the annual net growth (growth – mortality) within a region. The remainder is an estimate of the amount of additional wood volume being added to the forest inventory each year, a portion of which can be removed for use in energy applications. Table 1 below summarizes the annual quantity of logging residues estimated to be available on a sustainable basis in each state, as well as current annual removals, current net-growth, and potential net growth under optimal silvicultural practices based on site productivity. Data were derived from two sources; estimates of annual residues were calculated by the National Renewable Energy Laboratory (NREL, Milbrandt 2005) and estimates of net-growth and removals were tabulated by Shifley (2006). Data were originally collected by the U.S. Forest Service. Millebrandt (2005) includes residues from both land clearing and forestry activities, whereas data in Shifley (2006) pertain to forestry alone. Table 2 summarizes the annual availability of woody biomass in each state under each of four scenarios. Each scenario includes the total quantity of logging residues, plus either 70% or 100% of either the current or potential net annual growth (minus current removals). The scenarios in which only 70% of net annual growth is utilized for biomass would be possible even in the event that timber removals increase from current rates. Should removals decrease in the future (a trend consistent with the recent past), more biomass would be available under all four scenarios.

Table 1: Current net forest growth, potential net forest growth, current logging removals, and annual availability of logging residues in each of the 50 U.S. states. Volume to mass conversions done using the ratio of 50 cubic feet of wood per ODT (approximately 1.4 cubic meters per tonne). Data in thousand ODT yr^{-1}

State	Net growth	Potential net growth	Annual removals	Annual availability of logging residues
AK	4140	10980	2840	738
AL	29200	43120	25980	2555
AR	17920	31240	15920	2874
AZ	2480	3100	280	59
CA	26500	33780	12680	1303
CO	5820	10580	420	70
CT	1100	1820	240	78
DE	320	440	160	51
FL	13700	18840	11200	1778
GA	30380	36420	28960	3556
HI	20	1920	0	0
IA	820	2880	500	359
ID	12700	27300	5060	873
IL	3440	7000	1380	664

IN	4480	8220	1940	863
KS	520	1880	140	134
KY	7680	16140	5520	2055
LA	16680	30260	19180	3384
MA	1940	3400	320	89
MD	2140	3180	820	263
ME	8040	18680	8840	2890
MI	15120	25800	6320	1275
MN	7400	18220	6320	2242
MO	4780	14440	3360	1840
MS	22100	40900	23000	3825
MT	11660	21760	3360	704
NC	23200	29040	19160	2995
ND	140	400	20	27
NE	280	1080	200	72
NH	3400	4780	2800	986
NJ	1100	1860	220	29
NM	2800	3900	380	71
NV	120	420	20	5
NY	11800	16980	2820	1111
OH	5860	7820	2020	796
OK	4860	7480	2660	655
OR	34560	48620	17260	1041
PA	12600	16980	4320	1679
RI	160	360	40	8
SC	18900	18520	13660	1733
SD	800	1240	420	125
TN	14760	23840	7680	1319
TX	14100	23960	15400	2060
UT	1540	4460	160	30
VA	16960	22400	13100	2403
VT	3800	4700	1540	496
WA	28520	38100	17340	1034
WI	9780	22940	6940	2011
WV	10200	16420	3340	1347
WY	2380	4920	280	58

Table 2: Annual availability of woody biomass from forests in each of the 50 U.S. states under four growth and removal scenarios. Volume to mass conversions done using the ratio of 50 cubic feet of wood per ODT (approximately 1.4 cubic meters per tonne). Data in thousand ODT yr^{-1}.

State	Scenario A[1]	Scenario B[2]	Scenario C[3]	Scenario D[4]
AK	1648	2038	6436	8878
AL	4809	5775	14553	19695
AR	4274	4874	13598	18194
AZ	1599	2259	2033	2879
CA	10977	15123	16073	22403
CO	3850	5470	7182	10230
CT	680	938	1184	1658

DE	163	211	247	331
FL	3528	4278	7126	9418
GA	4550	4976	8778	11016
HI	14	20	1344	1920
IA	583	679	2025	2739
ID	6221	8513	16441	23113
IL	2106	2724	4598	6284
IN	2641	3403	5259	7143
KS	400	514	1352	1874
KY	3567	4215	9489	12675
LA	1634	884	11140	14464
MA	1223	1709	2245	3169
MD	1187	1583	1915	2623
ME	2330	2090	9778	12730
MI	7435	10075	14911	20755
MN	2998	3322	10572	14142
MO	2834	3260	9596	12920
MS	3195	2925	16355	21725
MT	6514	9004	13584	19104
NC	5823	7035	9911	12875
ND	111	147	293	407
NE	128	152	688	952
NH	1406	1586	2372	2966
NJ	645	909	1177	1669
NM	1765	2491	2535	3591
NV	75	105	285	405
NY	7397	10091	11023	15271
OH	3484	4636	4856	6596
OK	2195	2855	4029	5475
OR	13151	18341	22993	32401
PA	7475	9959	10541	14339
RI	92	128	232	328
SC	5401	6973	5135	6593
SD	391	505	699	945
TN	6275	8399	12631	17479
TX	1150	760	8052	10620
UT	996	1410	3040	4330
VA	5105	6263	8913	11703
VT	2078	2756	2708	3656
WA	8860	12214	15566	21794
WI	3999	4851	13211	18011
WV	6149	8207	10503	14427
WY	1528	2158	3306	4698

[1] logging residues + 70%*(current net growth – removals)

[2] logging residues + 100%*(current net growth – removals)
[3] logging residues + 70%*(potential net growth – removals)
[4] logging residues + 100%*(potential net growth – removals)

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