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Ecosystem Services of Woody Crop Production Systems

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Abstract Short-rotation woody crops are an integral component of regional and national energy portfolios, as well as providing essential ecosystem services such as biomass supplies, carbon sinks, clean water, and healthy soils. We review recent USDA Forest Service Research and Development efforts from the USDA Biomass Research Centers on the provisioning of these ecosystem services from woody crop production systems. For biomass, we highlight productivity and yield potential, pest susceptibility, and bioenergy siting applications. We describe carbon storage in aboveground woody biomass and studies assessing the provision of clean and plentiful water. Soil protection and wildlife habitat are also mentioned, in the context of converting lands from traditional row-crop agriculture to woody production systems.

Keywords Biomass · Carbon · *Eucalyptus* · *Pinus* · *Populus* · Provisioning services · Regulating services · *Salix* · Soils · Water

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Abbreviations

$\delta^{13}C$	Leaf carbon isotope composition
3-PG	Physiological Principles Predicting Growth model
AHA	Auburn Harvest Analyzer
BioSAT	Biomass Site Assessment Tools
DBH	Diameter at breast height
FIA	USDA Forest Service Forest Inventory and Analysis
FRCS	USDA Forest Service Fuel Reduction Simulator
GIS	Geographic information system
LAI	Leaf area index
MAV	Mississippi Alluvial Valley
MSW	Municipal solid waste
OPEC	Organization of the Petroleum Exporting Countries
SRIC	Short-rotation intensive culture

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SRWC	Short-rotation woody crops
USDA ARS	USDA Agricultural Research Service
USDA FS	USDA Forest Service
USDA FS R&D	USDA Forest Service Research and Development
USDA NASS	USDA National Agriculture Statistics Service
WUE	Water use efficiency
ZCTA	ZIP Code Tabulation Area

Introduction

Prior to the Industrial Revolution, most societies depended on trees for energy as well as other uses (e.g., building materials, fodder, and medicinals). Wood was the primary energy source in the USA for both residential (fuelwood) and industrial (charcoal) purposes until the mid-nineteenth century [1]. As late as 1900, wood provided 21 % of energy consumption, but declined to 5 % by 1950 [2]. The Organization of the Petroleum Exporting Countries (OPEC) Oil Embargo of 1973–1974 caused a resurgence of interest in bioenergy from wood. A Society of American Foresters Task Force Report [3] estimated that dedicating 10 % of the arable private land in the USA to bioenergy plantations would add 4.5 quads (i.e., quadrillion BTUs) of energy to US production (estimated at 75 quads in 1976), with the potential to increase to 8.3 quads if new technology was used [4]. Since that time, the annual US primary energy consumption has increased to 98.5 quads in 2014, with 4.8 quads (i.e., ~5 % of the total energy consumption) coming from renewable biomass [5]. According to the baseline scenario of the US Billion-Ton Update [6], at US$60 per dry ton, energy crops [which include short-rotation woody crops (SRWC) as well as perennial grasses and annual energy crops] will have the potential to contribute 400 million dry tons of biomass (i.e., ~37 % of total) in 2030. This potential increases to a range of 540–799 million dry tons of biomass (i.e., ~39–49 % of total) under the high-yield scenario, which assumes a 2–4 % annual increase in yield.

One advantage of woody biomass for bioenergy is that it can be produced on land marginal or unsuitable for commercial agriculture; thus, it does not compete for land with food crops. By one estimate, there are more than 2.0 million ha of marginal land in the northeastern USA alone, thought to be suitable mostly for willow (*Salix* spp.) [7]. In the Southeast, econometric models of the potential of genetically modified freeze-tolerant rose gum (*Eucalyptus grandis* Hill ex Maiden) × Timor mountain gum (*Eucalyptus urophylla* S.T. Blake) predicted an expansion of up to 1.1 million ha of *Eucalyptus* plantations, replacing pine plantations and naturally regenerated pine stands [8]. An assessment of lands suitable for purpose-grown, short-rotation hybrid poplars (*Populus* species and their hybrids, excluding the aspens) showed that 0.4 million ha were potentially available in Wisconsin and Minnesota, representing nearly one third (i.e., 31 %) of the land base across these states [9].

USDA Forest Service Biomass Research

The use of fast-growing forest tree species to produce biomass for fuel, fodder, and building materials has a long history. For example, Dickmann [10] traced the development of SRWC from coppice systems in antiquity to the beginnings of structured genetic improvement with poplars in the early twentieth century. Research programs on SRWC began in the 1960s; 50 years ago, the concept of silage sycamore (*Platanus* sp.) was conceived in Georgia [11, 12]. The basic premise was to grow woody crops in a fashion similar to agronomic crops, with close spacing (1000–35,000 stems ha^{-1}) and short rotation cycles (1, 2, or 3 years). A series of hardwood plantations was established, beginning in 1966 on a variety of sites. The objectives were to screen species for differences in productivity and to evaluate different spacings and rotation lengths [13]. Although the original systems were impractical for most hardwood species [12], an even more densely planted system termed woodgrass was proposed in the late 1970s for hybrid poplar [14] and shrub willow [15], the latter of which is still used today. The concept of short-rotation intensive culture (SRIC) spread to other regions, spurred by the OPEC Oil Embargo of 1973–1974. Many species, both hardwoods and softwoods, have been investigated for bioenergy, fiber, timber production, or some combination (Table 1). Two growth characteristics, however, have dominated species choices and favored hardwoods: rapid initial stem growth and coppicing ability. However, certain species' demand for specific site requirements has worked against many hardwoods.

Three locations were instrumental for advancing USDA Forest Service (USDA FS) research into biomass and bioenergy: Stoneville, MS (33.42°N, 90.90°W); Rhinelander, WI (45.64°N, 89.47°W); and Lehigh Acres, FL (26.67°N, 81.81°W). Researchers at these three locations and others cooperated with university and industry colleagues on breeding, testing, growing, harvesting, and processing (Fig. 1 and ESM Online Resource 1). While others have been tested, *Populus* has been the most popular taxon for research on SRWC [21] (Table 2). *Populus* spp. have been widely studied and planted operationally because of their rapid juvenile growth, ease of hybridization, and vegetative propagation [68, 69]. Researchers at the Stoneville and Rhinelander locations have been intimately involved in developing material and systems for SRWC. Research on eucalypts for pulpwood, begun in 1959 by the Florida Forests Foundation, was the origin of the research program begun in 1968 by the USDA FS and the Florida Division of Forestry at Lehigh Acres [70].

Table 1 Species considered promising for short-rotation woody crop production systems in the USA (adapted from [16, 17, 18, 19])

Species	Common name	Region							
		NW	W/SW	GP	LS	MW	S/SE	NE	SB/T
Acer saccharinum L.	Silver maple			X				X	
Ailanthus altissima (Mill.) Swingle	Tree of heaven				X				
Falcataria moluccana (Miq.) Barneby & Grimes (formerly *Albizia falcataria*)	Peacocksplume								X
Alnus glutinosa (L.) Gaertn.	European alder					X			
Alnus rubra Bong.	Red alder	X							
Atriplex canescens (Pursh) Nutt.	Four-wing saltbush		X						
Elaeagnus umbellata Thunb.	Autumn olive					X			
Eucalyptus amplifolia Naudin	Cabbage gum						X		X
Eucalyptus dorrigoensis (Blakely) L.A.S. Johnson & K.D. Hill (syn. *Eucalyptus benthamii*)	Camden white gum						X		
Eucalyptus camaldulensis Dehnh.	River red gum								X
Corymbia citriodora (Hook.) K.D. Hill & L.A.S. Johnson (syn. *Eucalyptus citriodora*)	Lemon-scented gum								X
Eucalyptus dalrympleana Maiden	Mountain white gum								X
Eucalyptus globulus Labill.	Tasmanian blue gum								X
Eucalyptus grandis W. Hill ex Maid.	Grand eucalyptus								X
Eucalyptus macarthurii H. Deane & Maiden	Camden woollybutt								X
Eucalyptus robusta Sm.	Swamp mahogany						X		
Eucalyptus saligna Sm.	Sydney blue gum								X
Eucalyptus sideroxylon A. Cunn. ex Woolls	Red ironbark								X
Eucalyptus viminalis Labill.	Manna gum								X
Eucalyptus grandis × *Eucalyptus urophylla*[a]	Hybrid eucalypt						X		X
Liquidambar styraciflua L.	Sweetgum						X		
Pinus banksiana L.	Jack pine				X				
Pinus clausa (Chapm. ex Engelm.) Vasey ex Sarg.	Sand pine						X		
Pinus elliottii Engelm.	Slash pine						X		
Pinus nigra × *Pinus densiflora*	Hybrid pine				X				
Pinus sylvestris L.	Scots pine				X				
Pinus taeda L.	Loblolly pine						X		
Platanus occidentalis L.	American sycamore						X		
Populus deltoides Bartr. ex Marsh.	Eastern cottonwood					X	X		
Populus hybrids	Hybrid cottonwood	X				X			
Populus hybrids	Hybrid aspen				X				
Populus hybrids	Hybrid poplar	X			X			X	
Populus tremuloides Michx.	Quaking aspen				X				
Populus balsamifera L. subsp. *trichocarpa* (Torr. & A. Gray ex Hook.) Brayshaw	Black cottonwood	X							
Prosopis alba Griseb.	Mesquite		X						
Robinia pseudoacacia L.	Black locust			X		X		X	
Salix spp.	Willow spp.				X				
Triadica sebifera (L.) Small (syn. *Sapium sebiferum*)	Chinese tallow						X		
Tamarix L.	Tamarisk		X						
Ulmus pumila L.	Siberian elm			X					

NW Northwest, *W/SW* West/Southwest, *GP* Great Plains, *LS* Lake States, *MW* Midwest, *S/SE* South/Southeast, *NE* Northeast, *SB/T* Subtropics/Tropics

[a] Genetically engineered for cold tolerance or lignin biosynthesis [20]

The SRWC focus at the USDA FS Southern Hardwoods Laboratory in Stoneville, MS, has been the native eastern cottonwood (*Populus deltoides* Bartr. ex Marsh). An early evaluation of hybrid poplar was conducted in cooperation with the Oxford Paper Company [71], but generally, hybrids have not done as well in the Deep South as the native eastern

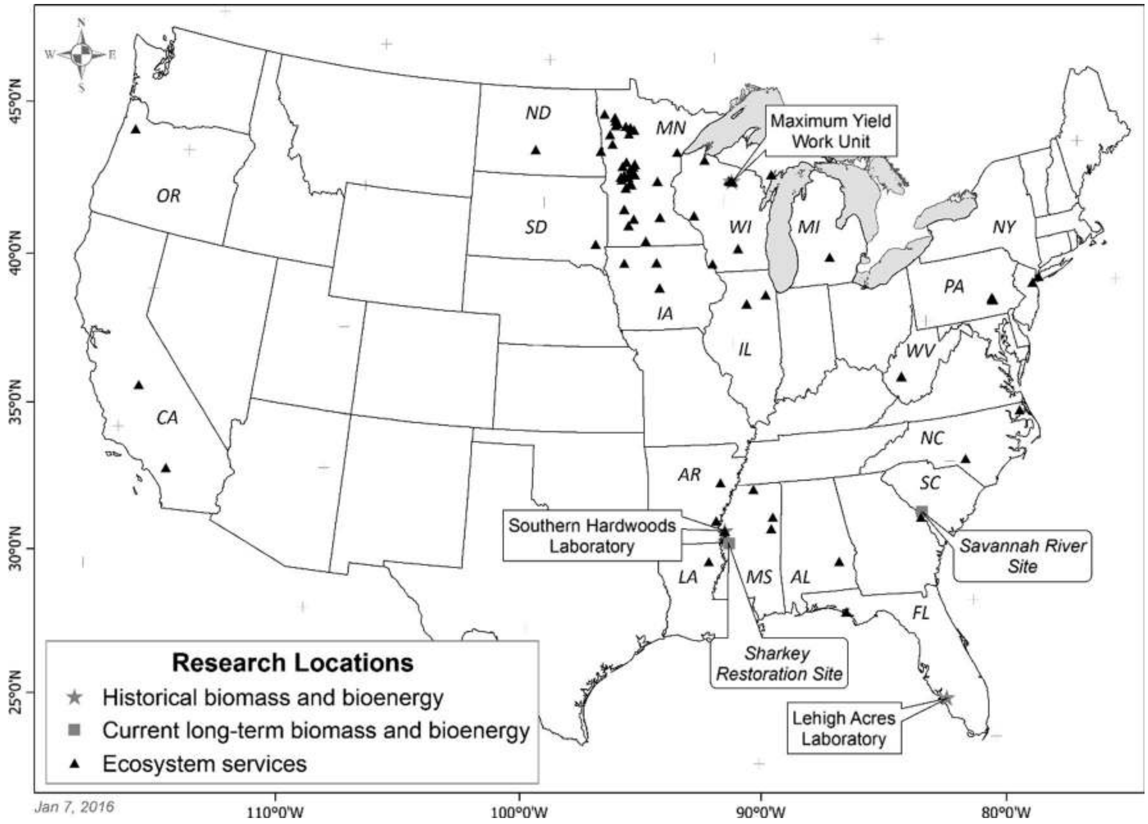

Fig. 1 Map of research sites for ecosystem services of woody crop production systems in the USA. The three sites indicated in *rectangular boxes* (*with square edges*) are historic locations for USDA Forest Service woody crop biomass research and development. The two sites indicated in the *remaining two boxes* (*with round edges*) are current, long-term biomass and bioenergy research locations

cottonwood, in part due to greater susceptibility to *Septoria* stem canker [68]. Early work on poplar breeding in the South was done at Stoneville during the 1950s [72]. Phenotypically superior trees were selected, clonally propagated, tested, and released [73]. The clonal cottonwood selections released by researchers at Stoneville, taken from native populations growing along the Mississippi River and rivers elsewhere in the Southern USA, are the foundation of poplar breeding programs around the world [68, 74]. Of the 14 superior clones described by Mohn et al. [74], five of these were given a "blue tag" certification (i.e., highest level) in 1974. This was the first blue tag certification of any forest reproductive material in the USA [75]. Observations of cottonwood growing in natural stands provided the information needed to specify the basic requirements for establishing and growing cottonwood, but until 1960 only pilot tests were established [76]. Working with cooperators, a flexible system of *Populus* culture was developed [77], and in 1960, industrial plantings were initiated by Crown Zellerbach Corporation with the purchase of a 6070-ha cattle and cotton plantation near Fitler, MS, that was developed into a cottonwood plantation. Other companies in the region followed suit [76].

The Maximum Yield Work Unit was established at the USDA FS Northern Institute of Forest Genetics in Rhinelander, WI, in 1971. The work unit took a systems approach, with researchers from different disciplines, to select promising species, investigate establishment methods for SRWC culture, and evaluate pulping qualities and the economic viability [78]. More basic research was incorporated in 1976 and furthered by funding from the US Department of Energy from 1977 to 2002. Poplars are prone to hybridizing, and *P. deltoides* introduced to Europe by botanists spontaneously crossed with the native black poplar (*Populus nigra* L.) and came to be known as Canadian poplars (*Populus* × *canadensis* Moench). These wild Euro-American hybrids stimulated interest in producing controlled crosses. The first documented controlled cross of western black poplar (*Populus trichocarpa* Torr. & Gray) and *P. deltoides* in 1924 led to vegetative propagation of selected clones, and by the 1930s, poplar breeding programs were widespread in Europe and North America [10]. Researchers at Rhinelander have concentrated on hybrid poplars for SRWC [79], although they have also investigated other species including jack pine (*Pinus banksiana* Lamb.), larch [*Larix laricina* (Du Roi) K. Koch], alder (*Alnus* spp. Mill.), and green ash (*Fraxinus pennsylvanica* Marshall) [78].

The history of *Eucalyptus* in the continental USA dates back to the California Gold Rush of the mid-1800s [70], but

Table 2 Short-rotation woody crop genomic groups and genotypes tested for the provision of ecosystem services and development of environmental technologies in the United States

Genus/genomic group	Genotype(s)	Reference(s)
Populus		
P. deltoides	91.05.02, 91.08.09, 110531, 110804, 112127, 112830, 5910100, 7300500, 7300501, 7300502, 7302801, 7302810, 8000104, 8000105, 3-1, 14-71, 14-129, 32-5, 42-7, 51-5, 61–2, 61-4, 61-8, 62-4, 63-1, 66-9, 72C-2, 79-4, 90-3, 92-4, 93-6, 94-4, 100-3, 115-1, 119-6, 147-1, 171-1, 180-1, 189-4, 192-2, 193-5, 220-5, 252-4, 42-7, 51-2, C910401, C910502, C910506, C910508, C910510, C910613, C910706, C910809, C910903, C912500, C916000, C916001, C916013, C916021, C916101, C916201, C916304, C916305, C916306, C916323, C916325, C916400, C916401, C916413, C916500, C917900, C918001, C918012, CHILI.2-01, CHILI.2-02, D1, D3, D5, D7, D9, D10, D11, D101, D102, D103, D104, D105, D106, D107, D108, D109, D110, D111, D112, D113, D114, D117, D118, D119, D120, D121, D122, D123, D124, D125, D126, D129, D130, D132, D133, D134, D135, D137, D139, D141, D144, D147, Kentucky 8, M2-9, M3-4, M7-3, Ohio Red, S7C1, S7C8, S7C15, S13C20, ST66, ST70, ST71, ST72, ST75, ST109, ST260, ST261, ST264, WV99, WV316, WV415, WV416, wild-type collections	[22–43]
P. grandidentata	Wild-type collections	[42]
P. suaveolens subsp. m*aximowiczii*	897-1, 898-1, 900-2, 904-2, 1050-10, 1051-4, 1051-10, 77331, 77341, 77441	[41]
P. nigra	13-17, 13-308, 22SNOP01, 21SNOP12	[22, 23, 40]
P. trichocarpa	062, 065, 072, 322, 12-106, 91-568, 93-968	[40, 44]
P. deltoides × *P. deltoides*	119.16, 11428.03, 12111911, 80X00601, 80X00603, 80X00605, 80X01015, 80X01038, 80X01059, 80X01107, 80X01109, 80X01110, 80X01112, 80X01132, 91X01-02, 91X02-01, 91X02-02, 91X04-01, 91X04-02, 91X04-04, 91X04-05, C9425R3, C9425R5, C9425S11, GB123602, GB250205, ISU.25-4, ISU.25-12, ISU.25-21, ISU.25-35, ISU.25-R2, ISU.25-R4, ISU.25-R5, WV94	[22, 23, 25, 26, 34, 41–43]
P. deltoides × *P. nigra*	13-366, 13-818, 13-822, 14-66, 117.53, DN5, DN17, DN21, DN31, DN34 (aka Eugenei), DN70, DN182, I45-51, NE222, OP367, PL-1, Simplot Alkaline, Tassman	[22–26, 34, 36, 40, 43, 45–53]
P. deltoides × *P. suaveolens* subsp. *maximowiczii*	25, 113.64, 202.37, 313.23, 313.55, DM101, DM105, DM113, DM115, Eridano, MWH2, MWH3, MWH5, MWH7, MWH10, MWH11, MWH12, MWH13, MWH14, MWH15, MWH17, NC14103, NC14104, NC14105, NC14106, NC14107	[22, 23, 25, 26, 34, 39, 40, 44, 54]
P. nigra × *P. suaveolens* subsp. *maximowiczii*	NM2, NM6	[22–26, 34, 36, 47]
P. alba × *P. alba*	12XAA9005, 8XAA9004	[22, 23]
P. alba × *P. grandidentata*	Crandon	[22–24, 55]
P. alba × (*P. alba* × *P. grandidentata*)	11XAAG9102	[22, 23]
P. trichocarpa × *P. deltoides*	15-29, 23-91, 23-96, 24-305, 49-177, 50-197, 50-194, 52-225, 52-229, 184-40, 184-402, 184-408, 184-411, 195-529, 272-97	[25, 26, 34, 40, 49, 50, 53]
(*P. trichocarpa* × *P. deltoides*) × *P. deltoides*	NC13377, NC13446, NC13451, NC13460, NC13475, NC13544, NC13548, NC13552, NC13559, NC13563, NC13568, NC13570, NC13608, NC13609, NC13624, NC13649, NC13652, NC13661, NC13668, NC13670, NC13672, NC13680, NC13684, NC13685, NC13686, NC13724, NC13747, NC13749, NC13800, NC13801, NC13807, NC13845, NC13850, NC13857, NC13863, NC13992, NC13999, NC14002, NC14015, NC14018, NC14042	[22–24, 36, 39, 44, 51, 56]
(*P. trichocarpa* × *P. deltoides*) × *P. suaveolens* subsp. *maximowiczii*	233-3, 289-69	[40]
(*P. trichocarpa* × *P. deltoides*) × *P. nigra*	345-1, 346-12, 347-13, 347-13, 347-14	[40]
P. trichocarpa × *P. suaveolens* subsp. *maximowiczii*	262-4, 272-98, 272-239, 281-181, 282-139, 286-74	[40]
P. suaveolens subsp. m*aximowiczii* × *P. trichocarpa*	NE41	[43]

Table 2 (continued)

Genus/genomic group	Genotype(s)	Reference(s)
P. trichocarpa × *P. nigra*	302-1, 302-4, 302-5, 302-6, 303-11, 303-12, 303-13, 303-14, 304-21, 304-22, 304-23, 304-24, 304-25, 304-26, 304-27, 304-28, 305-31, 305-32, 305-33, 305-34, 305-35, 306-41, 306-42, 306-43, 306-44, 306-45, 306-46, 306-47, 306-49, 306-52, 306-448, 307-51, 308-61, 309-71, 309-72, 310-84, 310-85, 310-87, 311-93, 312-101, 313-111, 313-112, 313-113, 313-114, 313-115, 314-121, 314-122, 314-123, 314-124, 315-131, 315-132, 315-134, 315-135, 315-136, 315-137, 316-141, 316-142, 316-143, 317-152, 317-153, 317-154, 318-161, 318-162, 318-164, 345-1	[25, 26, 34, 40]
P. trichocarpa × *P. trichocarpa*	D-01	[53]
P. trichocarpa × (*P. trichocarpa* × *P. deltoides*)	353-273	[40]
P. charkowiensis × *P. cv incrassata*	NE308	[43]
Salix		
S. dasyclados	SV1	[42]
S. eriocephala	9837-77, S25, S287, wild-type collections	[42, 57]
S. eriocephala × *S. eriocephala*	S566	[57]
S. interior	Wild-type collections	[58–60]
S. miyabeana	SX64	[42]
S. nigra	Wild-type collections	[42, 58–63]
S. purpurea	94003, 94012	[57]
S. sachalinensis	SX61	[57]
Pinus		
P. taeda	7-56	[27–30, 64, 65]
Platanus		
P. occidentalis	Control-pollinated families	[27–31, 66, 67]
Liquidambar		
L. styracifula	Control-pollinated families	[27–31]

Sections (in bold) and authorities for the aforementioned *Populus* species are: ***Aigeiros* Duby**—*P. charkowiensis* R. I. Schrod., *P. deltoides* Bartr. ex Marsh, *P. incrassata* Dode, *P. nigra* L.; ***Tacamahaca* Spach**—*P. suaveolens* Fischer subsp. *maximowiczii* A. Henry, *P. trichocarpa* Torr. & Gray; ***Populus* L.**—*P. alba* L., *P. grandidentata* Michx

Authorities for the remaining genera and species include: ***Salix***—*S. dasyclados* Wimm., *S. eriocephala* Michx., *S. interior* Rowlee, *S. miyabeana* Seemen., *S. nigra* Marsh., *S. purpurea* L., *S. sachalinensis* F. Schmidt; ***Pinus taeda* L.**; ***Platanus occidentalis* L.**; ***Liquidambar styracifula* L.**

eucalypts fell out of favor by the turn of the century. Interest spiked again from 1950 to 1970 and USDA FS research in California and Hawaii continued into the 1990s [80–82]. A sustained interest developed in the Southern USA, specifically in Florida [70, 83]. Industry-funded cooperative research programs provided support for the USDA FS Lehigh Acres Laboratory [84]. From 1965 to 1984, USDA FS researchers tested the best of 156 seed sources of 76 eucalypts for southern Florida, resulting in more than 1500 selected clones of *E. grandis* [85]. Swamp mahogany (*Eucalyptus robusta* Sm.), river red gum (*Eucalyptus camaldulensis* Dehnh.), and forest red gum (*Eucalyptus tereticornis* Sm.) were also selected and received lesser levels of genetic improvement [70, 84]. Commercial plantations persist today in southern Florida and Hawaii [21, 85]. In the past, deployment of *Eucalyptus* in the South north of lower Florida has been limited by severe freezes [70]. Nevertheless, a renewed search has begun for freeze-tolerant species and provenances [86], as well as development of transgenic *E. grandis* × *E. urophylla* [8, 20].

Recently, a group of forest industry experts in the southeastern USA were asked what hardwood species were best suited for biomass production [87]. They agreed that sweetgum (*Liquidambar styraciflua* L.) had broad regional application, although they acknowledged its relatively low growth rates. Frost-tolerant *Eucalyptus* spp. were recommended for the coastal zone, and poplar (*P. deltoides* and hybrids) was particularly favorable if cultivars tolerant of marginal site conditions became available. While acknowledging the potential for several hardwoods, the forest industry experts recommended considering loblolly pine (*Pinus taeda* L.) for SRWC. The proven capabilities of southern pines to sustainably produce biomass and a well-developed supply chain, particularly for plantation loblolly pine, certainly support the consideration of southern pine for SRWC [21, 88, 89]. Loblolly pine does not readily sprout; hence, coppice rotations are infeasible. Because there are substantial markets for larger roundwood, biomass systems for loblolly pine can be flexible, running the gamut from dedicated single-product stands for bioenergy [90], dual-cropping for bioenergy and conventional products [91, 92], or intercropping pine with perennial energy grasses [93].

Over 50 years of intensive research and experimentation in the USA and globally has validated the basic premises of SRWC: use of species with rapid (indeterminate) initial stem growth and coppicing ability, in dense plantings, with short clear-felling cycles. In large part due to USDA FS Research and Development (USDA FS R&D), intensive cultural techniques have been developed, including genetically superior material, weed control, fertilization, and irrigation strategies [10, 88]. Optimizing cultural practices that match genetics to site and regulate density and rotation length to achieve greater leaf area maximize yield [78]. Advances in genetic and physiological biotechnology have opened the door to a new world of possibilities for tree growth and wood properties [10, 88]. Realization of these possibilities will be determined by regulatory constraints, public attitudes, and, of course, markets.

While historical efforts for the development of SRWC focused on the production of biomass for bioenergy, biofuels, and bioproducts, much of the more recent work has expanded to include broader objectives of achieving multiple ecosystem services. Specifically, USDA FS research conducted across the USDA Biomass Research Centers has utilized baseline information from these former studies to further develop and refine woody crop production systems for biomass production, carbon sequestration, water quality and quantity, and soil health. In addition, current systems have been expanded beyond traditional fiber production to other environmental technologies that incorporate SRWC as vital components for phytoremediation, urban afforestation, forest restoration, and mine reclamation (see [94] in this special issue).

Ecosystem Services

The Millennium Ecosystem Assessment [95] categorizes ecosystem services into four groups. *Provisioning services* are the goods and products obtained from ecosystems (e.g., biomass, freshwater), while *regulating services* include the benefits obtained from an ecosystem's control of natural processes (e.g., carbon sequestration, soil quality). The four specific ecosystem services listed are highlighted below with respect to recent USDA FS research conducted at the USDA Biomass Research Centers. For biomass, we describe productivity potential and realized yields, as well as growth impacts from pests. The section ends with a discussion about the development of bioenergy siting applications. For carbon, regional implications are discussed, followed by a section highlighting water quality and quantity across genera. The final ecosystem services section describes research on soils and wildlife habitat. Although it is beyond the scope of this paper, the remaining two groups include *cultural services* which are the nonmaterial benefits obtained from ecosystems (e.g., spiritual and educational values) and *supporting services* that include the natural processes that maintain the other ecosystem services (e.g., nitrogen and water cycles) [95].

Biomass

Productivity Potential

Hybrid Poplar

Typical hybrid poplar productivity potential in the North Central USA has ranged from 4.0 to 13.0 dry Mg ha^{-1} year^{-1}, with some values exceeding 20.0 dry Mg ha^{-1} year^{-1} when matching genotypes to specific adaptation zones [22, 45]. The most common method for estimating hybrid poplar productivity has been to develop biomass equations based on simple traits such as diameter at breast height (DBH) and/or height [96, 97]. Others have developed more complex equations using additional allometric characteristics and wood properties [98]. While these equations have been useful and accurate when used only for the specific genotype or genomic groups they were developed for, even the seemingly more complex equations have not been robust enough to account for the broad amount of genetic variability among *Populus* species and their hybrids. More specifically, an equation developed for one clone is likely not adequate for other genotypes, especially those belonging to different species and taxonomic sections.

Recent work at the Central-Eastern and Northern-East Regional USDA Biomass Research Centers has included the development of biomass equations based on harvests of 198 hybrid poplar trees from two different regional testing networks [23, 46] that were established between the years 1987 and 2001 at 15 sites across the North Central USA (Fig. 1). Analyses are still ongoing, yet two initial trends are apparent. First, older equations commonly used in the region are not well suited for estimating biomass of newer genotypes, with previous equations consistently overestimating biomass productivity potential. Second, equations specific to genomic groups were sufficient for estimating biomass of the newer genotypes, with clone-specific equations resulting in minimal improvements in model fit compared to group-specific equations [99]. Hence, using group-specific equations was shown to be robust enough for the newer genotypes.

Nevertheless, recognizing limitations in robustness and complexity associated with biomass productivity equations, USDA FS scientists partnered with researchers from

Iowa State University to parameterize, calibrate, and validate the Physiological Principles Predicting Growth (3-PG) process-based growth model for hybrid poplars in the North Central USA [45]. While others have validated the model for loblolly pine and eucalypts [100] and poplars [101], this was the first validation for hybrid poplar in the USA. The aforementioned limitations are important to understand because biomass is largely driven by the response of genetic and physiological mechanisms controlling growth to site conditions such as climate and soils. Unlike biomass productivity equations, estimates from 3-PG are substantially more accurate given that the model accounts for differences in these genotype- and location-specific characteristics. More specifically, 3-PG uses solar radiation and temperature data along with species-specific photosynthetic parameters to establish maximum potential productivity, from which actual productivity is estimated based on limiting factors such as site fertility and water availability (as influenced by precipitation, soil water holding capacity, water table access, etc.) and allocated among tree components (stems, foliage, and roots) based on allometric relationships. Thus, productivity is estimated based on the site-specific availability of key resources and the species-specific physiological processes which govern the conversion of these resources into biomass. Based on this model development, estimates of hybrid poplar productivity were developed for Minnesota and Wisconsin [45]. The mean annual productivity ranged from 4.4 to 13.0 dry Mg ha^{-1} year^{-1}, and the highest productivity potential was located in South Central Minnesota and southern Wisconsin. Productivity values decreased at higher latitudes.

These productivity modeling efforts were then further expanded with the development of an approach for deploying hybrid poplar production systems to increase yield and associated ecosystem services across the landscape [9]. Specifically, building on SRWC research dating back to the Maximum Yield Work Unit described above, knowledge of poplar silviculture was merged with large-scale spatial analyses to predefine zones of potential hybrid poplar adaptation that were ecologically sustainable [24] and economically feasible [102] across the landscape. Across both states, eligible lands were identified, field reconnaissance was conducted across 143 test sites, and the 3-PG model of Headlee et al. [45] was refined to estimate poplar productivity within the suitable areas. Two changes were made to the original model. First, SSURGO soil data replaced STATSGO soil data, resulting in increased mapping resolutions. Second, to capture the potential implications of genotypic selection, two clonal groups were tested. Estimates for *generalist clones*, defined as those performing well across the region, were developed using the default settings from Headlee et al. [45] and SSURGO soil data. In contrast, productivity for *specialist clones*, defined as those adapted to specific locations, was modeled as with generalist clones plus the adjustment of setting the optimum temperature for growth equal to each site's mean maximum growing season temperature (June to August) [9]. Overall, hybrid poplar productivity ranged from 9.5 to 11.9 dry Mg ha^{-1} year^{-1}, with a mean of 10.0 dry Mg ha^{-1} year^{-1}. Specialist clones exhibited an 18 % increase in productivity potential compared with their generalist counterparts, thereby expressing the importance of considering genotype × environment interactions when deploying hybrid poplars in the region, regardless of end use.

Cottonwood

Eastern cottonwood (*P. deltoides*) is a prime candidate for SRWC because it is the fastest growing tree in North America and is easy to propagate vegetatively [69, 103]. Eastern cottonwood is one of the tallest hardwood species, achieving heights of 53–59 m in natural stands with diameters of 120–180 cm [104, 105]. Cottonwood is intolerant of shading, with much variability among clones. Generally, crowns of cottonwood do not touch even in closely spaced plantings and belowground competition may commence before crown closure [106]. Individual tree volume equations were developed by Krinard [107] and form the basis for the compatible growth and yield model developed by Cao and Durand [108]. Site index, developed from stand data, is used in the model; polymorphic site index curves for cottonwood plantations in the Lower Mississippi Alluvial Valley for base age 10 years were developed by Cao and Durand [109]. In plantations, the mean annual height growth at age 10 was reported as 1.9–2.4 m year^{-1} [108].

Cottonwood grows best on well- and moderately well-drained soils and most clones do not tolerate saturation and anaerobic soil conditions during the growing season [69]. Expanding cottonwood to less favorable sites will require identification of adapted clones. The need to control competing vegetation early in the rotation presents a limitation on some heavy-textured soils due to equipment limitations that make weed control difficult as well as increased costs. Improved genetic material and other advances in SRWC culture could produce higher productivity than has been achieved in industrial pulpwood plantations, which have sustained yields of more than 10.0 dry Mg ha^{-1} year^{-1} [69]. Proven clones on good sites, tended with appropriate and timely cultural treatments, in 5 years can produce more than 13.0 dry Mg ha^{-1} year^{-1} [110]. Potential SRWC yields, with higher initial density and shorter rotations, have been estimated as 27.0 dry Mg ha^{-1} year^{-1} [111, 112]. Advanced breeding to match clones to site, and for disease resistance and appropriate silvicultural practices, will be needed to achieve a doubling of productivity.

Loblolly Pine

The establishment of the Southern Forest Experiment Station in New Orleans, LA, and the Appalachian Forest Experiment Station in Asheville, NC, by the USDA FS was a milestone in the development of forestry and forest research in the South [113]. The actual and potential productivity of southern pine species became apparent with the publication of Miscellaneous Publication 50 [114], and the technology for establishing pine plantations on cutover land was advanced by the work of USDA FS scientist Dr. Philip Wakeley [115]. Half a century of research and breeding by USDA FS, forest industry, and university scientists and implementation by forest industry and other large private landowners have produced plantations of loblolly pines that grow ten times faster than naturally regenerated stands [116–118]. Of the southern pines, loblolly pine exhibits the fastest early growth and is the most responsive to amendments [21]. Genetic improvement of planting stock, along with advances in silvicultural techniques and a well-developed value chain, provides a broad foundation for SRWC pine. Over the years, USDA FS scientists have contributed directly and through cooperative research programs to the development of plantation pine culture, including growth and yield [119–124].

There is relatively little published information on the use of loblolly pine for SRWC, but before forest industry divested much of their land in the 1990s, they experimented with SRIC for pulpwood. By controlling height growth losses to Nantucket pine tip moth (*Rhyacionia frustrana* Scudder *in* Comstock), they obtained annual growth increments of 3.1–3.6 dry Mg ha^{-1} at ages 10–12 years on some sites [117, 125] and on most sites routinely obtained annual increments averaging 2.1–2.7 dry Mg ha^{-1} [126, 127]. Studies comparing planting density and genotypes provide insight into potential growth under SRWC. For example, there was no difference in growth under two dense plantings (3700 and 4400 trees ha^{-1}) after 4 years and stem biomass growth in the fourth year was 17.4 dry Mg ha^{-1} [128]. Using the same improved family, Adegbidi et al. [129] reported biomass accumulation from four intensively managed stands planted at the same density, 1495 trees ha^{-1}. After 4 years, stemwood growth was 10.1 dry Mg ha^{-1} year^{-1} and accounted for 34 % of the net primary production.

Eucalypts

Short-rotation *Eucalyptus* potentially could produce more biomass than loblolly pine if frost-tolerant site-adapted genotypes can be identified. Short rotation systems in Peninsular Florida using *E. grandis* and cabbage gum (*Eucalyptus amplifolia* Naudin) can produce up to 67.0 green Mg ha^{-1} year^{-1} in multiple 3-year rotations [83]. Appropriate sites are likely on soils of sandy clay loam and clay loam textures and moderately well- to well-drained soils, avoiding sites with imperfect or excessive drainage [70]. Managing competing vegetation and developing appropriate fertilization regimes are needed to achieve high levels of productivity [70]. Weed control treatments are not well developed for eucalypts in the South; herbicides used for pine culture are not appropriate for eucalypt plantations. Because *Eucalyptus* spp. are not native to North America, there is concern for their potential invasiveness and effects on natural ecosystems [130]. Potential invasiveness was investigated based on field assessment of actual escapes from *Eucalyptus* plantings on three sites in South Carolina and 16 sites in Florida [131]. They found a small number of *E. amplifolia*, *E. robusta*, and *E. grandis* seedlings growing within and nearby to *Eucalyptus* plantations at four sites in Florida, but only two individuals were detected more than 45 m from plantation boundaries.

Callaham et al. [131] concluded that the invasiveness potential for *Eucalyptus* species considered for the Southern USA is generally low. The species with the greatest potential for the Southern USA have limited ability to disperse and produce small seeds with low viability. Seedlings are light-demanding and grow poorly under closed forest or understory canopies. Some eucalypt species may naturalize (spontaneously reproduce in their introduced range) in the South, but there was no evidence for invasion (reproducing and spreading long distances, i.e., hundreds of meters in large numbers). Nevertheless, Callaham et al. [131] cautioned that the potential for spread into unmanaged areas should not be dismissed.

Another potential concern for expanding eucalypt plantations in the South is increased fire risk. Goodrick and Stanturf [132] examined the effect of widespread plantings of eucalypts on the risk of wildfires and whether fire behavior in eucalypt stands would differ from fires in commonly occurring vegetation types such as pine plantations. They used the Fuel Characteristic Classification System and literature values for fuel characteristics and loads to model surface fire behavior in young *Eucalyptus* plantations and found little difference as compared to surface fires in fuels common to pine forests characteristic of the Lower Coastal Plain. Spotting behavior (i.e., when a fire produces sparks or embers that are carried by the wind and start new fires beyond the zone of direct ignition by the main fire) is a characteristic of eucalypts that existing models do not adequately account for, but stands managed on short rotation (less than 10 years) will likely be harvested before bark shedding presents a significant spotting problem. Fires are more likely to start outside *Eucalyptus* plantations than inside, but once a crown fire is initiated, it will spread rapidly and the potential is for more severe crown fire behavior than in pine stands.

Cottonwood, Loblolly Pine, and Eucalypts

The genus-specific research described above is very important for the advancement of SRWC production systems. However, there is a need for additional studies comparing these genera (and their species) side-by-side across multiple temporal and spatial scales. Currently, 3-PG is being used to account for environmental influences on tree growth while comparing the productivity potential of cottonwood, loblolly pine, and eucalypts across a range of environmental conditions in a quantitative, spatially explicit manner [133]. The specific objectives of this research include: (1) adapting the 3-PG model for cottonwood, loblolly pine, and eucalypts within the southeastern USA; (2) using existing geographic information system (GIS) layers for soils and climate to generate productivity estimates within the region by climate zone and soil type; and (3) determining the optimum (i.e., highest economic value) species and rotation age by climate zone and soil type. Preliminary outcomes of model fitting and mapping efforts, assuming low-intensity management and planting densities typical of each species, indicate that peak productivity of 9.5–15.7 dry Mg ha^{-1} year^{-1} can be expected for eucalypts on 3- to 4-year rotations, 12.2–17.2 dry Mg ha^{-1} year^{-1} for loblolly pine on 13- to 15-year rotations, and 9.6–18.6 dry Mg ha^{-1} year^{-1} for poplars on 12- to 13-year rotations [134]. In the northern part of the region, productivity estimates for loamy and clay soils were highest under poplar production, whereas they were highest on sandy soils with loblolly pine; in the southern part of the region, productivity estimates were generally highest for eucalypts across soil types.

Yield

Hybrid Poplar

In the southeastern USA, the survival and growth of 31 pure species and hybrid *Populus* selections were evaluated on an upland sandy and bottomland sandy loam site [25]. All trees received irrigation at the upland site, while trees received irrigation or no irrigation (control) at the bottomland site. One pure *P. deltoides* selection and two *P. trichocarpa* × *P. deltoides* hybrids accumulated the most stem volume (ranging from 25.6 to 31.6 dm^3) after 3 years at the upland site. The hybrid clones originated in the Pacific Northwest, while the pure *P. deltoides* was from Mississippi. At the bottomland site, pure *P. deltoides* selections (one from Arkansas and one from Mississippi) accumulated the most stem volume (ranging from 17.5 to 20.8 dm^3) after three growing seasons, and irrigation resulted in substantial growth increases. These studies highlight the importance of irrigation in the absence of a natural water source for *Populus* growth in the southeastern USA. These trees were also evaluated after ten growing seasons [26]. Early survival (i.e., up to 3 years old) correlated well with survival after 10 years, and stem volume of 3-year-old trees correlated well with stem volume after 10 years on an upland site. This work supports the screening of multiple *Populus* selections if they are to be a viable biomass alternative in the southeastern USA. These data are needed to find selections that will both survive and produce in the warm climate and on (often) sandy, non-alluvial soils.

In the North Central USA, the gap between hybrid poplar yields in small-plot versus field-scale trials has decreased in the past decades, making hybrid poplars more economically feasible in some areas [102]. However, despite promising gains from selection coupled with increased silvicultural knowledge, genotype × environment interactions continue to dominate yields [22]. Hansen [135] published one of the first papers on hybrid poplar yield potential, where estimates ranged from 7.6 to 15.7 dry Mg ha^{-1} year^{-1} in Wisconsin. Along with others, he later reported that superior clones in small-plot trials exhibited 300 %, and those in field trials 200 %, greater yield than commercial clones at mid-rotation [79]. At rotation age (i.e., 10–12 years), Netzer et al. [46] reported similar results from many of these same sites.

There are two notable examples of recent USDA FS hybrid poplar yield research in the North Central USA. First, the US Department of Energy at the Oak Ridge National Laboratory funded a regional field testing network that spanned four states (Iowa, Michigan, Minnesota, Wisconsin), three planting years (1995, 1997, 2000), and roughly 200 genotypes belonging to 10 genomic groups [23]. Zalesny et al. [22] conducted a remeasurement campaign and reported that new, superior clonal selections exhibited 1.4–2.7 times as much biomass as commercial clones and that some of these selections had mean annual increments greater than 20.0 dry Mg ha^{-1} year^{-1} (i.e., 50 % greater biomass than estimates for previous superior selections). Second, with funding from the USDA FS R&D Washington Office Woody Biomass, Bioenergy, and Bioproducts Program, Northern Research Station scientists have partnered with university collaborators to develop an integrated network from the original Hansen et al. [79] and Riemenschneider et al. [23] trials to test long-term ecosystem services of hybrid poplars, with biomass yield being one of these services. The resultant ecosystem services network that is also currently being used for carbon (see below), water use (see below), and conversion [47, 48, 136] studies (Fig. 2) is comprised of 11 of the original Hansen et al. [79] sites (i.e., 20-year-olds) and four of the original Riemenshneider et al. [23] plantings (i.e., 10-year-olds) located in Iowa, Michigan, Minnesota, and Wisconsin (Fig. 1). In total, 12 clones belonging to five genomic groups are being tested, with 10 clones from the 10-year-old network and two clones from the 20-year-old plantations (Table 2). Site × clone interactions governed yield for both age groups (10 years, $P = 0.0421$; 20 years, $P < 0.0001$). For the 10-year-old trees, the interaction means of biomass ranged from 3.3 to 16.9 dry Mg ha^{-1} year^{-1},

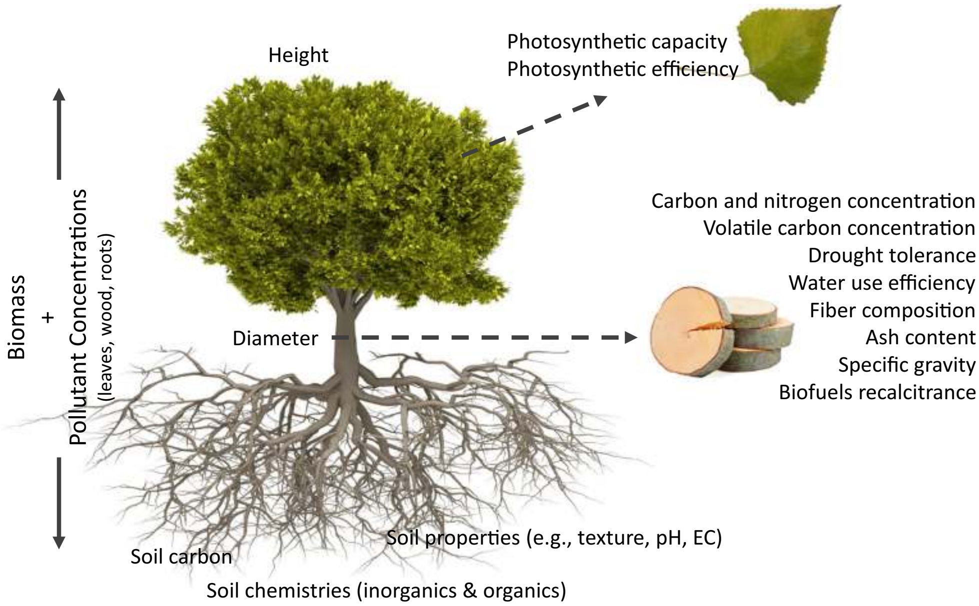

Fig. 2 Ecosystem services (biomass, carbon, water, soils) and associated allometric and physiological traits of *Populus* tested in multiple woody crop production system networks in the USA (see Fig 1)

with an overall mean of 8.7 dry Mg ha^{-1} year^{-1}. The least biomass was from a *P. deltoides* × *P. deltoides* F_1 hybrid ('C918001') growing in Escanaba, MI (45.77°N, 87.20°W), while the most biomass was from another hybrid from that genomic group ('C916400') growing at Arlington, WI (43.29°N, 89.37°W). For the 20-year-old trees, the interaction means of biomass ranged from 5.8 to 21.7 dry Mg ha^{-1} year^{-1}, with an overall mean of 11.9 dry Mg ha^{-1} year^{-1}. Of particular note is the biomass yield of clone 'DN182', a *P. deltoides* × *P. nigra* F_1 hybrid, that exhibited greater than 18.0 dry Mg ha^{-1} year^{-1} at three sites [Rhinelander, WI (45.63°N, 89.46°W); Granite Falls, MN (44.80°N, 95.52°W); and Fairmont, MN (43.69°N, 94.35°W)]. This yield is more than three times higher than those reported in Hansen et al. [79], indicating that silvicultural research was successful at increasing yields in the region.

Cottonwood

A long-term replicated experiment was established in 2000 at the USDA FS Southern Research Station Savannah River Site in New Ellenton, SC (33.38°N, 81.67°W) [27] (Fig. 1). Two pure *P. deltoides* clones ('ST66' of Mississippi origin and 'S7C15' of East Texas origin) were included in this study that measured growth and productivity responses to varying levels of irrigation and fertilization. In a non-replicated experiment designed to find optimal nitrogen fertilization rates [28], the optimal nitrogen fertilization rates were 131 and 71 kg N ha^{-1} year^{-1} for irrigated and non-irrigated 'ST66', respectively. Maximum aboveground biomass differed little, however, between irrigated and non-irrigated trees (i.e., range from 3.6 to 4.3 dry Mg ha^{-1} year^{-1}). Clone 'S7C15' was more N-demanding, as the optimal rate for irrigated trees was 232 kg N ha^{-1} year^{-1} and for non-irrigated trees was 94 kg N ha^{-1} year^{-1}. Furthermore, growth responses for 'S7C15' differed greatly between irrigated (6.3 dry Mg ha^{-1} year^{-1}) and non-irrigated (2.9 dry Mg ha^{-1} year^{-1}) trees. Overall, the use of irrigation would not be economically feasible for these two *P. deltoides* clones in this area, or likely on this type of soil throughout the southeastern USA.

Furthermore, the growth of both clones was significantly improved by increasing resource availability throughout the harvest rotation [29, 30]. After nine growing seasons, aboveground woody production was 7.2 and 6.4 dry Mg ha^{-1} year^{-1} in 'ST66' and 'S7C15', respectively [30]. Irrigation and fertilization resulted in aboveground productivity increases of >177 %. The relative proportion of above- and belowground tissue allocation was affected by both tree size and resource availability [30].

Research directed at eastern cottonwood yields in the Mississippi Alluvial Valley (MAV) has not kept pace with SRWC in other regions primarily due to a lack of industrial plantation management in the region. Two companies that most recently managed industrial plantations in the region, Tembec (formerly Crown Vantage) in Fitler, MS, and Westvaco in Wickliffe, KY, terminated cottonwood management and sold their holdings in 1998 and 2007, respectively. The vast majority of eastern cottonwood plantations established in the region today are intended for forest restoration, carbon sequestration, wildlife habitat, and recreational purposes [137]. In the late 1980s, Krinard [107] released volume equations for plantation-grown eastern cottonwood, and these equations are still used today for predicting cubic volume of individual trees. In 1991, Cao and Durand [108] published the first growth and yield model to predict whole-stand volume for eastern cottonwood plantations in the MAV. This model was developed from cottonwood plantations throughout the southern half of the MAV [108], and it appears to conform well to operational yields produced locally [138].

The Cao and Durand [108] model is a compatible growth and yield model that predicts cubic-foot volume yield and projects volume from site index, initial age, and basal area. The model was the basis for an Excel spreadsheet called Cotton, prepared by Cao for Crown Vantage (later Tembec) in 1994. Stanturf and Portwood [138] used this software to estimate volume to a 7.5-cm top and yield of green megagrams per hectare for stands on three representative soil/site productivity classes to evaluate the economic potential of pulpwood rotations of 10 and 11 years. These soils are suitable for growing cottonwood, but vary in productivity. Stocking and height measurements at age 3 were taken from stands on the Fitler Plantation, on old-field sites, protected by the river levee, with good survival. Stands were planted with improved stock, fertilized at site preparation, and competing vegetation was controlled with herbicides [138].

The modeled yields are shown in Table 3. The stand on the Commerce soil (Aeric Fluvaquents) represented the highest productivity sites and yielded 76.7 dry Mg ha^{-1} at age 10. The medium productivity sites on Tunica-Bowdre soils (Vertic Haplaquepts-Fluvaquentic Hapludolls) and the lowest productivity sites on the Sharkey soil (Vertic Haplaquepts) yielded considerably less, 56.0 and 47.0 dry Mg ha^{-1}, respectively. One deficiency of the model is that it is not valid for coppice rotations, and operational experience from the Fitler plantation indicates that merchantable yields from stands of coppice origin are typically reduced by half because most trees develop with multiple stems [138]. Byrd et al. [139] recently attempted to develop a simple model for predicting aboveground biomass of multi-stemmed eastern cottonwood, but the authors were not satisfied that their model was useful across a range of soil types and regeneration methods. While coppicing results in a loss of merchantability for pulp markets, this may or may not be an issue for biomass markets, but a robust growth and yield model for stands of coppice-origin eastern cottonwood remains unavailable for the MAV.

Loblolly Pine

The growth and productivity of loblolly pine selection '7–56' was evaluated over an 11-year harvest rotation (i.e., from 2000 to 2010) on a sandy upland site in South Carolina (33.38°N, 81.67°W). Trees received irrigation (0.5 cm day^{-1}, for a total of 3.0 cm week^{-1}), fertilization (120 kg N ha^{-1} year^{-1}), and irrigation + fertilization or were untreated (control). Loblolly pine did not respond to irrigation during early [31] or late [30] development, indicating that fertilization was the primary limiting factor of tree productivity. Maximum aboveground woody production of loblolly pine exceeded 19.0 dry Mg ha^{-1} year^{-1}, and annual stem productivity was nearly 10.0 dry Mg ha^{-1} year^{-1}. With fertilization, trees reached a basal area at which thinning is required at 8 years of age—3 years sooner than without fertilization (control). Trees allocated more biomass to belowground tissues as resource availability increased, even as trees increased in size [30].

Pest Susceptibility: Resistance Screening and Impacts on Growth

Short-rotation woody crop systems are known to be susceptible to a number of insect pests [32], and work at the Savannah River Site (Fig. 1) supported examining of the influence of resource availability on tree susceptibility to pests. Pest infestations occurred on several tree genera over the course of the growing rotation. The cottonwood leafcurl mite, *Aculops lobuliferus* Keifer, causes premature leaf curling and abscission, and terminal mortality, early in the rotation [33]. The mite showed preference for 'S7C15' during spring and 'ST66' during summer and fall. Miticide applications successfully controlled the pest infestation, but not before several instances of high defoliation. In general, mite damage was greatest on fertilized trees. Shortly after the mite infestation, several species of ambrosia beetles attacked live *P. deltoides* trees—a relatively rare occurrence for this insect group [32]. Clone 'ST66' was more susceptible than 'S7C15', and the highest attack rates were found on fertilized trees. A leafhopper, *Erythroneura lawsoni* Robinson, had very high

Table 3 Estimated cottonwood plantation yields in the Lower Mississippi Alluvial Valley at rotation age 10 years on three representative soil/site productivity classes (stands were age 3 years when measured) (adapted from [138])

	Site		
	Commerce	Tunica-Bowdre	Sharkey
Site index (m; base age 10)	24.1	22.3	20.1
Basal area (m^2 ha^{-1})	6.7	3.9	3.4
Stems (ha^{-1})	682	622	642
Survival percent	91	83	86
Yield at age 10 years (dry Mg ha^{-1})	76.7	56.3	47.1
Cumulative annual increment (dry Mg ha^{-1}, age 10)	8.4	7.0	6.0
Mean annual increment (dry Mg ha^{-1}, age 10)	7.7	5.6	4.7

populations in sycamore, and while little foliar feeding injury occurred, higher numbers of leafhoppers were generally captured in non-fertilized plots [66]. In loblolly pine, irrigation and fertilization did not consistently impact Nantucket pine tip moth damage levels or pupal weight [64].

Cottonwood leaf beetle (*Chrysomela scripta* F.), cottonwood leafcurl mite, and poplar leaf rust (*Melampsora medusa* Thüm) incidence and damage were monitored on 31 *Populus* clones over 3 years in South Carolina [34]. Irrigated trees had significantly greater cottonwood leaf beetle and poplar leaf rust damage levels in each year, and damage tended to increase throughout the growing season. Clone rankings varied widely among clones and years, depending on the specific pest and environment. For instance, *P. deltoides* × *P. nigra* clones 'OP367' and 'I45-51' and the *P. trichocarpa* × *P. nigra* clone '311-93' were most resistant to the cottonwood leaf beetle on the upland site, but pure *P. deltoides* clones 'S7C1' and '7302801' and the *P. nigra* × Japanese poplar (*Populus suaveolens* Fischer subsp. *maximowiczii* A. Henry) clone 'NM6' were most resistant on a bottomland site. Furthermore, clones 'OP367', '7302810', and the *P. deltoides* clone 'ST109' were most resistant to the cottonwood leafcurl mite on an upland site, while 'NM6', 'I45-51', and the *P. deltoides* × *P. suaveolens* subsp. *maximowiczii* clone 'Eridano' were most resistant on a bottomland site. Clones 'NM6', 'I45-51', and the *P. trichocarpa* × *P. deltoides* clone '15–29' were highly resistant to leaf rust on both sites.

Bioenergy Siting Applications

In addition to the biological productivity of these SRWC, USDA FS researchers and their collaborators have made substantial progress on understanding the economic drivers of woody biomass. In particular, since 2007, the Southern Research Station and the University of Tennessee have partnered to develop a biomass and bioenergy assessment collaborative. Since that time, the collaborative has added other universities and federal agency partners to conduct research for the development, enhancement, and deployment of innovative decision support tools.

The Biomass Site Assessment Tools (BioSAT) partnership delivers landscape-scale decision support and web-based assessments for agricultural, grassland, and forest ecosystems (Fig. 3). The "genesis" of BioSAT grew from the knowledge that stability of the biomass markets depends on improved methods to display the risk and cost of supply and logistics from farms and forests to collection or conversion facilities. The context was to develop an integrated resource assessment model to spatially define and compare socioeconomic and biophysical drivers paired with community-based human–environmental conditions impacting the bio-economy.

Conceptual Framework

The collaborative is responsive to research needs expressed in the literature and reports on the economic availability of biomass including: (1) US Department of Energy US Billion-Ton Study [140], (2) US Billion-Ton Update [6], (3) USDA FS Woody Biomass Utilization Strategy [141], and (4) USDA FS Strategic Energy Framework [142].

As noted, one of the first challenges for any commercial activity is to determine where suitable and available lands are located [143]. Site selection must consider biological, economic, and societal factors with information on soils, geology, vegetation, current land uses, topography, etc., compared and spatially defined using GIS. Potential constraints on the availability of biomass feedstock also need to be better understood [144]. Primary constraints include a lack of production capacity along with the high relative costs of production, logistics, and transportation.

Constraints within the natural, built, and social environments limit available biomass supplies. These constraints affect the amount and type of biomass potentially available locally, as well as at broader landscape scales. To address these constraints, USDA FS researchers are working with partners to develop decision-making tools that support intelligent alignment of the production and use of biomass with other existing ecological, social, and economic objectives [145]. Developing the new bio-economy involves understanding and establishing many complex relationships [146–148].

Methods

Assessing the bio-economy is not straightforward. The bio-based sector of the US economy is multidimensional. There is the lack of clear definition of what attributes, indices, or combinations best measure the bio-economy. Multiple-attribute landscape characterization helps decision-makers discover potential risks and opportunities for local lands. Composite indices visually summarizing information from an array of individual attributes provide a clear picture for the public, industry, media, and policy makers. The data and analyses are not meant to represent the total state of a geographic region, but rather to demonstrate what types of information give reasonable measures of the landscape conditions and opportunities for developing a bio-based economy. Researchers use the results of ongoing studies to explore additional attributes with the intent of adding value and improving the reliability of the spatially defined framework.

More than 125 attributes have or are being explored for use as indices within BioSAT (Table 4). These attributes belong to seven categories: (1) initial siting and economic indices and models (26 attributes); (2) opportunity zone indices and model (×12); (3) SRWC production indices and model (×51); (4) race and origin of population in the USA (×13); (5) natural

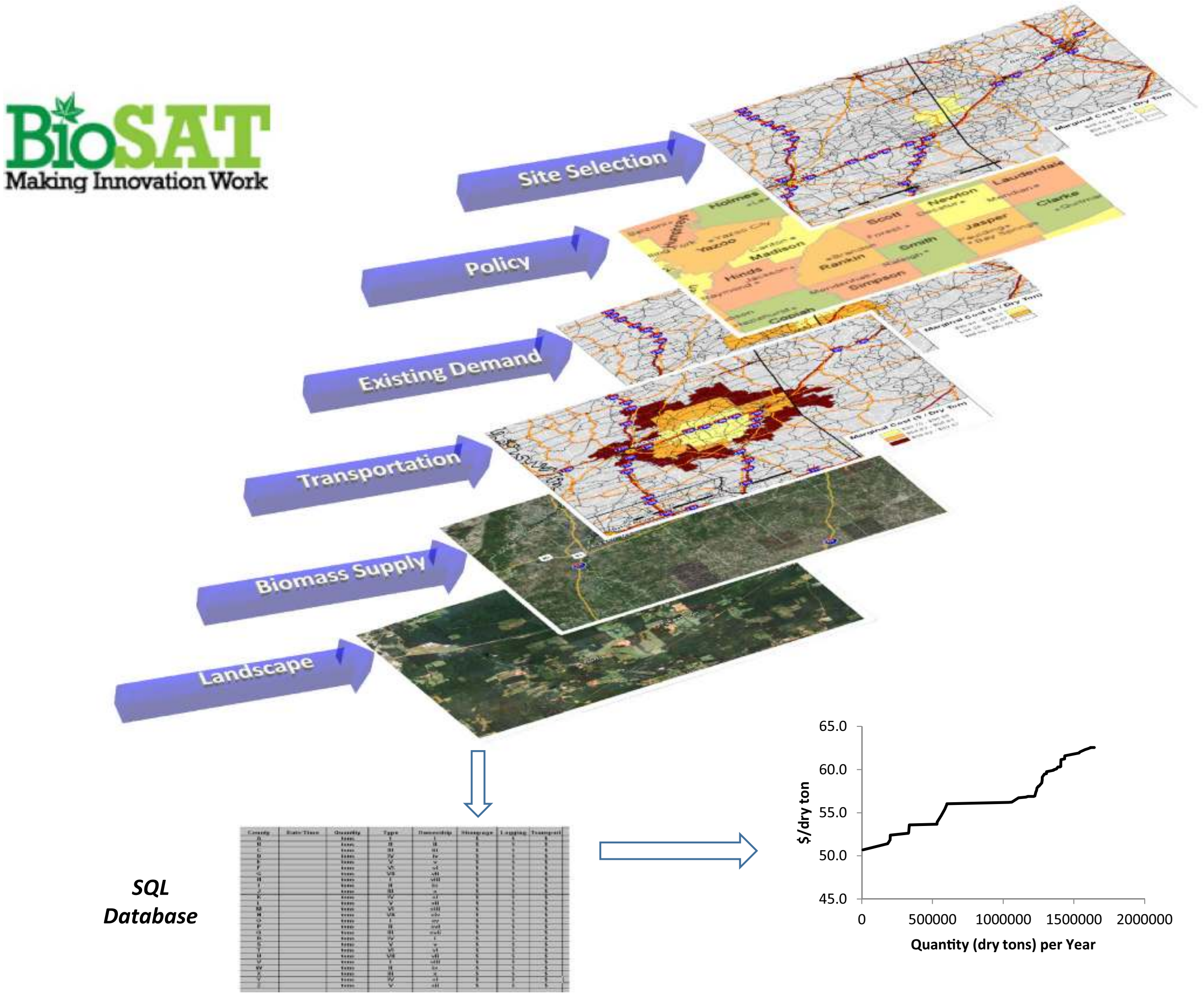

Fig. 3 Conceptual diagram of BioSAT, a model that fuses layers of spatial and economic data together to create a relational database for geographic-based economic cost assessment for woody and agricultural residue biomass collection or processing demand centers

disaster vulnerability indices (×16); (6) carbon (×8); and (7) plant-available soil water holding capacities to 1.5-m depth (×1).

Approaches and Results

Phases I and II BioSAT integrates contemporary web-based information technology (e.g., Virtual Earth and Microsoft SQL) with existing data: *forestry* [USDA FS Forest Inventory and Analysis (FIA)]; *agriculture* [USDA National Agriculture Statistics Service (USDA NASS)]; *harvesting* [USDA FS Fuel Reduction Simulator (FRCS), Auburn Harvest Analyzer (AHA)]; and *transportation* (enhanced model by [149]).

The BioSAT applications data, models, and results provide spatially explicit indices for bio-basins. The sub-county multidimensional framework is used to conduct analyses to evaluate various aspects of growth, profitability, and uncertainty. All records are organized at a five-digit ZIP Code Tabulation Area (ZCTA) resolution and matched with zip codes. The average area for the five-digit ZCTAs in the 33-state study region is about 169 km^2. The five-digit ZCTAs result in more than 25,000 potential analytical polygons or site locations. The model uses relatively simple and readily available GIS-based landscape characterization and socioeconomic inputs to derive and generate visual evidence of biomass supply/demand, risk potential, biomass accessibility and landscape suitability, opportunity zones, energy crop production potential, and ecological vulnerability. The BioSAT decision support tools are available at http://www.biosat.net/.

Research reports and journal publications outline the process, results of analysis, and the relevance of selected indices to measure the potential of the bio-economy. With a focus on supply chain components, the system maps and

Table 4 BioSAT model inputs and outputs (adapted from the BioSAT public domain website, www.BioSAT.net)

Input variable	Collection level	Unit	Data source (current date)	Output
Forest pulpwood	County	Dry tons	USDA FS FIA (2005–2010)	BioSAT model estimates for biomass quantities (dry tons)
Forest sawtimber	County	Dry tons	USDA FS FIA (2005–2010)	BioSAT model estimates for biomass quantities (dry tons)
Logging residues	County	Dry tons	USDA FS FIA/SRTS model (2006–2010)	BioSAT model estimates for biomass quantities (dry tons)
Mill residues	County	Dry tons	USDA FS TPO (2009)	BioSAT model estimates for biomass quantities (dry tons)
Ag residues	County	Dry tons	USDA NASS (2009)	BioSAT model estimates for biomass quantities (dry tons)
Crop-cultivated land area ratio	5-digit ZCTA[a]	Percent	U.S. National Land Cover Database (2006)	Allocation of inventory at 30 × 30-m resolution (spatial)
Forest land area ratio	5-digit ZCTA	Percent	U.S. National Land Cover Database (2006)	Allocation of inventory at 30 × 30-m resolution (spatial)
Pulpwood stumpage	Intrastate and state	US$ dry ton^{-1}	Timber Mart South (2012) Timber Mart North (2012) Reporting by state agencies (2009–2012)	BioSAT model resource costs for biomass (US$ dry ton^{-1})
Sawtimber stumpage	Intrastate and state	US$ dry ton^{-1}	Timber Mart South (2012) Timber Mart North (2012) Reporting by state agencies (2009–2012)	BioSAT model resource costs for biomass (US$ dry ton^{-1})
Mill residue prices	Intrastate and state	US$ dry ton^{-1}	Timber Mart South (2012) Timber Mart North (2012) Reporting by state agencies (2009–2012)	BioSAT model resource costs for biomass (US$ dry ton^{-1})
Harvesting costs for roundwood (5 options)	EcoRegion	US$ dry ton^{-1}	Auburn Harvesting Analyzer enhanced for BioSAT	BioSAT model harvesting costs for biomass (US$ dry ton^{-1})
Harvesting costs for logging residues (2 options)	EcoRegion	US$ dry ton^{-1}	USDA FS FRCS Model	BioSAT model harvesting costs for biomass (US$ dry ton^{-1})
Harvesting costs for ag residues (2 options)	County	US$ dry ton^{-1}	Literature	BioSAT model harvesting costs for biomass (US$ dry ton^{-1})
Travel distance	5-digit ZCTA	Miles	Microsoft MapPoint (2009)	BioSAT model trucking model (US$ dry ton-mile^{-1})
Travel time	5-digit ZCTA	Minutes	Microsoft MapPoint (2009)	BioSAT model trucking model (US$ dry ton-mile^{-1})
Diesel prices	State	US$ gallon^{-1}	U.S. Energy Information Agency (2012)	BioSAT model trucking model (US$ dry ton-mile^{-1})
Labor rates	State	US$ hour^{-1}	Reporting by state agencies (2010)	BioSAT model trucking model (US$ dry ton-mile^{-1})
License and tax rates	State	US$ year^{-1}	Reporting by state agencies (2010)	BioSAT model trucking model (US$ dry ton-mile^{-1})
Truck weight limits	State	Dry tons	Reporting by state agencies (2010)	BioSAT model trucking model (US$ dry ton-mile^{-1})
Intra truck-rail locations	5-digit ZCTA	Latitude longitude	Reporting by rail companies (2010)	BioSAT model rail-truck locations (spatial)

Overall outputs include total, average, and marginal costs for biomass in a spatial context for opportunity zones and bio-basins, as well as marginal cost curves or producer supply curves in a spatial context for opportunity zones and bio-basins

[a] *5-digit ZCTA* five-digit zip code tabulation area. All GIS analysis levels were at the five-digit ZCTA

displays baseline data for public and business leaders, assesses the economic availability of woody and agricultural-derived biomass, identifies local market conditions, and thereby reduces screening time to locate sites favorable for full economic or business case due diligence [150–153].

The following phases built upon the initial research to improve and extend the utility of the web-based system.

Phase III: The Wood to Energy Project The objectives included providing a complete literature review on the state of the science and developing a database of wood-to-energy-related industries in the USA and Canada. The database includes major forest product industries that produce residues, users of residues for energy (e.g., boilers, ethanol producers, etc.), and related industries. Such information is vital to making sound planning and business decisions to expand uses of wood for energy. The system is being continuously updated to ensure that it is comprehensive as it is practical [154].

Phase IV: Logistic Regression Models of Factors Influencing the Location of Bioenergy and Biofuel Plants In addition to the broad range of forest types across the country, there are regional and local differences in silvicultural systems, demand for traditional wood products, land use, landowner attitudes, energy opportunities, and local and state policies [155]. Phase IV builds upon previous research and is the first study to use logistic regression models to quantify significant factors influencing site location of woody biomass-using bioenergy and biofuel plants and predict potential locations based on probability. The logistic regression model is the most widely used method to relate a binary outcome (i.e., success/failure) to a set of explanatory variables in a regression setting. Logistic regression models were developed to identify significant factors that influence the location of existing wood-using bioenergy/biofuel plants and traditional wood-using facilities. Existing data on favorable and unfavorable locations for woody biomass-using facilities were used to train logistic regression models. These models were then used to evaluate the suitability of new locations. Economic factors, transportation-related factors, and the availability of biomass feedstocks were included as predictor variables in the logistic regression models. A de-clustering algorithm was developed to move sites identified by the logistic models away from sources of competition. Based on the logistic models, 25 locations were predicted for bioenergy or biofuel plants for a 13-state study region in the Southern USA [153].

Phase V: A Spatial Index for Identifying Opportunity Zones for Woody Cellulosic Conversion Facilities The use of renewable biomass can help diversity markets for agriculture and forestry, create jobs, and promote rural development [156, 157]. There are many factors that influence the amount of biomass that is actually available. Phase V integrates geographical landscape characterization and socioeconomic GIS data with BioSAT to display and visualize the risk while identifying opportunity zones for potential biomass-using facilities (e.g., biorefineries, wood pellet mills, biopower) [152, 153, 158]. Emerging opportunities that compete against existing uses of property or raw resources are often socially constrained or permanently denied regardless of economic viability. The opportunity zones are derived from the use of landscape suitability and competition indices. Landscape features (measure to which a competing land use is physically restricted by current land use) may adversely impact economically viable competing uses of property and thereby restrict biomass access and positive location decisions. Spatial competition is particularly important for access to biomass resources. Existence of competing biomass-using facilities reduces the probability of making a positive location decision, and this impact decreases with distance from competition. Landscape and competition indices were developed in the study, and combining these indices in a spatial-geographic context derives a classification of “opportunity zones” for potential users of woody cellulosic feedstocks [159].

Phase VI: An Economic Geospatial Analysis of SRWC Short-rotation woody crops are part of the bioenergy solution in the USA [160], especially in the Southeast where plantation forestry is economical [116]. Currently, SRWC productivity is not cost-effective; assessing optimal site locations for large geographic regions is essential for lowering costs [9, 102, 111]. Short-rotation woody crops are ideal renewable feedstocks because they can be strategically located near conversion facilities and provide ecological services, conserve soil and water, recycle nutrients, and sequester carbon [65]. To that end, the objective of phase VI was to improve the economic assessments of SRWC based on the suitability of lands and enhance the economic assessments in a geospatial context. With BioSAT, the when and where of production and logistics of SRWCs were identified to build efficiencies for profitability and sustainability of biomass supply chains, assuming deployment in conjunction with potential facility locations. Risk probabilities for SRWC production and processing locations using Bayesian inference are unique to SRWC research. Site requirements for four genera (*Populus*, *Salix*, *Pinus*, and *Eucalyptus*) are defined that have the potential for large-scale production. Soils, climatology, 3-PG modeling, and land cover data are developed and will be fused with existing BioSAT model physiognomic, economic, and societal data for 33 Eastern US states [161].

Phase VII: Modeling the Impact of the Emerging Bio-economy on Transportation Network Flows with Simulation and Bayesian Inference The impact of the emerging bio-economy on transportation infrastructure and related concerns is a top priority for the US Department of Transportation and Southeastern Sun Grant Program. Phase VII addressed this priority through modeling of specific impacts of the emerging bio-economy on truck transportation network flow for the Southern US. In phase VII, Bayesian logistic regression and GIS spatial analysis were applied to estimate site locations for biorefineries in the presence of uncertainty as related to resource competition, delivered costs at the plant gate, and trucking transportation flow. Procurement zones assumed a one-way haul distance of 129 km as a function of the available road network and interrelated resource as estimated from the BioSAT model. Attributes such as *median family income*, *timberland annual growth-to-removal ratio*, and *transportation delays* were highly significant in influencing mill location. Transportation delays for trucks greatly impacted the cost of trucking biomass resources. For example, trucking costs increased 60 % in some areas of the Southern USA. The logistic model using Bayesian inference was a good model for predicting preferred site locations and identifying non-preferred locations [162].

Carbon

Southeast Region

In the MAV, a region in which agricultural land use predominates, interests in carbon (C) sequestration have played a prominent role in the restoration of farmland to forests [163]. In 1994, scientists and collaborators at the Center for Bottomland Hardwoods Research in Stoneville, MS, initiated work on the Sharkey Restoration Research and Demonstration Site (32.96°N, 90.74°W), an area devoted to the study of forest restoration on farmed bottomlands in the MAV (Fig. 1) [164]. A primary focus of the research has been an afforestation system inspired from knowledge of developmental patterns of natural eastern cottonwood stands [164]. The eastern cottonwood–hardwood interplanting system provides a novel approach for C sequestration on former agricultural lands. Accumulation of above- and belowground biomass is maximized by the eastern cottonwood nurse crop during the initial stages of stand establishment and maintained through the life of the stand by development of the slower-growing, later-successional interplanted hardwoods. Modeling the C balance of these plantations projects an annual C gain greater than 9.0 Mg C ha^{-1} over a 100-year rotation. Ongoing long-term research will enable further calibration of C storage models for variation resulting from stand dynamics of various cottonwood genotypes, stand densities, stand management alternatives, and site productivity. However, demand from the C economy has already led to private refinement and wide-scale implementation of this plantation approach for the production of verifiable forestry C offsets and renewable biomass feedstock supplies [165].

Additional research on dedicated energy crop systems for farmed bottomlands was initiated in 2011 to analyze the costs and benefits associated with a range of production system alternatives [35]. The study, established near Hollandale, MS, in the MAV (Fig. 1), examines four planting densities and associated harvest regimes of eastern cottonwood, including: (1) 10,127 trees ha^{-1} with harvests in years 2, 4, 6, 8, and 10; (2) 6147 trees ha^{-1} with harvests in years 4, 7, and 10; (3) 1993 trees ha^{-1} with thinning in year 3 followed by complete harvest with reestablishment in year 5; and (4) 745 trees ha^{-1} with harvest in year 10 [35]. Initial measurements on tree establishment and growth, biomass accumulation, and soil respiration are being analyzed to gain an understanding of how plantation density and harvest regime impact biomass yields and C balance on farmed bottomlands in the MAV [61].

North Central Region

Aboveground C storage potential is currently being tested from the 10- and 20-year-old trees ($n = 198$) belonging to the ecosystem services network defined in the biomass section above (Fig. 2). During felling, cross-sectional disks were harvested from each bole at 1.4-m height (i.e., DBH), 1/3 height of the tree, and 2/3 height of the tree. The disks were oven-dried at 55 °C until constant mass. One cross-sectional area of each disk was sanded and the sanded disks were then cut in half along a plane extending through the pith. A wafer, free of bark and defects, was cut from one half-disk and sanded. For each tree, three subsamples were collected from each growth ring from each positional cross-sectional disk, resulting in approximately 25,000 samples for analyses. Samples were analyzed for total C using a Flash EA1112 N-C analyzer (Thermo Electron, via CE Elantech, Inc., Lakewood, NJ) with a model MAS 200 autosampler. Data analyses are currently underway. In summary, the C concentrations of individual samples ranged from 40.1 to 52.8 %, with an overall mean of 47.2 %. For the 10-year-old trees, clone means ranged from 46.8 % (‘C916000’; *P. deltoides* × *P. deltoides*) to 48.5 % (‘NM2’; *P. nigra* × *P. suaveolens* subsp. *maximowiczii*). For the 20-year-olds, clone ‘DN34’ (*P. deltoides* × *P. nigra*) exhibited a mean C concentration of 47.4 %, while ‘DN182’ (*P. deltoides* × *P. nigra*) had 47.2 %, on average. Stand-level C storage across genotypes and sites of the 10-year-olds ranged from 1.5 to 8.0 Mg C ha^{-1} year^{-1} (mean = 4.2 Mg C ha^{-1} year^{-1}), while values for the older stands were 1.9–10.2 Mg C ha^{-1} year^{-1} (mean = 5.5 Mg C ha^{-1} year^{-1}) [36]. Depending on specific genotype × environment interactions, these results have substantial ecological and economic practical implications when compared to the commonly accepted value of C comprising 50 % of wood [166]. For example, at 10 years after planting, the Birdsey [166] estimate would overestimate the mean C storage potential of all clones by 3–6 %, regardless of where they were grown. Given the broad genetic variability within the genus *Populus* [167–169], generalizations for many traits should be used with caution, and this is certainly true for C.

Water

Hybrid Poplar

Chemical analysis of stable isotope ratios in tree growth rings has been proven useful in evaluating water use efficiency (WUE) in trees [170], as previous research has demonstrated for various species including poplars and their hybrids [171–173]. Despite the importance of this information for species and genotype selection in the face of changing climates, a limited amount of information exists for hybrid poplar in the USA. Therefore, as part of the ecosystem services network described above (Fig. 2), the WUE of seven clones of 10-year-old hybrid poplars is being evaluated at three sites in the North Central USA. The overarching objective is to identify genotypes with high WUE that are less susceptible to water stress compared to those with low WUE [174], thereby increasing the biomass yield potential on drier and/or water-limited sites [172]. Wood samples from annual growth rings were collected from the carbon wafers described above (i.e., carbon section) and analyzed for carbon isotope composition ($\delta^{13}C$). These $\delta^{13}C$ data are being analyzed to test for significant differences attributed to three genomic groups [*P. deltoides* (pure species); (*P. trichocarpa* × *P. deltoides*) × *P. deltoides* (first-generation backcross hybrids); and *P. nigra* × *P. suaveolens* subsp. *maximowiczii* (F_1 hybrid commercial control)] (and, separately, genotypes), sites, and their interactions. In addition, the $\delta^{13}C$ data are being evaluated together as covariates with climate and soil variables to further improve our understanding of how genotype-specific WUE interacts with site conditions to impact biomass yields and associated ecosystem services. Preliminary data indicate that the sites differed in terms of water stress, as general trends in $\delta^{13}C$ levels were apparent across sites and were consistent across genotypes. The results also suggest the potential for genetic selection based on WUE, as several genotypes exhibited stable or increased growth rates under elevated water stress (high WUE), whereas others exhibited reduced growth under such conditions (Headlee et al., unpublished data).

Eucalypts

Water use of eucalypts has been a controversial issue internationally [175], and much has been made of the effect of converting other land uses to *Eucalyptus* plantations. Eucalypts have potentially higher water use and WUE compared to pasture, pine plantations, and native forests. In addition, WUE is a major determinant of productivity [175]. Water use at the individual tree and stand levels varies significantly among *Eucalyptus* clones and is not a constant characteristic of a given genotype, but overall, eucalypts have similar WUE to other tree species. Water consumption at the stand level depends upon water availability and vapor pressure deficit. Actual water use by eucalypts in a watershed depends on many factors including the areal extent, size, spatial distribution, productivity, and age–class distribution of planted stands. Studies in other countries suggest that water consumption by *Eucalyptus* plantations will be higher in terms of percentage of water supply in drier regions, but absolute water consumption will be higher in wetter regions [175].

Ongoing modeling studies are examining the potential water use of expanded *Eucalyptus* plantations in the South at the tree, stand, and watershed levels. Ouyang et al. [176] modeled hydrological processes and water use in a *E. urophylla* plantation. They examined the potential impacts on water use of wet and dry sandy soil conditions. The maximum rate of leaf transpiration was about five times greater than that of soil evaporation. The cumulative annual water use by the eucalypts was 3200 L tree^{-1}. Vose et al. [177] focused on water yield (Q) at the stand and the regional scales (12-digit Hydrologic Unit Code watershed) in the Lower Coastal Plain of the South where there is potential to expand freeze-tolerant eucalypt plantations [8]. They found that at the stand level, the Q for *Eucalyptus* was comparable to some pine plantations or slightly reduced by 9–16 % of precipitation (1300 mm year^{-1}). This occurred at a leaf area index (LAI) of 4. Greater reduction in Q occurred at higher productivity levels, by as much as 500 mm year^{-1} (a reduction of 33–63 % of precipitation) when the LAI was 5.

These studies suggest that predicted watershed-level response to small and moderate amounts of land in *Eucalyptus* plantations in the Southern USA may be difficult to detect. Economic analysis indicates a 20 % conversion of conifer to frost-tolerant eucalypts [8]. At this scale of conversion, reductions in water yield at the 12-digit HUC scale will be negligible. The variability in WUE among *Eucalyptus* clones suggests a potential for breeding trees with improved WUE and drought resistance, which could be important under future climate and land uses that compete with forestry for available water.

Mixed Species

Recent joint USDA FS–USDA Agricultural Research Service (USDA ARS) partnerships extend beyond the scope of the USA and North America. The USDA FS International Programs (http://www.fs.fed.us/about-agency/international-programs) has collaborated with the USAID Mission in Cairo, Egypt, where the water resource is arguably the most important ecosystem service. In short, since 2004, Egypt has been developing wastewater reuse strategies for non-edible crops (including trees grown along rural to urban gradients) because they will not be able to meet the increasing water demand from the Nile River, which supplies the country with almost 97 % of its freshwater. Given the treaties with Sudan, Egypt is limited to 55.5 billion m^3 of Nile freshwater annually.

Following the establishment of 24 forests designed to irrigate the trees with treated wastewater, a joint USDA FS–USDA ARS technical assistance team evaluated the feasibility of scaling up similar afforestation projects in the country. In addition to the final report, the team evaluated strategies for afforestation [178] and irrigation [179]. Six suitable tree genera were identified based on soil characteristics and water quality/quantity issues: (1) *Populus*, *Pinus*, and *Eucalyptus* for pulpwood or sawnwood (versatile species); (2) *Khaya* (mahogany) and *Tectona* (teak) for high-value products; and (3) *Gmelina* (beechwood) for pulpwood [178]. Water quality was a major component of the recommended silvicultural prescriptions for successful biomass production using treated wastewater outside of the Nile Delta. Two overarching concerns for water quality improvement were identified: (1) mitigating return flow of treated wastewater back into Nile surface waters and its tributaries and (2) mitigating deep percolation losses into the alluvial aquifer as a result of irrigating the sandy delta soils. Using the trees as filters to reduce subsurface movement of nitrogen, phosphorus, and other potential pollutants (e.g., heavy metals, salts) was also a consideration for water quality improvements following irrigation [178]. To address these collective concerns, Evett et al. [179] developed irrigation strategies based on species' water use requirements, climate, and soil conditions. Given the high water use of *Populus*, one pertinent outcome that can be applied to North American poplar production systems is the potential increase in irrigation frequency in order to meet the trees' water requirements without sustaining the aforementioned deep percolation losses and subsequent aquifer contamination [179], especially in phytoremediation systems as described in Zalesny et al. [94] of this special issue.

Soils and Wildlife Habitat Restoration

Soil protection and establishment of forest habitats for wildlife are central thrusts of USDA conservation easement programs available to owners of agricultural land. The infrastructure of large-scale, forest restoration research established on the Sharkey Restoration Research and Demonstration Site (Fig. 1) has provided opportunity to examine soil development and the development of forest habitats and wildlife use in short-rotation eastern cottonwood plantations. Pre-restoration measurement of soil variables including carbon, nutrients, and bulk density enables future study of the trajectory of soil recovery from agriculture [37]. Initial measurements from the surface (0–7.5 cm) illustrated a 31 % loss in soil N and a 33 % loss in soil carbon on this degraded agricultural site [37]. At year 5, foliar N levels in eastern cottonwood were substantially lower than the levels required for optimal biomass production, revealing persistence of soil nutrient depletion during early forest restoration [180]. Other ecosystem functions responded more rapidly to the establishment of eastern cottonwood forest cover. Hamel [181], who studied winter bird use, reported that avian communities in 4- to 6-year-old eastern cottonwood stands held twice as many species as communities in stands of slower-growing hardwoods. He concluded that the fast vertical growth of eastern cottonwood stands, such as those established for bioenergy purposes, facilitates a more rapid assembly of forest canopy birds than stands of slower-growing trees [181]. Research conducted to date supports the premise that biomass plantations can play a role in the restoration and conservation of biodiversity, particularly within landscapes such as the MAV which is dominated by agricultural land use.

Research to Advance Other Genera

Efforts to develop SRWC systems in the Southern USA have brought significant focus on plantation culture of several species not previously covered in this manuscript. These efforts were generally initiated to develop alternative plantation options for addressing particular site requirements, producing desirable fiber or feedstock qualities, or providing for particular ecosystem services not offered by conventional plantation species. American sycamore (*Platanus occidentalis* L.), sweetgum, yellow poplar (*Liriodendron tulipifera* L.), black locust (*Robinia pseudoacacia* L.), and green ash are among the trees that have been investigated for plantation culture because of their potential as alternatives to the currently utilized plantation species [12, 182, 183]. Three broadleaf species—American sycamore, sweetgum, and black willow (*Salix nigra* Marshall)—are currently being studied by the USDA FS Southern Research Station because they hold a strong potential for future use in woody crop feedstock production systems in the Southern USA.

American Sycamore and Sweetgum

For many decades, forest industry championed University of Georgia and USDA FS research on American sycamore fiber and feedstock production. This species demonstrates high productivity on a wide range of upland and bottomland sites, it has favorable pulping properties, and its biology is amenable to intensive silviculture (i.e., it can be propagated from stem cuttings and can be coppiced over several rotations) [12, 184]. This research investment led to substantial gains in appropriate silvicultural practices, plantation system management, and productivity [12].

In the southeastern USA, the growth and productivity of sycamore and sweetgum grown with a range of water and nutrient availability were evaluated in two separate experiments on the Upper Coastal Plain of South Carolina. After 8 years, Coyle et al. [28] found that the optimal fertilization rates were 147 and 141 kg N ha^{-1} year^{-1} for irrigated and non-irrigated sycamore, respectively. The productivity of sycamore receiving irrigation was 6.5 dry Mg aboveground woody biomass per hectare per year, a 20 % increase over the biomass production rate without irrigation. In contrast, the optimal fertilization rates for sweetgum differed with (85 kg N ha^{-1} year^{-1}) and without (111 kg N ha^{-1} year^{-1}) irrigation. The aboveground woody biomass of sweetgum was 52 % greater with compared to without irrigation.

A concurrent study examined sycamore and sweetgum growth and productivity in a 2 × 2 factorial experiment with and without irrigation and fertilization (0 or 120 kg N ha^{-1} year^{-1}) [27]. After nine growing seasons, sycamore responded significantly to both irrigation and fertilization, as aboveground woody biomass productivity in trees receiving irrigation and fertilization was 8.6 dry Mg ha^{-1} year^{-1}; productivity was 219 % greater compared to trees that received no resource amendments (i.e., control) [30]. Sweetgum productivity was 21.3 dry Mg ha^{-1} year^{-1} in irrigated and fertilized treatments after 11 growing seasons, and this rate was 344 % greater than trees in the control plots [30]. After accounting for tree size, the proportion of belowground biomass was not affected by resource availability in sycamore, but decreased as resource availability increased in sweetgum.

In spite of these positive gains, wide-scale use of American sycamore in plantation culture has been impeded by chronic disease problems [87]. Particularly problematic is the endemic xylem disease bacterial leaf scorch, which is caused by the pathogen *Xylella fastidiosa* Wells et al. and is transmitted to American sycamore by a xylem-feeding insect, the glassy-winged sharpshooter (*Homalodisca vitripennis* Germar) [185]. Upon infection of the host, colonization of xylem vessels by the bacterium leads to dysfunction of the vascular system and water stress that results in leaf scorching, foliage dieback, and tree decline [186]. Plantations in the Southern USA are typically symptomatic a few years after establishment, with progression to mortality within 5–7 years [187, 188].

Ongoing research is focused on traditional tree breeding to address the bacterial leaf scorch issue. Adams et al. [67] identified American sycamore families that exhibit resistance to bacterial leaf scorch and demonstrated that breeding for disease resistance can substantially decrease symptoms. Concurrent investigation into the mechanism of disease resistance indicates that the concentrations of certain glycosides with known bactericidal efficacy on *X. fastidiosa* vary considerably among American sycamore families (Leininger, personal communication). Indeed, glycoside concentration in sycamore leaves was positively correlated with healthy, asymptomatic trees (Leininger, personal communication). In the future, American sycamore could account for a greater role in biomass feedstock production if the breeding program currently focused on disease resistance is successful in producing cultivars suitable for deployment.

Black Willow

Willows, particularly shrub willows, have gained prominent use in short-rotation applications in several regions of the world [189]. Black willow is a fast-growing tree species that is endemic to alluvial forests throughout much of the Eastern USA. This species exhibits relatively high productivity on wet alluvial sites, is readily propagated through vegetative reproduction, and can be regenerated through coppicing. For these reasons, researchers have long recognized the potential of black willow for genetic improvement and use as a biomass species [190, 191], but this potential has not resulted in a sustained effort to forward the species for plantation culture. The current emphasis on the development of sustainable alternatives for biomass feedstock production and the availability of alluvial land that is marginal for agricultural production have created an opportunity for the development of black willow as a plantation species [35, 58].

The USDA FS has initiated collaboration with researchers at other organizations, including Mississippi State University and Louisiana Tech University, in an effort to advance black willow as an alternative plantation species for use on marginal agricultural land in alluvial floodplains. Initial and ongoing research primarily addresses the development of sustainable plantation systems and tree improvement. Experiments designed to provide reliable planting stock and propagation techniques [62], inform pest management practices [63], delineate planting densities and rotation lengths that optimize productivity [35], quantify carbon and nutrient life cycle dynamics [61], and refine harvesting practices [38] are providing the foundation for the development of sustainable black willow plantation systems. Equally vital to sustainability is the implementation of a tree improvement program that can produce genetically superior cultivars suitable for operational deployment into dedicated biomass plantations on alluvial soils [58]. In 2009, researchers began collecting genotypes from selected geographical sources and established cutting orchards to replicate the genotypes for intensive trials. Replicated clonal screening trials, early-age selection, and clonal refinement tests on material from 10 geographic areas are demonstrating significant geographic source and clone variation [59, 60]. Ongoing screening trials and refinement tests will identify the best-performing clones for increased gain and eventually selection of superior genotypes for the production of biomass on marginal agricultural land.

Future Research Directions

Four areas of continuing research are in progress to further advance biomass, carbon, water, and soil research.

1. Integrate energy, climate, and tree genetics to test the physiological and environmental effects on biomass, bioenergy, soil health, erosion control, and water quality and quantity.
2. Develop quantitative genetic models to predict the outcome of genotype × environment interactions as they affect limits to the geographic transfer of clonal selections and the design of environmental technologies, including phytoremediation.
3. Develop silvicultural guidelines for the establishment and growth of short-rotation woody crops, with special emphasis on genetic and environmental effects on rooting.
4. Enhance regional and national feedstock resource assessments and economic analyses to integrate biomass productivity models with carbon sequestration throughout the energy supply chain.

Four areas of continuing research are in progress to further extend BioSAT.

1. BioSAT for Kansas. The primary goal is to create a web-accessible model for Kansas and its border states (i.e., Nebraska, Iowa, Missouri, Arkansas, and Oklahoma) to evaluate agricultural, range, and forest locations for sustainable biomass facilities.
2. Suitability indices for Washington, Oregon, Idaho, and Montana in the Context of BioSAT. The goals are to (a) create new tools that enable complex interactions within the operations of the biomass supply chains to be studied and refined and (b) facilitate a sustainable supply chain for alternative aviation fuels using geospatial suitability overlays to screen for biomass production, secondary data collection, and strategic analysis (e.g., key features of the BioSAT model—land features and socioeconomic factors).
3. Next-generation logistics systems for delivering optimal biomass feedstocks to biorefining industries in the southeastern USA utilizing BioSAT. The goals are to (a) develop and demonstrate a state-of-the-art biomass merchandising and processing depot to identify and reduce sources of variation along the supply chain of multiple high-impact biomass sources (loblolly pine and switchgrass) and (b) develop practices that manage biomass variability to deliver a consistent feedstock optimized for performance in specific technology platforms.
4. Natural Disaster Vulnerability Index (NDVI) in the context of BioSAT. The primary goal is to integrate a spatially explicit NDVI into the current web-based BioSAT system, wherein vulnerability refers to different variables that make biomass-using facilities less able to absorb the impact and recover from a disaster event [192, 193]. This research is important for improving biomass and bioenergy analysis by integrating risk visualization to help recognize and reduce risk from potential natural disasters for small-scale biomass supply chain operations.

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