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Forest Operations and Woody Biomass Logistics to Improve Efficiency, Value, and Sustainability

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Abstract This paper reviews the most recent work conducted by scientists and engineers of the Forest Service of the US Department of Agriculture (USDA) in the areas of forest operations and woody biomass logistics, with an emphasis on feedstock supply for emerging bioenergy, biofuels, and bioproducts applications. This work is presented in the context of previous research in this field by the agency and is measured against the goals and objectives provided by several important national-level initiatives, including the USDA Regional Biomass Research Centers. Research conducted over the past 5 years in cooperation with a diverse group of research partners is organized in four topic sections: innovative practices, innovative machines, sustainability, and integration. A wide range of studies in operations and logistics address advances in harvest and processing technology, transportation systems, scheduling and planning, feedstock quality, biomass conversion processes, and environmental impacts, including greenhouse gas emissions. We also discuss potential future research to address persistent knowledge gaps, especially those in fire and fuel management. Overall, the research reviewed here aligns well with broad national goals of providing the USA with sustainable and efficient forest biomass management and production systems, specifically including: (1) improved harvest, collection, handling, and transportation systems for woody biomass; (2) cost and equipment information and options for field processing biomass to improve efficiency and mitigate impacts; and (3) forest biomass management systems and technologies to offset impacts and enhance environmental outcomes. However, as needs evolve, professionals in this field must strive to adapt research, development, and dissemination to address relevant future challenges and strengthen capabilities to solve critical problems in the forest sector.

Keywords Biomass · Feedstocks · Harvesting · Logistics · Operations · Processing

Abbreviations

ac	Acre
bf	Board feet
BMP	Best management practices
cf	Cubic feet
dbh	Diameter at breast height
ft	Feet
FIA	Forest Inventory and Analysis Program
in.	Inches
LCA	Life cycle assessment
MC	Moisture content
mbf	1000 board ft
mcf	1000 cubic ft
USA	United States
USFS	US Forest Service
USFS R&D	US Forest Service, Research and Development Unit
USDA	US Department of Agriculture
yd^3	Cubic yards

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Introduction

In a forestry context, woody biomass is defined as the stems, limbs, tops, needles, leaves, and sometimes roots of trees and other woody plants grown in a forest, woodland, or rangeland environment that are generated as the by-products of forest management. As such, the use of woody biomass from forests for energy and products is closely linked to the production of timber for wood products manufacturing. For much of the mid-twentieth century, US national forests provided up to 20 % of the total annual national timber harvest [1], and scientists and engineers from the US Forest Service (USFS) of the US Department of Agriculture (USDA) studied forest biomass primarily as a byproduct of timber production on both public and private land. Much like today, forest biomass was variably a primary product, byproduct, or waste depending on market conditions and site characteristics. USFS research of this era covered many topics that remain highly relevant, including the development of empirical models to estimate standing biomass [2], slash yields [3–5], production costs [6], and recoverable energy [7]. Government-funded biomass research in the forest sector was particularly vigorous following the 1973 oil crisis and subsequent oil price hikes, which lasted into the mid-1980s. A forest bioenergy bibliography of the time could easily pass for a contemporary one, with articles on the economics of wood energy [8], development of new equipment to harvest forest biomass [9, 10], biomass utilization decision tools [11], the potential to significantly displace imported oil [12], and even thermochemical conversion technologies for liquid fuel production [13].

Despite many topical similarities, the landscape has changed significantly for USFS biomass research in the twenty-first century. The needs of key stakeholders have evolved. USFS programs deliver new knowledge, technical assistance, and other resources to national forests, states, tribes, private landowners, businesses, local communities, and international partners. National forest managers are now charged with providing a broad spectrum of market and non-market benefits to diverse stakeholders who value timber, recreation, water, soil, carbon sequestration, threatened and endangered species, wilderness, and other ecosystem goods and services. Frequently, these stakeholders are directly and formally involved in collaborative planning to guide management activities, which take place under evolving political, regulatory, and legal frameworks, especially with regards to endangered species and pollution. Forests have also changed. Ecological patterns and processes in many forests have been altered by wildfire, invasive species, climate change, urbanization, disease and insect outbreaks, and other stressors and disturbances. Thinning and other partial treatments are widely used to reduce fire risk, remove non-native and invasive species, and restore forests to historic reference conditions, often at high net cost. And markets have changed. In addition to periodic market fluctuations including the Great Recession (2007–2009), global restructuring in the forest sector has reconfigured production capacity at the national level, with sawlog, fiber and biomass demand declining dramatically in some regions, like the Rocky Mountain West, while increasing in others, like the US South. Traditional uses for forest biomass, such as fuel for heat and power, exist alongside new and emerging uses, such as feedstocks for biofuels, bioproducts, and wood pellets for export to Europe.

These changes have brought exciting opportunities for innovation in forest operations and biomass logistics. Improving the productivity, costs, and quality of biomass recovered from logging and mill operations remains a major focus, but USFS research in this field has grown well beyond conventional systems to encompass everything from reducing carbon emissions to improving multi-product agroforestry practices. More than ever before, operations and logistics research is integrated with work focused on other segments of the supply chain, often as a principal component of large, cross-disciplinary efforts that include life cycle assessment, techno-economic analysis, conversion technology development, social science research, and education. Studies are conducted on both private and public land, and in collaboration with diverse stakeholders and research partners in academia, government, non-government organizations, and industry. The purpose of this paper is to review the most recent work conducted by USFS scientists and engineers in the areas of forest operations and woody biomass logistics, with an emphasis on feedstock supply for emerging bioenergy, biofuels, and bioproducts applications (Table 1). In many cases, USFS contributions were made as part of larger teams of researchers, including personnel from other organizations, and are included here if one or more authors has USFS affiliation.

After a brief presentation of background and context, we review a wide range of studies in four topic sections: innovative practices, innovative machines, sustainability, and integration. We also discuss potential future research to address persistent knowledge gaps, and conclude with a summary of the major accomplishments of the USFS Research and Development Unit (USFS R&D) in this field over the past 5 years.

USFS Operations and Logistics Research in Context

This Special Issue of BioEnergy Research spans the bioenergy and bioproducts supply chain (Fig. 1), from feedstock production (i.e., cultivation and silviculture) to logistics to conversion to end use, with additional sections on economics, public policy, and sustainability. From a business management perspective, a supply chain is a network of organizations that efficiently manufacture and deliver a product that effectively meets the needs of end users. In the supply chain framework, logistics encompasses all of the organizations, technologies,

Table 1 Published forest operations and biomass logistics studies conducted by the US Forest Service since 2009. Many of these studies cover multiple segments of the supply chain but have been categorized based on their dominant emphasis

Emphasis	Description	Feedstock(s)	Equipment/system(s)	Authors [Ref.]
Utilization	Utilization and yield equations	Mixed species	Multiple systems	Simmons et al. [14], Grushecky et al. [15]
On-unit operations	General harvesting systems	Mixed conifers, logging residue, southern pine, pinyon-juniper, poplar, willow, cottonwood, stumps	Multiple systems	Mitchell [16], Rummer and Mitchell [17], Cardoso et al. [18], Rummer and McAvoy [19], Rummer [20]
	Small diameter harvest	Southern pine	Ground-based systems, feller-buncher	Klepac [21], Klepac et al. [22], Jernigan et al. [23]
	Grinding and chipping	Mixed conifers, various feedstocks	In-woods grinding, concentration yard grinding, multiple systems, microchipping	Sprinkle and Mitchell [24], Anderson et al. [25], Thompson and Sprinkle [26], Smidt and Mitchell [27]
	Bailing and bundling	Pine, understory vegetation, various feedstocks	Multiple systems	do Canto et al. [28], Klepac and Rummer [29], Mitchell [30], Meadows et al. [31, 32]
	Mastication	Pinyon-juniper	Mastication, thinning with pile burning	Gottfried [33]
Transportation systems	On-unit/forest road transportation	Mixed conifers, logging residue, pinyon-juniper	Slash forwarding, off-road transportation	Klepac and Rummer [34], Anderson et al. [25]
	On-road transportation	Southern pine, slash pine, loblolly pine	Field drying, untrimmed wood transport	Thompson et al. [35–37]
Improving product value	Concentration and sort yards	Mixed conifer	Log sorting, sorting technologies	Chung et al. [38], Han et al. [39], Wang [40], Mitchell [41]
	Moisture and ash content	Southern pine, loblolly pine, various feedstocks	Whole tree chipping, plantation, field drying, multiple systems	Cutshall et al. [42], Klepac et al. [43], Sprinkle and Mitchell [24], Neary [44]
Conversion processes	Mobile and modular thermochemical conversion	Various feedstocks	Multiple systems	Page-Dumroese et al. [45], Mitchell and Elder [46], Anderson et al. [47], Kim et al. [48], Gu and Bergman [49]
Scheduling	Machine and labor scheduling	Southern pine	Multiple systems	Mitchell and Gallagher [50], Mitchell [51]
Planning	Spatial feedstock models	General biomass, forest biomass	Multiple systems	Perdue et al. [52], Wells et al. [53], Hogland and Anderson [54], Hogland et al. [55], Chung and Anderson [56]
	Bioproducts supply chains	General biomass	Multiple systems, decision tools	Keefe et al. [57], Rummer [58], Anderson et al. [59], SRS [60], Miller et al. [61]
Best management practices	Soil damage, stand damage, regeneration	Eucalypt, cottonwood, willow, aspen, pinyon-juniper, various feedstocks	Multiple systems	De Souza et al. [62, 63], Neary [44], Wear et al. [64], Curzon et al. [65], Mitchell and Klepac [66], Thompson et al. [67], Stottlemyer et al. [68]
Fire and fuels management	Economics, operations	Mixed conifer, pine	Multiple systems	Rummer [58], Lowell et al. [69], Jain et al. [70], Thompson and Anderson [71]
Environmental impacts	Supply chain analysis, life cycle assessment	Redwood, mixed conifer mill residues, various feedstocks	Multiple systems	Gu et al. [49], Han et al. [39], Schweinle et al. [72]
Emissions	Air quality, greenhouse gas emissions	Southern pine, logging residue, various feedstocks	Ground based harvesting, chipping, multiple systems.	Domke et al. [73], Rummer et al. [74], Loeffler and Anderson [75], Mitchell [76]

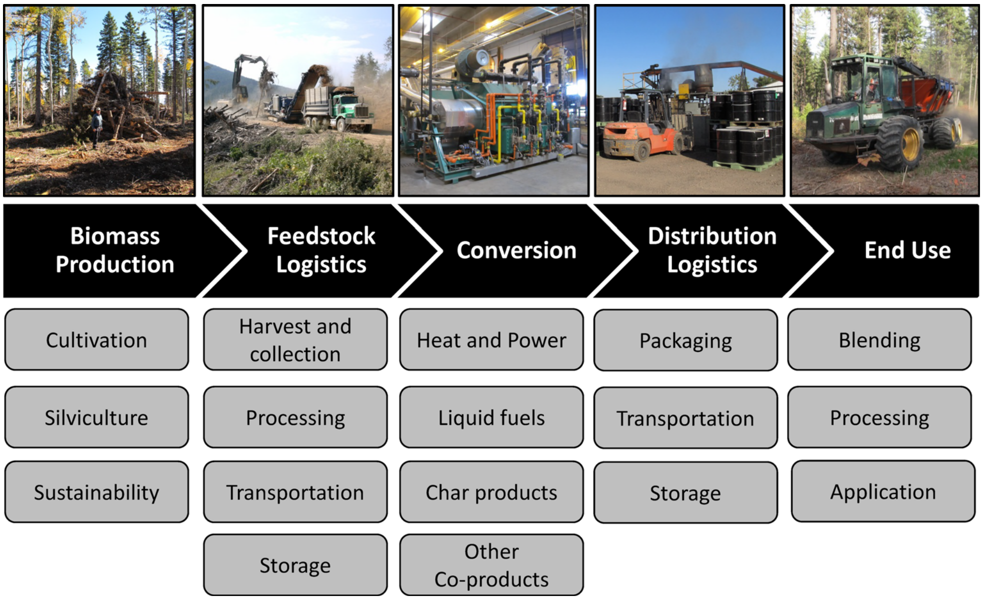

Fig. 1 The bioenergy and bioproducts supply chain. Each link in the chain is illustrated with photos from USFS research. Photos: Anderson

and functions that facilitate the flow of services, raw material, intermediate products, and finished products. In the case of woody biomass, this includes harvest, handling, processing, transportation, and storage [57]. As a discipline, forest operations engineering is a branch of industrial engineering that applies scientific methods to design, plan, implement, control, and improve technologies, processes, and systems in the forest sector, typically from "forest to gate" (Fig. 2). Though it is most often associated with harvesting and transportation systems, forest operations also includes activities related to tree cultivation, labor, ergonomics, health and safety, non-timber forest products, and other areas. In practice, operations and logistics blend science, engineering, and management functions to efficiently and effectively meet the needs of customers and society, including providing forest products like biomass, and also clean air, water, wildlife, recreation, and other benefits.

The directive to aggressively pursue innovative research and development in operations and logistics is formalized by USDA and USFS in several documents that span inter-departmental, inter-agency, and USFS-specific goals and objectives and operate under various legislative authorities, including the Energy Independence and Security Act of 2007 (Public Law 110-140) and the Agricultural Act of 2014 (Public Law 113-79, commonly known as the Farm Bill). These include the USFS R&D *Bioenergy and Biobased Products Strategic Direction, 2009–2014* [77], the charter of the USDA Biomass Research Centers [78], and the USDA Biomass Research and Development Initiative (BRDI) [79], among others. Broad USDA goals include providing the USA with sustainable and economical forest biomass management and production systems, specifically including: (1) improved harvest, collection, handling, and transportation systems for woody biomass; (2) cost and equipment information and options for field processing biomass to improve efficiency and mitigate impacts; and (3) forest biomass management systems and technologies to offset impacts and enhance environmental outcomes. Much of the work undertaken by USFS R&D since 2010 directly addresses these needs. Several critical areas of operations and logistics research have been emphasized, including: (1) new processes and machines for efficiently harvesting biomass from naturally regenerating forests, plantations, and short-rotation woody crops; (2) a better understanding of systems deployed primarily for fuel reduction, forest health, and restoration benefits, including the economics and direct and indirect environmental impacts of such operations; (3) removal of woody species that can be invasive to rangelands, such as eastern red cedar (*Juniperus virginiana*), pinion pine (*Pinus* spp. subsection *Cembroides*), and western juniper (*Juniperus occidentalis*); (4) the use of trees killed by insects, fire, and disease, often over large areas following high mortality disturbances; and (5) deployment of in-woods processing and thermochemical conversion technologies to produce value-added products and improve transportation efficiency.

In operations and logistics, much of the policy, law, and strategy associated with woody biomass utilization can be boiled down to three interrelated objectives: increase efficiency, improve value, and minimize environmental impacts for cost competitive products. Efficiency in this context is the ratio of inputs (e.g., fuel, labor, time, and capital) to outputs (e.g., sawlogs, biomass, water, and habitat) and is often improved by increasing productivity and decreasing costs. In some cases, these objectives can be achieved by using existing resources and equipment in new ways. In the first topic section

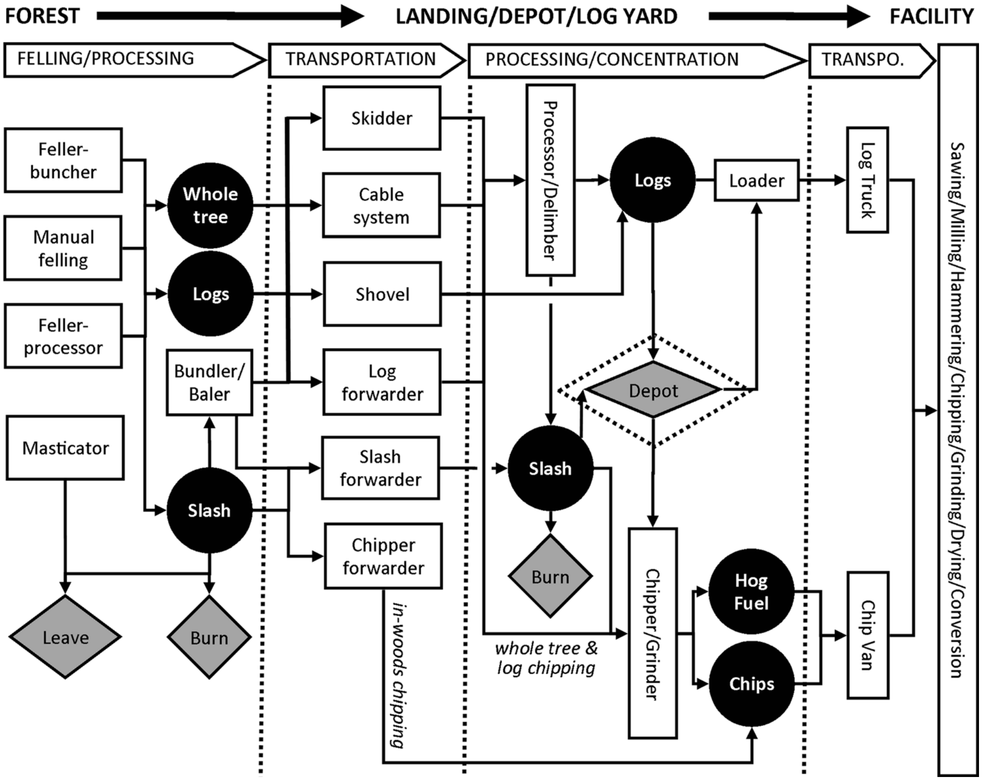

Fig. 2 Schematic of the conventional and novel equipment configurations addressed by USFS research in forest operations and biomass logistics since 2010

below, we highlight research to discover and develop new processes and practices in the context of ongoing forest operations using conventional systems and equipment. Sometimes, these objectives can only be met with new, innovative equipment, frequently involving close coordination with equipment manufacturers and painstaking design, fabrication, and field testing. Such equipment innovation efforts are covered in the second topic section.

In forestry, the "product" often includes environmental benefits and ecosystem services, such as clean water and wildlife, which are frequently considered non-market public goods. The "customer" commonly includes the landowner and the purchaser of intermediate forest products like sawlogs, pulpwood and biomass, but also the public at large, especially on public land. The third section below is focused on research specifically devoted to increasing environmental benefits and reducing environmental costs associated with forest operations, as well as achieving ecosystem-oriented goals as a primary objective. Finally, as components of a larger supply chain, forest operations and biomass logistics are integrated directly upstream with feedstock production and downstream with conversion technology, and more broadly with the supply and demand of end-use product like heat, electricity, biofuels, and bioproducts. We describe a number of integrated projects that include USFS operations and logistics research, as well as knowledge and technology transfer activities that benefit project partners, stakeholders and the public.

Innovative Processes and Practices

Though forest biometrics and product utilization have been important components of USFS R&D for over 100 years, there remains a significant need to develop new empirical models to accurately predict stocks, yield, and recovery of biomass and incorporate them effectively into forest operations. This need is due in part to changes in harvest conditions and objectives on the ground. Shorter rotation intervals in commercial timber and partial treatments applied to meet ecological objectives in difficult and small diameter stands on public lands have become much more common compared with the expansive clearcuts in large diameter timber that informed much of the earlier work on biomass [4]. New size and quality specifications for biofuels and bioproducts feedstocks are also a factor.

Allometric work is addressed in detail by Zalesny et al. (this issue), but several recent efforts connect biomass models with operations and logistics. In a recent logging utilization study in Idaho, Simmons et al. [14] observed both declining average diameter of harvested timber and declining amounts of logging residue generated per unit of delivered volume between 1990 and later studies in 2008 and 2011. Over that period, the proportion of felled tree volume from trees 17 in. or smaller in diameter at breast height (dbh) increased from 33 to 51 %, and the proportion from trees greater than 27 in dbh fell from 28 % to just 2 %. Every 1000 cubic feet (mcf) delivered to the mill is associated with 1.011 mcf of timber volume removed from growing stock and 0.024 mcf of growing-stock logging residue. The USFS Forest Inventory and Analysis Program (FIA) is conducting similar logging utilization studies in many parts of the country. In West Virginia, Grushecky et al. [15] found that 100 % of 30 active logging jobs produced wood waste, with an overall roundwood utilization rate of 87 %, with in-woods and landing utilization variable by species. Results indicated that roundwood residues were a relatively small component of the potentially available biomass associated with operations, especially at the landing, in large part because of the diverse markets available to loggers in this area. This contrasts significantly with the interior western USA, where closures in the pulp and panel sectors have reduced demand for smaller-diameter logs with grade and scale defects like sweep, crook, rot, seams and large knots [80], resulting in lower utilization compared with the US South and Pacific Northwest.

The types of biomass products leaving the landing are evolving to include clean, dry microchips (e.g., low bark content chips less than 20 % moisture content (MC) and smaller than 0.5 in. in the longest dimension) in addition to traditional hog fuel, pulp chips, and firewood. This can have significant impacts on operations [24]. For example, traditional operations that produce hog fuel from roadside harvest and processing residues often use a skidder blade or bulldozer to push and pile slash, contaminating the material with soil and rock that increases the ash content to levels that may be acceptable for hog fuel but are problematic for other applications such as gasification. Furthermore, firms that typically burn these residues for disposal may not have a good understanding of the typical biomass yields that can be recovered from treatments, nor the quality requirements and value of biomass if local markets become available. Yield and utilization studies are useful for predicting stocks and flows available under different market and operational conditions for the purposes of planning but can also inform the development of new practices and equipment.

Quantifying and improving the performance of conventional machines under new conditions and management goals is an important objective of the USFS and USDA biomass research strategies. To this end, USFS researchers, together with industry and university partners, have conducted studies to evaluate innovative uses of available equipment, including: forwarders used for the removal of woody species from rangeland [34]; feller-bunchers with shear heads operating in young, small diameter stands [21]; multi-stage transportation systems to access biomass over low-standard forest roads [25]; harvest and transportation of untrimmed trees that are trucked with limbs and tops attached to the stem [35, 36]; conventional systems for small tree harvesting for bioenergy [22]; grinding and chipping to meet narrow feedstock specifications [26]; stump harvesting using specialized and modified equipment [16]; and modified forage harvesters and mulcher-balers deployed in poplar and willow plantations [17]. Results of these studies are especially useful to contractors and other producers looking to improve the efficiency of existing operations or offer new services and biomass products in challenging market environments, without high capital investment in specialized equipment (Fig. 3).

Several important themes flow from the results of these studies. Conventional equipment can be successfully adapted to new woody biomass applications. For example, carrying out rangeland restoration in pinyon-juniper woodlands, an eight-wheel forwarder paired with a rubber-tracked skid steer with a shear-head-cleared trees at a rate of 54.6 trees per load, which translated into a payload of 5.08 t/load, at a stump to roadside cost of approximately \$218/acre^{-1} (ac^{-1}) and \$7.56 t^{-1} [34]. In another study using a shear head mounted on a Tigercat 845D-tracked feller-buncher, small diameter

Fig. 3 A beetle-kill salvage operation in Montana, including product sorts for sawlogs, post and pole wood, firewood, and biomass. Because of long transportation distances to the nearest pulp mill, there was not a pulpwood component to this harvest. Photo: Anderson

stems in a loblolly pine (*Pinus taeda*) plantation and a natural mixed pine and hardwood stand were harvested at a productivity of 77.9 and 118.7 t h^{-1}, respectively, with low ground disturbance [21]. In Alabama, conventional whole-tree logging systems were shown to be effective for producing energy chips in small diameter sands, at a cost of \$8.80 t^{-1} in thinning and \$4.73 t^{-1} in clearcutting (stump to landing cost), using smaller wheeled feller-bunchers to match smaller tree diameter [22]. Results in small diameter plantation and natural forest compare favorably with coppice harvesting in short-rotation poplar using modified forage harvesters and modified mulcher-balers, with roadside costs ranging from \$9.98 to \$13.61 t^{-1} in those systems [17].

Processing and transportation systems can also been improved through operations and logistics research. For example, microchipping at the landing can be used to add value and access new markets by meeting narrow feedstock specifications, but this is not without challenges. Using a Precision Husky WTC-26752 disc chipper equipped with an eight-knife disc rather than the traditional three- or four-knife disc, Thompson and Sprinkle [26] documented the cost increases in lost productivity and fuel consumption that would need to be recovered on microchip value (i.e., price), with microchipping reducing the production rate by 10 t h^{-1} and increasing fuel consumption by 15 % over conventional pulp chips. This type of information can help actors across the supply chain evaluate the costs and benefits of in-woods processing compared with processing large chips or roundwood at the facility.

Transportation systems can be improved to reduce costs and access biomass stocks that were previously inaccessible. In many parts of the USA, especially in the west, log trucks have been designed to access harvest sites over low-standard forest roads on steep terrain. These sites are often inaccessible to large chip vans, which are considered the most efficient way to transport chips and hog fuel. In addition to developing new truck designs that can access these sites (e.g., with higher clearance, rear drive wheels and active trailer steering), two potential solutions to this problem are (1) loading slash into large, high clearance dump trucks and delivering it to a central landing where it can be stockpiled and processed directly into large chip vans and (2) grinding or chipping slash on the treatment unit directly into dump trucks, and then delivering it to a central landing where it can be stockpiled and loaded into chip vans using a front-end loader. In a study to compare these options, Anderson et al. [25] found that the two options have similar costs, with roadside to loaded chip van costs of \$23.62 t^{-1} for slash forwarding and \$24.52 t^{-1} for in-woods grinding. Results indicated that slash forwarding is most appropriate for sites with residues occurring in dispersed piles and in-wood grinding is likely to be a more productive and less costly option when slash is densely concentrated on the roadside. Though unconventional, leaving tops and branches attached to untrimmed whole trees delivered to the mill is also an option, and research in Florida showed that the main benefit of this practice is higher in-woods productivity attributable to less processing time, but this comes at a cost associated with purchasing specialized trailers and adding time to trim and bind loads before they leave the landing [35, 36]. Trimming and binding time for trimmed pulpwood was 29 % longer than that of the untrimmed chip-n-saw logs, at 8.7 and 6.2 min, respectively.

For high-value sawlogs and veneer, it is well understood that effective product sorting and merchandizing can enhance value in the supply chain, especially when harvests occur in areas with diverse species and highly differentiated roundwood markets. Timber harvests can have many different sorts on the landing, each targeting the mill or buyer offering the highest price for a particular species and grade. However, the costs and benefits of sorting are less clear for low-grade products, such as pulpwood and biomass for energy, especially when they are produced from forest restoration treatments. Several recent studies have evaluated the use of dedicated concentration yards for sorting as many as seven different roundwood products from such treatments. Chung et al. [38] found value recovery of a modest 5 %, with a general conclusion that benefits are closely tied to forest type and proximity to premium markets, such as those for house logs (i.e., cabin logs). For a similar case, log sort yard operating costs were reported as \$3.74/piece or \$79.53/1000 board ft (mbf) [39], setting a clear threshold for the value that must be recovered to offset costs. In general, the potential benefits of sorting and merchandizing low-quality products hinges on handling and processing costs measured against yield and market price, which can be difficult to predict without high resolution information. Recently, Wang [40] developed non-destructive acoustic technologies to assist in automated sorting for value recovery in this context.

For most thermochemical conversion applications, it is also possible to increase value by reducing moisture content because dry fuel has a higher energy density than wet fuel. However, capturing this value is not as simple as one might expect because of tradeoffs related to weather, climate, markets, vehicle weight limits, and other variables. Cutshall et al. [42] quantified the effects of in-field drying on moisture content and productivity and found that 8 weeks of field drying from August to October in Georgia reduced moisture content from 53 to 39 %, which resulted in slightly better chipping productivity (on a dry ton basis), but results regarding energy content and trucking efficiency were inconclusive. The 600 horsepower Morbark 40/36 drum-style chipper produced pulp chips from 14-year-old loblolly pine at a rate of 38 t h^{-1} for dry wood compared with 34 t h^{-1} for green wood.

The configuration, size and density of piles can have a significant effect on field drying—small piles are more sensitive to weather conditions than large piles, which impacts operations intended to speed field drying or reduce the impact of precipitation events [43]. Under favorable drying conditions, large piles dry more slowly. In this study, moisture content within a large pile of whole tree stems that were piled with intact tops and limbs showed higher within pile variability in moisture content than small piles. At the end of a drying period, stems on the outer layer had a moisture content of 29 % (wet basis), while those in the middle measured 41 % and the trees located at the bottom of the pile measured 49 %. Estimating this pile-size effect accurately has important financial implications when deciding if and how to dry material before processing to capture added value. With regards to transportation, Thompson et al. [37] compared payloads for wet and field dried material and observed that even when using larger-than-typical chip trailers with 123 cubic yard (yd^3) volume for the dried material, the payload was still 16 % below the legally allowed limit, though 10 % higher than payloads obtained using traditional 100 cubic yard trailers. Anderson et al. [25] observed similar results in Idaho with field drying roadside logging slash over 8 months from winter timber harvest to July biomass harvest, which reduced biomass moisture down to 24 %, resulting in some chip vans reaching volume before legal weight. This is generally considered inefficient from a transportation planning standpoint. However, the tradeoff between reaching maximum payload and field drying is closely tied to a variety of cost and revenue factors, especially price incentives for material quality. For example, some facilities incentivize field drying with pricing based on dry weight rather than green weight, while others pay the same price for a ton of wet or dry material. However, for long drying periods, mass loss and biomass degradation due to decay may negatively affect feedstock quality, yield, and value, especially in areas with high precipitation. Conversely, some applications require both a target moisture content and a limited time from cut to delivery, such as wood ethanol technologies that require feedstock be delivered relatively soon after cutting. Understanding the relationships among field drying, moisture content and value is critical in evaluating alternative operations.

When integrating biomass recovery into a work plan, forest contractors often face questions about how biomass operations will affect the costs and productivity of sawlog and pulpwood production, especially when biomass harvest, processing, and transportation occur simultaneously with ongoing roundwood harvest operations (i.e., concurrent or “hot” biomass operations), rather than after roundwood harvest is complete (i.e., two-stage or “cold” biomass operations). This is especially true of whole tree operations, which generate large amounts of slash on the landing. In most cases, the primary tradeoffs between hot and cold operations are related to the fixed costs of mobilizing equipment, system balance, and interaction effects on machine productivity, and potential benefits from field drying [57]. Leaving the material onsite to dry can improve value, but may result in additional fixed costs, such as equipment transportation, being added to a biomass operation when machines (e.g., a grapple loader) are redeployed to the same site. Collecting and processing slash at the landing as it is produced may keep landings clear of slash and reduce mobilization costs, but can interfere with log processing, log truck loading, and site access, reducing sawlog productivity and increasing unit costs for more valuable products. It may also be the case that a hot biomass operation is impossible due to difficult terrain. On flat ground, a large central landing can accommodate many pieces of equipment organized in a complimentary configuration, but in mountainous areas where large landings are difficult to find it may be impossible to co-locate concurrent sawlog and biomass operations. Mitchell [41] describes some work design analysis considerations for processing biomass on an active conventional operation. Machine and process interactions can also result in lower grinder or chipper productivity due to operational delays [25]. Operations research helps managers and contractors predict and mitigate such effects to better configure and balance hot operations and maximize value on cold operations.

Contractors can increase productive machine hours to increase daily production and the efficiency of capital investment in equipment, either by extending existing shifts or adding more shifts. This can have mixed effects on hourly productivity, costs, and safety. For example, Mitchell [51] found little effect of shift schedule on the number of stems cut by a feller-buncher in Alabama, but bunch size was smaller at night than during daylight hours, resulting in an 8.4 % reduction in productivity for the night shift. Furthermore, extended working hours can have negative physiological, psychological, and social impacts on employees, making it important to closely evaluate the effects of alternative shift lengths, shift rotation, and other aspects of scheduling [50].

Innovative Machines

The USFS has a long history of equipment research, especially in the US South [81]. Recent work in this area has focused on the design, fabrication, development, and deployment of new and modified machines for biomass handling, processing, and transportation. As with research to improve processes and practices, the broad objective is to reduce costs and increase productivity, typically by increasing recovery and yield on the treatment unit, densifying material to increase handling and transportation efficiency, and increasing product value with regards to particle size, moisture content, ash content, and other characteristics.

Harvesting production rates on a mass basis ($t\ h^{-1}$) are generally positively correlated with stem diameter. Small stems are lighter and require more handling for the same mass of material and incur higher costs on a mass basis than large stems. This fact typically translates to low efficiency for machines that were designed primarily for large diameter environments working in small diameter stands, especially for timber harvesting. Rummer et al. [58] worked with an equipment manufacturer to optimize a system for harvesting smaller-diameter trees. Modifications were made to a shear head to accumulate a larger load before dumping and to a skidder grapple to accommodate larger felled bunches of smaller stems. Testing on this new harvesting system showed that these modifications can help lower harvesting cost over conventional approaches [21, 23].

Biomass baling can improve handling and transportation efficiency by densifying material into compact bales. Understory stems cleared for fuels treatment, wildlife habitat improvement, or aesthetics are good candidates for baling because they tend to densify well compared with larger diameter woody materials like hardwood treetops. Currently, biomass baling involves two techniques. One requires a two-pass system where stems are severed and mulched in the first step, and then recovered and baled in the second step [28]. The other technique combines these processes into a single pass that severs, chops or mulches, and bales the material [28, 29]. When operating in a thinned southern pine plantation, a baling system produced 7.3 t h^{-1} with a system cost (including forwarding bales to roadside) of \$17 t^{-1}. When operating in a natural southern pine plantation, baling production rates ranged from 1.46 to 6.07 t h^{-1} with system costs of \$34.53 to \$86.36 t^{-1}. Stand characteristics such as planted or natural, and density of understory vegetation, are just two of the many variables contributing to the range of production rates and costs found in these studies. These systems produce round bales that can be handled with forks mounted on a tractor or other conventional agricultural equipment. Bales have an advantage over chipped material in that the bales can be collected and stored in stacks, which has some advantages over handling and storing loose chipped or ground material. Most notably, stacked bales can experience significant drying if stored under favorable conditions. Bales are typically broken apart before use, and some conversion methods may require that the mulched material from the bales be further ground or chipped into uniform pieces before use.

Fig. 4 A John Deere slash bundler. Photo: Mitchell

Bundling, like baling, densifies biomass to improve handling and transportation efficiency. However, bundling results in a “composite log” that retains more of the original physical characteristics of biomass generated from logging operations (Fig. 4) [30]. It does not receive a chopping or mulching treatment and can be handled effectively by conventional log handling equipment, specifically grapples on forwarders, loaders, log trucks, and other machines. A commercial bundler is typically mounted on a forwarder and operates by traveling within a stand to collect logging residues and compact them into a long cylindrical bundle. The “logs” are then forwarded to a landing where they can be stored in stacks, or loaded onto log trucks using a conventional loader. Unlike chippers and grinders that are often idle when trucks are not available in unbalanced operations, bundlers can continue to be productive as long as slash is available for bundling because the bundles can be stored onsite and loaded later.

In a recent study, a commercial bundler was modified to take advantage of the centralized location of logging residues on tree-length logging operations common in the southern USA. The bundler was mounted on a motorized trailer to reduce the costs associated with using a forwarder as a prime mover, which has a high machine rate (i.e., cost per hour) relative to the mounted trailer [31]. In addition to examining production rates and costs associated with this novel configuration, researchers evaluated the added processing activity required to integrate bundling into operations without negatively impacting the production of roundwood products [32]. The trailer mounted configuration produced bundles 8.2 ft long and 11.5 ft long at a production rate of 14.6 and 16.4 t h^{-1}, respectively, at a cost ranging from \$11.25 to \$12.85 t^{-1} for the bundling component of the system.

Harvesting short-rotation woody crops that are managed under a coppice silvicultural system pose unique operational challenges. For example, an initial cut to a single stem may be needed to begin coppice growth. Manual harvesting methods (e.g., brush saw) can be employed if stems are small or if the area requiring treatment is small. However, manual harvesting is costly over large areas and mechanical means are often more efficient. Researchers employed a skidsteer with a shear felling head attachment to initiate coppice responses on a variety of short-rotation woody crop plantings (Fig. 5) [18]. Coppice responses were examined based on the type of cutting mechanism, either shear or chainsaw [62]. Impacts from the harvesting system, such as bark damage and stump damage were also included in the study (and are discussed in the next section), with the skidsteer operating on a variety of sites,

Fig. 5 A John Deere skidsteer mounted with a sheer feller head attachment for harvest and tending in coppice systems. Photo: Mitchell

including bedded, dry, and wet sites, as well as in single-row and dual-row plantings [63]. Overall, these studies showed strong potential to integrate inexpensive skidsteer attachments into coppice systems for tending and harvesting operations. This work is complementary to ongoing equipment development by others, including universities and equipment manufacturers.

Feedstock processing and handling operations vary widely for different conversion technologies. Some technologies are more sensitive to chip size than others. When co-milling wood with coal, Mitchell et al. [82, 83] found that handling processes for biomass chips were nearly as important as the combustion time in influencing co-firing success. A prototype drum-style microchipper was developed and tested to not only meet the size requirement for the coal boiler residence time, but also to create chips that would flow effectively along a conveyor belt when blended with coal. In a later study, a disc chipper was modified to produce microchips in the field [26]. Chipper modifications included changing and configuring the number of knives, knife length, knife angle, and the number of chip breakers and paddles to improve production rates and meet a narrow-size specifications. A range of variables affected chipper and grinder production rates, such as the form and moisture content of the raw material, and the horsepower of the equipment. A chipping and grinding calculator [27] was developed to help predict the impact of these variables on production.

As mentioned earlier, Cutshall et al. [42] found that allowing trees to transpirationally dry during late summer and early fall in Georgia resulted in a moisture content reduction of 14 %. However, the dried material had lower bulk density compared with green material, raising the possibility that trucks reached maximum volume before maximum legal weight, which is inefficient from a logistics standpoint. This is also often true of dried bundles and bales. Chip vans with a 19 % larger capacity (123 yd^3) compared with traditional (100 yd^3) chip vans were designed and tested for chips made from field dried trees. Results indicated that the payload increased by only 10 %. One potential explanation for the reduced load density was that chips from dried material did not compact as effectively as wet chips during truck loading, leaving more air pockets and resulting in lower bulk density on a dry weight basis. Further research is needed to improve the efficiencies of using larger chip vans, including both new equipment and new processes, such as conveyors with accelerated feed velocity to improve compaction.

Hauling whole, untrimmed, pulpwood was examined as a way to improve biomass transportation and reduce onsite handling and processing costs [36]. This unusual practice occurs in Florida, where trees are processed into biomass and pulpwood after delivery to the facility rather than at the harvest site. In the woods, trees are loaded onto specially designed log trailers with branches and tops attached. Trimming is only used to make the load legal for hauling on public roads by removing material hanging from the truck. Trailer modifications used by contractors in the study included the addition of a pan near the rear of the trailer, the addition of a cross member at the back of the trailer, and side panels between the last two bolsters on each side to help contain sweeping branches. The pan keeps the tops and limbs from dragging under the trailer and the cross member helps lift the tops to keep the rear lights and license plate visible. This study found average payloads for untrimmed loads were within half a ton of payloads for trimmed loads.

Biomass conversion technology is addressed in detail by Rudie (this issue), but several studies have used operations research methods to evaluate conversion system performance and are worth mentioning here. Though outside the scope of conventional forest operations, there has been intense interest in the possibility of deploying mobile and modular thermochemical conversion systems to process forest biomass into energy-dense products that can be shipped more efficiently to distant markets [45]. Specifically, pyrolysis systems heat biomass under low oxygen conditions to produce gas, bio-oil, and char outputs that can be used in their raw form or as precursors in the manufacture of higher-value products (Fig. 6) [46, 47]. Interest in the forward deployment of these systems has generally outpaced technological advances and market development that make it possible at commercial scale [59], but early tests show promise. During a 22-day operations study at a sawmill in Colorado, Kim et al. [48] observed shift level system financial performance fluctuating between a net present value of −$536,031 (loss) and $467,353 (gain), extrapolated over a 10-year project period, with profitability highly dependent upon conversion rate, system productivity, and biochar price. Gu and Bergman [49] found that these systems can reduce net greenhouse gas emissions, depending

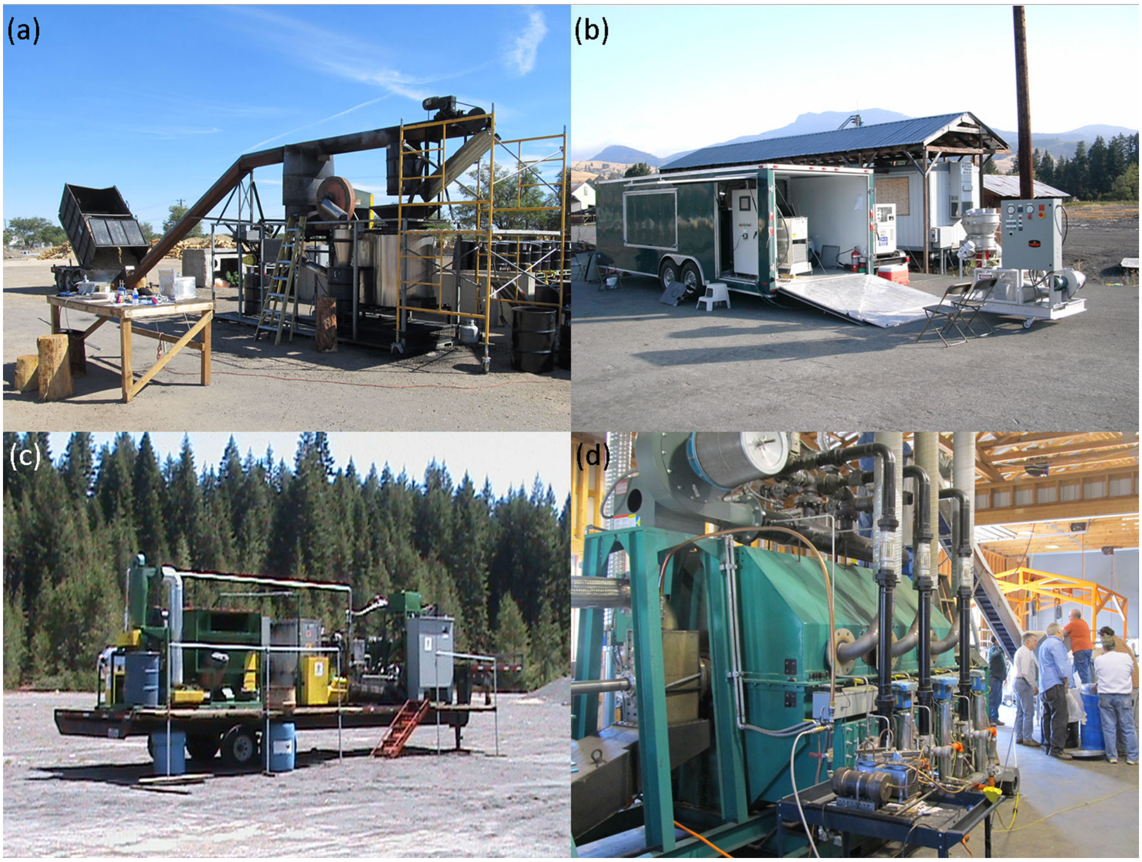

Fig. 6 Four different mobile and modular pyrolysis systems evaluated by USFS researchers for in-woods processing of forest biomass, producing: **a** biochar only, **b** biochar, bio-oil, and synthesis gas, **c** biochar, bio-oil, and synthesis gas, and **d** biochar and energy gas. Photos: Anderson

on product substitutability, market share, and conditions of deployment. More broadly, this work highlights the importance of studying these systems in industrial environments using operations research methods, in addition to conducting economic analysis based on engineering specifications and predicted (rather than observed) performance. Researching these systems in real world deployments can provide precise energy, cost, and emissions data to drive scientifically based evaluations of environmental costs and benefits, including life cycle assessments. Scientists and engineers of the USFS have worked to integrate operations and logistics research effectively into biomass conversion technology research and development in a variety of settings.

Sustainability in Operations and Logistics

Environmental sustainability is a major focus of operations research in forestry, particular with regards to impacts on soil, water, regeneration, and more recently, air pollution and greenhouse gas emissions. Research focused on sustainability across the supply chain is highlighted in other papers in this issue (e.g., Scott and Page-Dumroese), but recent operations research specifically focused on environmental impacts and ecosystem restoration is summarized here.

A wide range of best management practices (BMP) exist for minimizing the negative impacts of biomass production [44]. For example, Wear et al. [64] compared the relative effectiveness of alternative BMP to prevent erosion and sediment delivery to streams following logging, including slash, mulch, and silt fence options. Results of intensive field sampling for sediment delivery on experimental plots showed that such treatments used at stream crossings were effective in reducing the amount of sediment entering streams after harvest, and that slash and mulch options were more effective and less costly than silt fence. With regards to the impacts of biomass harvesting onsite productivity, soil properties are obviously important, and harvest effects have been effectively evaluated in rigorous experimental operations studies. In one examination of forest biomass harvest in aspen stands in Michigan that used stem only and whole tree systems, including whole tree removal with forest floor removal, sandy soils were associated with reduced above-ground biomass production following harvest, but no negative effect was observed on clayey and loamy soils [65]. In coppicing systems, De Souza et al. [62] observed different levels of damage caused to stumps by chainsaw and shear harvest methods, which can have negative impacts on coppice regeneration. Damage was quantified by visual inspection of the intensity of bark damage classified in quartiles of the circumference of the stump damaged (0 % to >75 %), and results indicated that the shear head caused more damage to the bark of the stumps compared with chainsaw cutting, which was predominantly in the "less than 25 %" damage class.

Compared with conventional silvicultural systems that include timber production as a primary objective, fuel, and restoration treatments, both with and without product recovery, have received less attention in operations engineering. However, as discussed in the introduction, operations implemented primarily to reduce fire risk and deliver forest health and ecosystem restoration benefits have become a major emphasis on federal lands. Removal of heavy fuel loading, woody species encroaching on rangelands, and trees killed by insects, fire, and disease are particularly important to the USFS, and represent a potential source of biomass feedstock for bioenergy, biofuels, and bioproducts. Removal of pinyon-juniper from rangeland has been a fruitful area of research for new applications of innovative equipment such as masticators, balers, bundlers, and harvesters [19, 66]. Mastication and thinning with pile burning are common treatments for pinyon-juniper encroachment, but have been shown to increase invasions by non-native plants (e.g., musk thistle (*Carduus nutans*) and cheatgrass (*Anisantha tectorum*)), alter surface fuels in both favorable and unfavorable ways, depending on the treatment, and alter soil microbial communities [33]. These results point to the need to better understand potential ecological effects of a wide range of treatment options. Recent projects have also focused attention on large-scale treatment of forests experiencing high mortality from mountain pine beetle (*Dendroctonus ponderosae*), particularly quantifying the effects of widespread mortality on productivity, costs, and safety [84], as well as on harvesting productivity and soil disturbance associated with mechanized harvest treatments to limit insect damage in hardwood forests [67]. A wide range of machines and configurations are available for fuel treatment, and significant effort was focused on fuel treatment operations research from 2000 to 2010 [20, 58].

In the context of global climate change, the greenhouse gas implications of alternative forest biomass feedstock production systems have become central to bioenergy sustainability [73, 74]. The environmental performance of products made from biomass includes the impacts of feedstock production and logistics, as well as all other components of the product supply chain. Life cycle assessment (LCA) is a widely accepted method of quantifying such impacts and comparing them in a supply chain context to substitute products like fossil fuels and products made from petroleum [72]. Though LCA of biomass harvest and the bioproduct supply chain is beyond the scope of this paper, it is worth noting that LCA often includes forest operations data to inform cost, energy, and emissions calculations. For example, in a recent study of redwood (*Sequoia sempervirens Lamb. ex D. Don Endl.*) forest management, on-unit primary transportation from stump to truck accounted for 50 % of the total environmental impact of production and logistics, compared wiht the 20 % of the impact attributed to on-road transportation, 17 % for loading, and 12 % for combined felling and processing [39]. A study of biomass co-firing in Colorado found that, although emissions from biomass logistics were significantly higher on an energy unit basis than those for coal, co-firing biomass from restoration treatments resulted in net emissions benefits, especially with regard to methane and particulate matter emissions [75]. In addition to emissions from fuel combustion, forest operations also produce particulate matter emissions in the form of dust, which can have negative impacts on air quality and human health, as well as feedstock quality, with airborne deposition resulting in higher ash content. Mitchell [76] quantified nuisance dust emissions for clean chipping in Alabama and found relatively low emissions, with residues padded on the landing likely limiting airborne particles compared with operations on bare soil.

Integration and Outreach

More than ever before, USFS research in forest operations and biomass logistics is integrated with research focused on other areas of the biomass supply chain, and embedded within research consortia that span the biofuels and bioproduct supply chain and its full economic, social, and environmental impacts. Over the past decade, research and development integration of biomass production, logistics, conversion technology, end use, and associated ecological, economic, and social analysis has been driven by agency-level coordination, including the establishment of five USDA Regional Biomass Research Centers, which serve to complement and coordinate Agricultural Research Service and USFS research across the country and help accelerate the establishment of commercial, region-based biofuel supply chains using agricultural and forestry-based feedstocks. National-level coordination among federal agencies has also intensified, including establishment of the US Biomass Research and Development Board, which synchronizes research and development of biobased fuels, products, and energy across eight federal agencies, including USDA. Grant programs of the USDA National Institute of Food and Agriculture (NIFA), like the Biomass Research and Development Initiative (BRDI) and the Agriculture and Food Research Initiative's (AFRI) Coordinated Agricultural Projects (CAP) program, have funded large and robust partnerships that include diverse groups of industry, academic, and government collaborators by design. In this environment, USFS researchers have provided leadership and expertise in operations and logistics on several integrated BRDI projects, and major CAP projects including the Northwest Advanced Renewables

Alliance (NARA) and Bioenergy Alliance Network of the Rockies (BANR).

Almost all of these integrated projects include significant education, extension, and technology transfer components, working to disseminate and operationalize research results. Because of their applied focus and close connections to landowners, foresters, contractors, and industry, USFS researchers in forest operations and woody biomass logistics are among the most prolific in terms of decision tool development, outreach, and technology transfer, especially in the Southern Region. For example, since 2000 the Operations Research Unit of the USFS Southern Research Station has developed a wide range of practitioner-oriented tools including the Forest Residue Trucking Simulator (FoRTS), the General Ground-Based Harvesting System Analysis tool (GenHarModel), the Green Ton Converter, and the Machine Rate Calculator (MRCalculator) [60]. Recent efforts across USFS R&D also include BioSAT (Zalesny et al., this issue), the chipping and grinding production rate calculator [27], outreach to landowners [58], webinars and practitioner-oriented publications [61], a biomass site assessment tool [52], and a suite of geographic information system (GIS) tools to integrate remote sensing and landscape analysis with operations and tactical procurement planning [53–55].

Future Research

This review is not exhaustive, but highlights many recent and ongoing efforts by USFS R&D to address the most prominent questions and barriers surrounding the harvest, processing, transportation, and storage of woody biomass from forests. Several areas of research stand out as needing more attention. Perhaps the most critical need for the agency based on expenditures on wildfire suppression, which now consume over half of the USFS budget, is better understanding the costs, benefits and impacts of mechanical fuel treatment and associated suppression cost savings [69–71], including treatments that combine prescribed burning with harvest or mastication [68]. To some degree, this will require developing and operationalizing fuel treatment options that are technically possible, but not yet widely deployed [20].

Another major need is to continue to develop new technologies and approaches to drive down the cost of production for “designer” feedstocks, such as low-ash, dry microchips for liquid fuel and bioproducts production. In this area, operations research must keep pace with the rapid rate of innovation in conversion technology, which is often punctuated by leaps in technology that fail to gain commercial traction in the forest sector due to economic and operational constraints. Similarly, operations research should continue to inform the techno-economic analysis of new technologies with empirical information to improve assumption-driven models. Reliable and accurate information on feedstock production costs, drying, variability in chemical and physical properties, and other operations and logistics constraints are needed, as are analyses of equipment deployed in industrial settings for extended periods. There is also a need to combine such research with spatial analysis of supply chains at the tactical, operational, and strategic levels to guide facility site selection and scale, and also efficiently and sustainably supply facilities with biomass once they are built [53, 56].

Conclusions

In 2007, Heinimann [85] issued a challenge to the global forest operations community to improve its scientific visibility, realign research to address relevant future challenges, and strengthen its confidence in providing solutions to critical problems in the forest sector. National goals of providing sustainable and efficient forest biomass management and production systems have provided a strong catalyst for USFS R&D to meet this challenge, which has been facilitated by cooperation with ARS through the USDA Regional Biomass Research Centers. Diverse research, development, demonstration, and outreach in this field over the past 5 years has improved logistics systems for woody biomass, provided new cost and equipment information and options for field processing biomass, and improved the environmental outcomes of forest biomass utilization. However, as needs evolve, researchers in this field must strive to adapt research, development, and dissemination to address relevant future challenges and strengthen capabilities to solve critical woody biomass problems in the forest sector.

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