Journal of Forestry, 2019, 1–19
doi:10.1093/jofore/fvz030
Research Article - policy
Received July 11, 2018; Accepted April 12, 2019
Advance Access publication May 20, 2019

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Research Article - policy

Forest Sector Research and Development Capacity

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Abstract

Current trends in the nation's forest-sector research capacity were analyzed in terms of funding and number of scientists, and compared with prior data in the National Research Council's 2002 report, *National Capacity in Forestry Research.* The total number of professors at institutions accredited by the Society of American Foresters, research scientists at the USDA Forest Service, and forest researchers in forest industry decreased approximately 12 percent since 2002. In 2016, there were an estimated 1,224 professors and 540 Forest Service research scientists, for a total of 1,764 scientists. Total estimated research funding in 2015 for universities, private sector, and USDA Forest Service, including appropriations from federal grant programs from the USDA National Institute for Food and Agriculture, National Science Foundation, National Aeronautics and Space Administration, and Department of Energy was US$598 million—a nominal increase over 2002, but a decrease when accounting for inflation. The proportion of reported scientists' disciplines shifted notably from production subjects to broader ecosystem services and forest health subjects, as well as from more applied to more fundamental or basic research. The data indicated that the nation's forest research capacity continues to erode, leading to declines in research development and innovation, and putting at increasing risk the future health and productivity of America's forests.

Keywords: forest research, research capacity, research funding, forestry, forest products, United States

Over the past 25 years, the National Research Council of the National Academy of Sciences has issued two reports on the nation's research capacity in the forest sector (National Research Council 1990, 2002). The latter report noted,

> In the committee's opinion, forestry research capacity is at a crossroads, if not a precipice. … [there have been] significant declines in real research capacity, fragmented cooperation and poor communication among the principal providers and users of forestry research, inadequate support of both foundation and emerging disciplines, and little strategic planning to address future forestry research needs. (pp. viii–ix)

While observers and advocates of the forest sector may perceive further declines in research capacity and shifts in research priorities since the 2002 report was published, a rigorous effort to examine these questions had not been undertaken until recently.

Two new projects have taken a fresh look at forest-sector research capacity. First, a Blue Ribbon Commission on Forest and Forest Products Research & Development in the 21st Century was convened by the US Endowment for Forestry and Communities to

Published by Oxford University Press on behalf of the Society of American Foresters 2019.
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Management and Policy Implications

Decreases in research personnel and in inflation-adjusted research funding document the recent decline in the nation's forest resources research capacity. Although improving the management of private and public forests using today's available science and today's cadre of forest managers could help sustain the current health and productivity of America's forests in the near-term, new science and new scientists will be essential to protecting future commodity and ecosystem service values from forests in the long-run. Substantial sector-wide collaboration among key actors—agency, university, and industry leaders and elected officials—will be needed to reverse recent trends to protect future commodity and ecosystem service values of forests.

examine the challenges facing the forest sector and the potential for its future growth (US Endowment 2017). A slowdown in innovation—precipitated by research and development (R&D) declines—was linked to impacts on forest management that jeopardize forest stewardship and forest-sector competitiveness in domestic and global markets. Ultimately, the commissioners concluded,

> Major changes in forest-sector research and development are needed to secure for the future the benefits that America's forests provide. (US Endowment 2017, p. 5)

The second project examined resources and capacity for forest R&D as part of the US initiative to periodically measure, monitor, and report on forest conditions and trends across a broad range of ecological, economic, and social criteria and indicators established through the Montréal Process for the Conservation and Sustainable Management of Temperate and Boreal Forests. The US has been an active member of the Montréal Process since its inception in 1996, reporting on the state of the nation's forests three times, with a fourth assessment report planned for release in 2018 (USDA Forest Service 1997, 2004, 2011). Under Criterion 7.—Legal, Institutional, and Economic Framework for Forest Conservation and Sustainable Management, Indicator 7.4.b.[1] addresses the "Development and application of research and technologies for the sustainable management of forests." The most recent efforts to measure, monitor, and report on this indicator showed that funding for forest R&D has remained fairly stable in real (i.e., inflation-adjusted) terms over the past several decades. However, the costs of forest-sector R&D have risen, whereas capacity in terms of the numbers of forest-sector scientists and professors has declined (McGinley and Cubbage 2017, Cubbage and McGinley 2018).

To analyze further the state of and trends in forest R&D and the implications for the nation's forest sector, we combined key data sets from these two distinct efforts and filled in some of the data gaps. In defining policy as a purposive course of action or inaction taken by an actor or set of actors to deal with an issue or matter of concern (Anderson 2015, Cubbage et al. 2017), it follows that the funding and personnel designated for any public program reflect in part the priority that policy- and decisionmakers place on the associated issue or subject matter. Carefully tracking forest research funding and personnel levels provides important indicators of public policy priorities at national and subnational levels. Given the relation between research and management, data on research funding and personnel also can provide early signals of potential effects that shifts in priorities may have on forest health and benefits to people over time.

Methods

Key metrics on research capacity from the National Research Council reports (NRC 1990, 2002) were extended through 2014 and beyond for the US Endowment (2017) and Indicator 7.4.b. of the forthcoming *National Report on Sustainable Forests* (Cubbage and McGinley 2018). Specifically, we focused on the state of and trends in researchers and funding available for forest-sector R&D. The particular methods and sources used are described briefly in this section.

Researchers

Forest research in the US is conducted primarily by three groups: university faculty in forestry and forest-related sciences, USDA Forest Service (FS) research scientists, and forest industry researchers.

University Forestry and Forest-Related Faculty

Information on university faculty came from two sources: databases and records from USDA's National Institute for Food and Agriculture (NIFA) for US

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Endowment (2017); and a canvass of professors at accredited forestry schools and programs for Cubbage and McGinley (2018). NIFA's Food and Agriculture Education Information System (FAEIS[2]) compiles nationwide higher-education data for the life, food, veterinary, human, natural resource, and agricultural sciences. Since 1993, FAEIS has been the most comprehensive and reliable source for information on enrollments and faculty for universities with these programs. However, some universities recently have fallen several years behind in entering their program data into FAEIS. Comprehensive data for forestry programs from FAEIS after 2012 are lacking—a challenging situation itself, because long lags and data gaps significantly impede contemporary capacity assessments.

In addition to university faculty data from FAEIS, a complete canvass of university tenure-track and nontenure-track professors at universities with Society of American Foresters (SAF) accredited forestry curricula (n = 45)[3] was conducted in 2016 (Cubbage and McGinley 2018). All forestry, wildlife, and solid wood products faculty listed in the "forestry" programs and schools and related departments, along with similar faculty from broader colleges and universities (e.g., schools of natural resources) who had "forestry" as their primary research or teaching role, were entered into a database. Recorded university professors were then categorized by the seven Montréal Process criteria spanning ecological, economic, and social forest aspects based on their main area(s) of research as indicated in their online research profile, publication records, and other sources. University instructors, part-time faculty, and emeritus and adjunct professors were not included in the database, mainly because they are not consistently reported across institutions, making them more difficult to measure and regularly track over time. Likewise, faculty whose expertise was peripheral to forestry, such as faculty teaching geology, geography, pulp and paper science, or parks and recreation that did not direct forestry research were not included in this count.

FS Research Scientists

Information on FS research scientists came from multiple sources. Staff in the Office of the FS Deputy Chief of R&D queried internal databases and provided annual performance and reporting documents on scientists, by scientific discipline from 2002 through 2015. In addition, similar to university professors, a complete canvass of FS research scientists was conducted in 2016 using information gleaned from FS R&D websites, reports, and other related sources. Only full-time researchers or senior research staff were included for replicability. Recorded research scientists then were categorized by the seven Montréal Process criteria according to their main area(s) of research and expertise as indicated in their online research profiles, publications records, and other sources.

Forest Industry Researchers

Data on forest industry research personnel are very sparse, due in part to the reduction and reorganization of previously integrated forest products firms, many of which historically maintained internal research programs. We estimated current forest industry research capacity based on informal discussions with some key leaders of the industrial forest sector, Sustainable Forestry Initiative® (SFI)[4] documents on certified participating members, and data from the National Council for Air and Stream Improvement (NCASI).

Funding

Forest research funding comes from federal and nonfederal sources. The primary federal sources are delivered through direct appropriations to FS R&D and through specific federal grant programs at NIFA, National Science Foundation (NSF), Department of Energy (DoE), and National Aeronautics and Space Administration (NASA). These sources all had at least some data available on research funding over time. Additional funding comes from other public agencies at federal, state, and local levels; private foundations; businesses; and nongovernment organizations. However, data for many of these sources are sparse, often anecdotal, and incomplete—both chronologically (because of many divestitures and mergers over the past decade) and across all players (e.g., some private companies and organizations do not divulge R&D expenditures).

FS R&D

Data on FS R&D funding were gathered from agency performance and monitoring reports for fiscal years 2000–15. Detailed data for fiscal years 2008–15 were provided by the Office of the FS Deputy Chief of R&D. Detailed data on research allocations prior to 2008 were not available, principally because FS R&D shifted budget reporting then to use seven "strategic program areas" that did not correlate with the program definitions used in National Research Council (2002), and which could not be "back-cast" into the current categories.

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NIFA

NIFA is the extramural funding agency within USDA's Research, Education, and Economics Mission Area. NIFA administers several grant programs that provide financial support for forestry research, education, and extension activities. These programs include capacity grants for land-grant universities and other public institutions that are based on statutory formulas (e.g., McIntire-Stennis [M-S] Act of 1962 [a k a M-S Cooperative Forestry Research Act], Smith–Lever Act of 1914 [a k a Agriculture Extension Act], and the Renewable Resources Extension Act of 1978). NIFA also administers the Agriculture and Food Research Initiative (AFRI)—the largest of its competitive grant programs. AFRI provides awards for forest R&D to colleges and universities, state agricultural experiment stations, and federal agencies, among many other research institutions, organizations, and individuals. NIFA personnel queried internal databases and provided comprehensive and detailed financial data from internal databases on awards for forestry and forest-related R&D from all of its grant programs from 2002 to 2015.

NSF

NSF supports research and education in all scientific and engineering disciplines. It maintains an online, searchable database of grants awarded to researchers (http://nsf.gov/awardsearch/). We conducted a broad search of this database using two key words—"forest" and "wood"—across the entire time history available. The search identified 8,693 awards from 1952 to 2015 with one or both key words in the title or abstract. The title of each project funded and its abstract were read and evaluated against several factors including research location and study topic or focus to determine whether the grant was germane to forest research and wood science research in the United States (core to the Endowment's project). Grants were excluded for the following reasons:

- Research projects outside the United States, except for projects based in Puerto Rico and the western Pacific Islands politically affiliated with the US, and grants to two major US-led forest research institutes—Smithsonian Tropical Research Institute (Panama) and La Selva Biological Station (Costa Rica).
- Grants with "wood" or "forest" used in a proper name (e.g., Woods Hole Research Center), unless their work actually focused on forest science or wood science issues.
- Projects whose title and/or abstract did not describe work directly related to contemporary forest or wood-related scientific issues, for example, archeological studies of wood buried during the Triassic period or population studies of wood-boring marine worms.
- Projects that provided summer instruction for secondary school teachers.
- Projects whose title and abstract were only marginally related to forest or wood research. For example, grants to acquire new scientific equipment may have been justified by describing its use across a wide range of scientific fields at a university, with forestry being one of a half-dozen possible fields mentioned; such were deleted. On the other hand, if the equipment was only for use by a forestry laboratory or experimental forest, the project was retained.

After screening was completed, 3,243 awards remained (37 percent of the original "hits"). This set was deemed the core NSF support for basic research supporting forest and wood sciences over 55 years.

NASA

NASA funds forest-related research primarily focused on remote sensing applications of ecological issues, including determining long-term forest trends in the context of climate change, modeling species distributions, and understanding the role(s) of forests in the carbon cycle. Information on NASA grants awarded to researchers as of 2007 are maintained in an online, searchable database (http://www.research.gov). Similar to the search of NSF awards, we conducted a broad search of NASA grants using "forest" and "wood" as key words. The search identified 305 awards from 2007 to 2015 with one or both key words in the title or abstract. Following the same screening criteria applied to NSF grants, 81 awards remained (27 percent of the original hits) after review and were considered to be the core NASA support for forest research germane to the US for the time period examined.

DoE

DoE funds research of interest to the forest sector that is primarily focused on growing and converting woody biomass into transportation fuels and other energy products. Information about programs and funding levels was obtained from online agency budget documents and program justification statements. In the Biological Research area, DoE's program in genomic science focused on plants that can be sustainably grown and harvested for their cellulosic biomass as feedstocks for liquid biofuels production. The program not only covers research on agricultural crops, such as sorghum and switchgrass, but also includes research on poplars, willows, and eucalypts. Some of this work is done

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in-house at DoE national laboratories and bioenergy research centers and some by university and other partners. DoE budget documents indicate the biofuels program was funded consistently at US$75 million/year from 2008 to 2015, but these documents do not break out funding for tree species versus nontree species or research focused on sustainable management and production of biomass versus conversion of biomass into biofuels.[5]

Universities

Funds for university forestry and forest-related research generally come from three main sources: (1) state legislature appropriations for public universities; (2) NIFA capacity grants to institutions; and (3) other grants to individual faculty members and students from other public and private sources. Unfortunately, for the purposes of this project and for tracking university forest research capacity in general, there is no single database or combined reporting system for university forest research funding sources.[6] Federal funding of university research was captured through the review of federal grants programs.

State and other nonfederal funding for public university forest research was determined from data on the matching funds reported for M-S capacity grants to state forestry schools and colleges. Program guidelines require participating institutions to declare nonfederal matching funds equal to or greater than the M-S grant. NIFA staff queried internal databases to provide detailed data on the matching funds reported by M-S institutions for 2012–16.

Forest Industry

Comprehensive data on forest industry internal funding and support for R&D are not widely available. Data through 2001 are available from the National Research Council (2002) report on forestry research capacity. Summary data on internal and external industry support for forest research are available from SFI's participating members. Data on research funded by SFI program partners were provided by SFI staff for 2007–15 and from summary reports. Data on funding levels for NCASI were gathered from summary reports. Additional information on forest industry research investments was gathered through informal discussions with key forest industry leaders.

Results

Number of Researchers

From 2002 to 2016, there was an estimated 15 percent decrease in scientists—at least 317 people—in the major forest-sector research institutions in the US (Table 1). Professors at SAF-accredited university forestry schools and programs declined from 1,361 in 2002 to 1,224 in 2016. The FS also reported a decrease from 618 to 500 permanent research scientists between 2002 and 2016. Our canvass of FS research stations compared to National Research Council (2002) data indicated a slightly larger decline than that determined from official FS reporting, but our canvass of scientists (Cubbage and McGinley 2018) and the National Research Council (2002) data were not directly comparable because of slight differences in scientist definitions. Forest industry research capacity also has declined, estimated at 62 in 2016, down from 124 in 2002 (National Research Council 2002).

In 2016, accredited forestry schools and programs listed 1,224 persons with PhD degrees or titles of Assistant Professor, Associate Professor, or Professor who listed their expertise in forestry and forest-related teaching, research, or extension. In contrast, universities reported 1,361 such scientists in 2002. At that time, faculty functions were identified as 44 percent teaching, 42 percent research, and 14 percent extension. University forest research capacity decreased by 137 professors from 2002 to 2016, or an overall decline of 10 percent. Based on the 2002 proportions, the 2016 tally would include approximately 540 research full-time equivalents (FTEs), 540 teaching FTEs, and 150 extension FTEs, putting university research capacity roughly equivalent to FS research capacity when teaching and extension activities are excluded.

Data on FS R&D's research scientist personnel trend by job series span 30 years and demonstrate a substantial decline from 985 scientists in 1985 to 503 scientists in 2015 (Table 2). National Research Council (1990, 2002) documented the larger, longer-term decline in FS research scientists beginning in the mid-1980s. Data in Table 2 reflect how agency research capacity was affected further by the Great Recession, which began around December 2007 and ended around June 2009. Specifically, in 2006, the agency had 583 researchers; that number had dropped to 482 by 2010 (a 17 percent drop). By 2015, with the economic recovery well under way, the agency had 503 researchers—a recovery of 21 individuals, but still down 14 percent compared to 2006.

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Table 1. US forestry scientists and professors by institution and criterion, 2002 and 2016.

	Montréal Process Sustainable Forest Management Criterion							
Year/Institution	1: Biological Diversity	2: Productive Capacity	3: Ecosystem Health	4: Soil and Water	5: Carbon Cycles	6: Socio-Economics	7: Legal & Policy	Total
2016								
University								
Number	453	141	119	113	8	353	38	1,225
Percentage	37	12	10	9	1	29	3	100
Forest Service								
Number	159	49	160	41	6	115	10	540
Percentage	30	9	30	8	1	21	2	100
2016 total								
Number	612	190	279	154	14	468	48	1,765
Percentage	35	11	16	9	1	26	3	100
2002								
University								
Number	318	221	128	186	77	293	138	1,361
Percentage	23	16	9	14	6	22	10	100
Forest Service								
Number	122	161	166	92	43	90	27	701
Percentage	17	23	24	13	6	13	4	100
Private								
Number	10	75	5	22	3	10	0	125
Percentage	8	60	4	18	2	8	0	100
2002 total								
Number	450	457	299	300	123	393	165	2,187
Percentage	21	21	14	14	6	18	8	100

Examining the regional distribution of tallied forestry research capacity at universities and FS R&D demonstrated that the South had the most professors, with 492, or 40 percent of the total in the country. The North and West had more FS researchers, however, with 38 percent in each region and only 24 percent in the South. Regional differences across sectors were balanced out when university and FS research capacities were considered together, with the South representing 35 percent of the total number of professors and scientists. The North had 33 percent, and the West had slightly less of the total forestry research capacity at 32 percent. These percentages did not change substantially between 2002 and 2016.

In the industrial forest sector, internal research capacity has declined due in large part to the reduction in and reorganization of most major forest industry firms. We estimated that researchers employed by forest industry totaled 62, having decreased by at least half from the 124 tallied in 1999 as reported by National Research Council (2002). Our estimate here was based on SFI data on corporate program participants and informal conversations with some key industry leaders.

Other capacity includes instructors and emeritus and adjunct professors, as well as research technicians and other staff who conduct and contribute to forest research capacity at public and private universities and colleges but who are not consistently reported and tracked across institutions. Also, there are approximately 20 universities with non-SAF-accredited programs with forestry faculty in their programs that are members of the NAUFRP, but because the FAEIS data for those institutions are not complete and because they are not accredited by SAF, their capacity was not included in the data reported here. Additionally, the FS has approximately 2,000 technical and administrative staff who contribute to the agency's scientific capacity through field data collection and management, laboratory work, infrastructure maintenance, and many other capacities. Last, there are other public and private organizations that conduct and contribute to forestry and forest-related research. For instance, in 2016 NCASI employed approximately 80 forest scientists and engineers who contributed to industrial forest research needs. Most of these focused on pulp and paper or industrial pollution prevention research, not forest management.[7] The

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Table 2. USDA Forest Service Research & Development scientist cadre, by top 12 job series.

Top 12 job series	1985	1995	2005	2010	2015	Percentage change	
						1985–2015	2005–15
Forester	350	138	146	112	104	–70	–29
Entomologist	70	38	33	25	27	–61	–18
Forest products technologist	63	25	21	13	18	–71	–14
Plant pathologist	50	35	23	15	13	–74	–43
Wildlife biologist	42	44	34	30	25	–40	–26
Chemist	41	21	17	10	10	–76	–41
General engineer	32	29	18	14	14	–56	–22
Geneticist	31	19	21	13	14	–55	–33
Biologist	30	14	22	12	19	–37	–14
Mathematical statistician	30	14	12	11	10	–67	–17
Ecologist	9	46	93	89	114	+1,167	+23
Plant physiologist	26	34	31	21	19	–27	–39
All other job series	211	150	126	117	116	–45	–8
Total	985	607	597	482	503	–49	–16
Percentage of scientist cadre in top 12 job series	78.6	75.3	78.9	75.7	76.9		

Department of Interior Bureau of Land Management and Fish and Wildlife Service also perform research. However, obtaining and separating out the amount related to forests were not possible. Data on these broad types of research capacity are even more dispersed and difficult to reliably track and parse out than those that were measured and reported here, nor have they been reported in any previous efforts.

Scientists Classed by Disciplines

The total efforts of researchers associated with universities, federal government, and industry shifted from 2002 to 2016, continuing a longer-term trend toward proportionately more researchers focusing on the biological diversity of forests, including forest ecology, biology, genetics, and wildlife (Montréal Process Criterion 1; Table 1). Researchers focusing on socioeconomics (e.g., production and consumption of wood resources, economics, forest values and perceptions) and ecosystem health (e.g., fire, pathology, entomology, climate change) also increased proportionally during this time period. These trends reflect shifts in public priorities and policy toward more and multiple uses and values associated with forests and their protection, particularly on federal lands.

In contrast, from 2002 to 2016, fewer researchers focused on the productive capacity of forests (e.g., forest management, harvesting, silviculture, monitoring, and inventory). This research area is fundamental to both private landowners and public land managers, particularly in terms of the sustainability of traditional and new commodity raw-material flows from forests. The number of researchers who focused on laws, policies, and institutional frameworks also decreased, despite the merits of this research area to private landowners, for instance, in terms of forest property rights and taxation, and public–private issues, including partnerships for managing lands and resources across different ownerships.

Shifts in forest research capacity were reflected in changes in FS research scientist job series distributions as well (Table 2). In 2015, ecologists represented the highest proportion of research scientists in the agency at 23 percent, followed by foresters (21 percent) and distantly by entomologists (5 percent). Ecologist was the only job series that grew between 2005 and 2015, rising from 93 to 114 scientists. Ecologists contribute significantly to understanding fundamental forest factors, such as those associated with biological diversity under MP Criterion 1, as well as forest health, productivity, and other issues addressed through the MP Criteria (Table 1). In contrast, between 2005 and 2015, four clusters of FS expertise lost more than one-third of their researchers: (1) forester; (2) entomologist and plant pathologist; (3) forest products technologist and chemist; and (4) geneticist, biologist, and plant physiologist. The first two clusters are critical to sustainable forest management, forest health and productivity, and resiliency to disturbances such as fires and insect and disease outbreaks. The third cluster encompasses the capacity to move fundamental or basic science on wood properties into innovations in products critical to forest industry manufacturing and jobs. The fourth

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cluster includes expertise to increase forest productivity for timber, to identify and understand unusual patterns in tree mortality, and to develop ways to improve tree resistance to health threats.

Overall, the shift in university faculty and FS scientists toward biological diversity and away from productive capacity (Tables 1 and 2) reflected trends in public policy priorities, as posited in our introduction. For decades, Congress and state legislatures have continued to provide broad mandates for forestry research, but with increasing focus on ecosystem services and forest health, as manifested in policy implementation by FS, NSF, NIFA, DoE, NASA, and public universities. These trends were tied to rising public demand for the production of a broader set of goods and services from forests; increasing focus on federal lands and away from privately owned forest lands; and an implicit depreciation of commodity production research. Additionally, modern forest science and scientists have become increasingly specialized, shifting from more applied to more fundamental or basic sciences, and moving away from the broad categories of Forester or Forest Scientist toward scientific specialties that have applications to forests and forestry (e.g., landscape ecologist, hydrologist, soil scientist). Tightening constraints on federal and state appropriations for forest research also compelled more university and FS researchers to increase their focus on winning competitions for grants from NIFA, NSF, NASA, and others primarily focused on basic or fundamental research and managed predominantly by scientists with expertise in the basic sciences but limited expertise, if any, in the applied sciences, despite their importance for public and private land management, commodity production, and related innovations.

For instance, during the 1990s, public priorities for multiple uses and forest values other than commodity production expanded across natural to urban settings. A few large-scale habitat conservation assessments of high interest (e.g., Pacific Anadromous Fish Strategy/Inland Fish Strategy, Northwest Forest Plan, Grizzly Bears in the Greater Yellowstone ecosystem) clarified what was known about key species while identifying the gaps in basic science needed to protect habitats for selected species. During the early 2000s, new habitat conservation assessments, resource-management strategies, and monitoring programs for more animal and plant species were developed. Likewise, during the 1990s and 2000s, increasing litigation on proposed federal actions to conserve affected species protected under the Endangered Species Act or challenging National Environmental Policy Act implementation intensified demand for more fundamental science by federal resource managers and others. Because many universities with forestry programs depend in part at least on federal funding and because the FS oversees 193 million acres of public lands, it is not so surprising that their research foci and capacities shifted away from prior applied research, including silviculture and water and soil resource management, toward more fundamental biological diversity, socioeconomics, and forest health topics in response to these issues, interests, and demands.

Research Funding

In 2014, estimated funding for forest-sector research from most major sources was US$598 million. Five federal agencies provided 70 percent of the total: FS (50 percent), NIFA (13 percent), NSF (6 percent), NASA (1 percent), and DoE (0.5 percent) (Figure 1). University funding from state appropriations and other nonfederal sources represented 20 percent. Forest industries and organizations certified by SFI represented 10 percent of total forest research funding. FS, universities, and some forest industries have in-house researchers and provide funding for external research. NASA has in-house research capacity, but most forest-related research is supported through its grants programs. NIFA and NSF are grants agencies without in-house research capacity.

Forest products-related research amounted to US$45 million in 2014, 7.5 percent of the US$598 million from most major sources (Figure 2). FS provided 53 percent of the funding for forest products research, largely through its national Forest Products Laboratory, NIFA provided 34 percent, and NSF and DoE provided the remaining 13 percent. Universities, forest industry, and other organizations also invest in forest products research, but detailed data on these investments were not collected through this effort.

Data on forest research funding from 2002 to 2014 show some distinct trends (Table 3). Principally, total funding from the major sources peaked in 2011, the last year in which there were substantial increases in NIFA funding and in NSF grants for forestry-related research. FS research funding peaked in 2010, and declined thereafter, as did NIFA funding after 2011. Funding of forest research for universities from state appropriations and other nonfederal sources has been declining since 2010 at least. Similarly, forest research funding from SFI-certified forest industries and organizations has been in decline since at least

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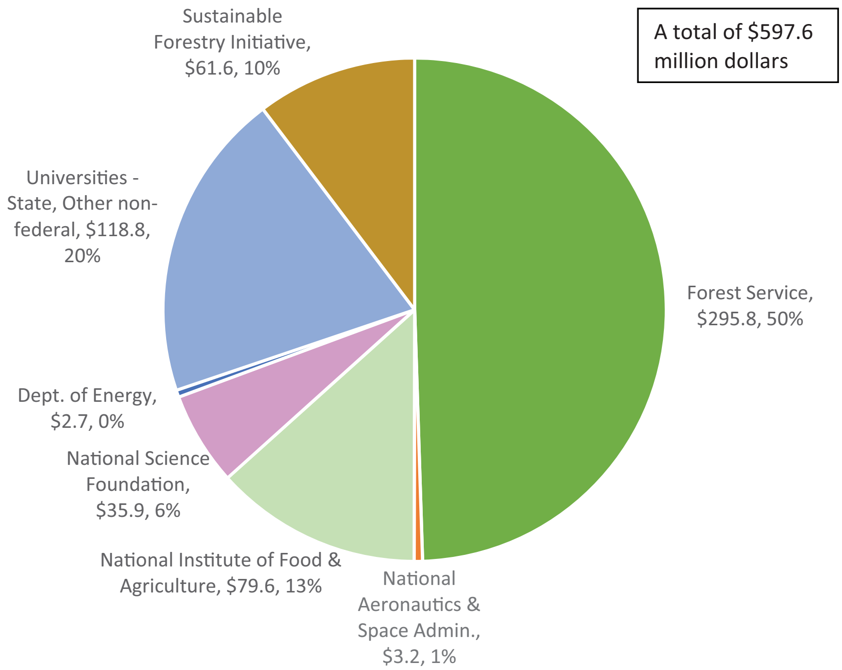

Figure 1. Research funding in forest sector, 2014 (million dollars).

2007. NSF and NASA funding fluctuated, with significant differences between the peaks and lows (e.g., NSF funding totaled US$100 million in 2011, US$13 million in 2008, and US$90 million in 2003). Details and drivers of these trends are discussed further in this section.

In contrast to these trends in the US, other forest-rich countries have invested more heavily in forestry and forest-related research. Canada spends approximately six times the US total on forest research—half from forest industries—for a forest sector about 18 percent the size of that in the US (US Endowment 2017). In 2016, Finland invested over US$1 billion (€948) in forest research, up from €450 million (US$600 million) in 2008 (Finnish Forest Association 2017). About one-third of forest research investments in Finland come from forest industry firms, and the total investment represents approximately 2.2 percent of forest-sector annual revenues. If 2.2 percent of US forest-sector annual revenues were invested in research, there would be US$6.1 billion available—ten times the current US level.

Universities

Funding for most university forestry and forest-related research is provided primarily through state appropriations, NIFA capacity grants, and other federal and nonfederal grants to individual faculty members and students. Federal and industry funds for university research are captured in the data and discussion presented in this section. We estimated state appropriations and other nonfederal funding for university forest research from data provided by NIFA on matching funds reported by M-S participating institutions (n = 79) from 2012 to 2016. In 2012, M-S institutions reported US$147.8 million in nonfederal matching forest research funds, including US$96.6 million from state appropriations, US$16.7 million in self-generated funds, and US$34.5 million in other nonfederal funds (excluding industry funding). Nonfederal funding for universities decreased to US$118.8 million in 2014, increasing by approximately half a million dollars in actual terms by 2016 to US$119.3 million.

FS R&D

Trends in appropriated funding for FS R&D were analyzed from fiscal year 2008 to 2015 for two reasons: (1) FY 2008 was the onset of the Great Recession, and (2) FS R&D shifted budget reporting then to use seven "strategic program areas." The latter change categorically complicates the analysis of longer time trends by program component because the abandoned program definitions that were used in National Research Council (2002) were not "cross-walked" into the new strategic program areas. Thus, older appropriations data could not be "back-cast" into the new categories.

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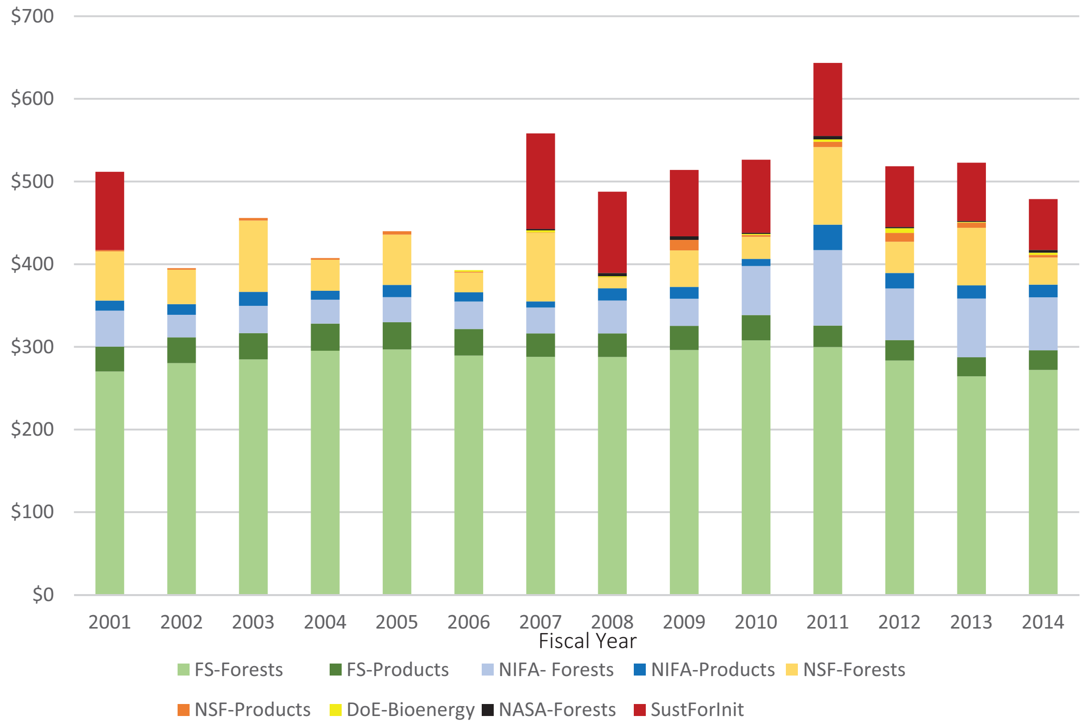

Figure 2. Major sources of research funding in the forest sector, by funder, 2001–14, (million constant dollars, 2015 base year). For each bar color, the darker tone represents funding for forest products-related research, and the lighter tone forestry and related research.

However, we were able to analyze longer-term data sets, splitting out funding for forest products research (Figure 3).

FS R&D appropriated funds in 2008 totaled US$285.9 million, increasing slightly to US$296.0 million in 2015. Actual FS R&D appropriations[8] for 2008–15 were converted to constant dollars using the Consumers Price Index-All Urban Consumers (CPI-U, base year 2015) (Table 4). Actual appropriations for the FS R&D program declined US$6.19 million dollars per year beyond CPI-U inflation (–2.0 percent per year) from 2008 to 2015. This decline does not take into account the fact that annual cost inflation in agriculture-related research is 3.73 percent greater than the general rate of inflation documented by the US Bureau of Labor Statistics (Heisey et al. 2011). Costs of doing research are rising faster than goods used to determine CPI-U because the costs of purchasing scientific equipment, running laboratories, and maintaining research facilities are rising faster than the market basket of consumer items priced by the CPI-U. Therefore, the annual impact on FS R&D programs is the sum of the two downward trends—actual appropriations failing to keep pace with CPI-U inflation and the added costs of doing research that exceed the CPI-U. This recent trend in inflation-adjusted appropriations has eroded the funds available to the FS R&D enterprise by an average of –5.74 percent annually since 2008, which equates to an estimated annual loss in research capacity of US$19.7 million; or a total reduction in R&D capacity of nearly US$160 million over the 8 years reported in Table 4.

Decreases in FS R&D funding varied by strategic program area. The constant dollar decline of –US$2.75 million per year in the Fire program was a combination of reduced appropriations to the base agency research budget plus reductions in funding for research in two other accounts—the National Fire Plan and the Joint Fire Science Program. When the higher rate of cost inflation for research programs was factored in, the overall impact on the Fire program was a mean loss of US$7.84 million annually. The Wildlife and Fish program area experienced the second-largest loss in funding; –US$1.25 million per year, or US$3.55 million per year when the higher cost inflation rate for research was included. Forest-products-related research was a component of the

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Table 3. Research funding in the forest sector, by major funder, 2001–14 (actual, millions).

	FS—Forests	FS—Products	NIFA—Forests	NIFA—Products	NSF—Forests	NSF—Products	DoE—Bioenergy	NASA—Forests	Universities—State, other nonfederal	SFI members	Total
2001	206.19	22.91	33.20	9.30	45.40	1.20	N/A	N/A	N/A	72.22	390.42
2002	217.17	24.13	21.10	10.00	32.30	1.40	N/A	N/A	N/A	N/A	306.10
2003	225.09	25.01	26.20	13.20	68.20	2.50	N/A	N/A	N/A	N/A	360.20
2004	239.76	26.64	23.40	8.80	30.50	1.70	N/A	N/A	N/A	N/A	330.80
2005	248.76	27.64	25.30	12.40	51.00	3.50	N/A	N/A	N/A	N/A	368.60
2006	249.93	27.77	28.80	9.60	20.60	0.90	1.70	N/A	N/A	N/A	339.30
2007	255.26	25.25	27.70	6.60	73.40	0.50	2.24	1.61	N/A	102.41	494.96
2008	260.17	25.73	35.90	13.40	11.70	0.30	1.20	3.54	N/A	88.96	440.90
2009	269.72	26.68	30.00	13.00	40.18	11.60	0.00	3.86	N/A	73.20	468.24
2010	283.92	28.08	54.80	7.90	24.67	1.90	1.34	1.31	N/A	81.43	485.35
2011	282.07	24.53	85.80	29.10	88.34	6.00	2.62	3.91	N/A	83.23	605.60
2012	271.68	23.62	59.90	17.90	36.32	10.30	5.32	1.57	147.8	70.26	644.67
2013	257.51	22.39	69.20	15.50	67.96	6.00	0.85	1.15	128.9	68.71	638.17
2014	272.08	23.70	64.24	15.35	32.80	3.13	2.73	3.21	118.8	61.65	597.69

Note: DoE, Department of Energy; FS, Forest Service; NASA, National Aeronautics and Space Administration; NIFA, National Institute for Food and Agriculture; NSF, National Science Foundation; SFI, Sustainable Forestry Initiative.

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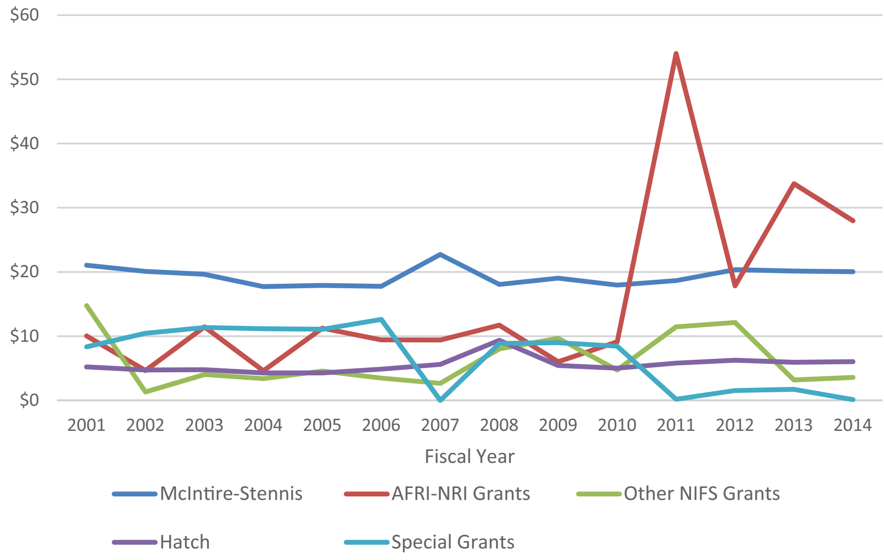

Figure 3. National Institute of Food and Agriculture funding trends by program (million constant dollars, 2015 base year).

Resource Management and Use strategic program area, not normally reported separately but separated out here. From FY 2008 to FY 2015, the annual loss trend was –US$80,000 per year. However, a substantial uptick in funding for FY 2015 colored the analysis; when excluded, funding for this program decreased –US$1.17 million per year between FY 2008 and FY 2014. These recent trends in FS R&D funding are quite different from those reported by the National Research Council (2002), which found that shifts in FS R&D appropriations from FY 1980 to FY 2000 were favorable to timber and forest management research, which increased by 27 percent, while quite negative for forest protection and health research, which fell by 44 percent.

NIFA

NIFA administers a number of different grant programs that contribute to the nation's forest research capacity (Figure 3). Two formula funding grant programs support the capacity of land grant colleges and universities to conduct forest-related research. Specifically, M-S capacity grants support forest-resource and wood-products research, education, and extension at state forestry schools and colleges, and the Hatch program supports research at state agriculture experiment stations, which may include forest research programs. Long-term trends in actual funding show slight increases (M-S: 2001 US$21 million, 2014 US$32 million; Hatch: 2001 US$3.9 million, 2014 US$5.9 million). However, when accounting for inflation, both programs showed little fluctuation in constant 2015 dollars, with M-S funded at about US$30 million per year in recent years and Hatch at about US$6 million.

NIFA also provides funding for forestry research through AFRI, which replaced USDA's previous competitive grants program known as the National Research Initiative (NRI) in 2008. Several special grants were eliminated and folded into NRI in 2007–8. Actual funds awarded for agriculture and forestry research through AFRI/NRI increased from US$7.5 million in 2001 to US$28 million in 2014 (Figure 3). With the establishment of AFRI in the 2008 Farm Bill, Congress significantly boosted the funding authorization for this competitive grants program up to US$700 million per year. However, there was a lag of a few years from authorization to implementation while NIFA redesigned its grant application process and to award funds through AFRI. The first set of AFRI awards occurred in 2011—reflected in the large uptick in NIFA grants appropriations data shown in Figures 3 and 4.

Most forestry and forest-related research topics benefited from the AFRI bump up in 2011 (Figure 4). However, sustaining an increase in funding to forests and general forestry has not been maintained, as shown by data for 2012–14. Moreover, the same higher rate of cost inflation for research programs identified by Heisey et al. (2011) has affected universities and state agriculture experiment stations, so the relatively flat lines for M-S and Hatch grants and the recent reductions for AFRI forest research funding directly impact research institutions' and researchers' capacity to conduct research.

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Table 4. Forest Service research and development funding trends (million constant 2015 base year).

	Strategic program areas									
				Resource management and use				Inventory and monitoring		
Year	Fire	Invasives	Recreation	Forest products	Other resource management and use	Water, air, and soils	Wildlife and fish	Forest inventory and analysis	Other inventory and analysis	Total research and development
2008	64.58	38.05	4.55	28.46	66.39	39.13	33.78	71.50	4.54	350.98
2009	66.48	38.93	5.42	29.28	68.28	40.00	34.70	71.94	5.34	360.39
2010	60.21	40.63	5.62	30.45	78.82	39.19	33.04	77.89	7.14	372.99
2011	59.06	38.26	5.54	26.06	76.10	38.60	32.55	75.92	7.67	359.67
2012	53.78	37.35	5.18	24.65	74.24	37.65	28.86	72.19	4.41	338.31
2013	50.26	34.92	4.84	22.99	69.45	35.20	26.98	67.21	3.69	315.52
2014	49.36	35.46	4.47	23.66	70.66	35.74	27.40	67.47	8.50	322.72
2015	48.87	35.11	4.42	34.90	58.48	35.39	27.13	70.00	8.41	322.71
Constant dollar loss trend	−2.75	−0.67	−0.10	−0.08	−0.87	−0.72	−1.25	−0.82	0.35	−6.91
Percentage of constant dollar loss trend	−0.80	−0.19	−0.03	−0.02	−0.25	−0.21	−0.36	−0.24	0.10	−2.01
Allocated research cost inflation	−1.48	−0.36	−0.05	−0.04	−0.47	−0.39	−0.67	−0.44	0.19	−3.73
Total loss trend	−7.83	−1.90	−0.28	−0.23	−2.49	−2.05	−3.56	−2.33	0.99	−19.69

Note: Constant dollar loss trend is the slope of the linear regression for the program's constant-dollar funding stream for 2008–15. Percentage of constant dollar loss trend is the program's portion of the overall annual percentage loss of 2.01 percent. Allocated research cost inflation is the program's portion of the overall annual percentage of research cost inflation above the CPI-U constant-dollar inflation adjustment—3.73 percent. Total loss trend is the sum of the program's percentage of constant dollar loss trend plus the program's allocated portion of Fiscal Year

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NSF

NSF administers competitive grants programs through several directorates that provide support for multiyear basic research projects. The long-term trend in NSF support for research on forests and forestry, and, to a lesser extent, on wood products, began to increase in the early 1990s in the Biology Directorate, and a decade later in several of the other NSF directorates (Figures 5 and 6). Peaks in funding for environmental biology programs in the Biology Directorate reflect major investments in the Center for Ecological Analysis (created in 2000 with a US$16 million grant) and consistent multiyear grants for various Long-Term Ecological Research (LTLER) sites, including FS experimental forests (EFs) such as H.J. Andrews EF, Oregon; Hubbard Brook EF, New Hampshire; and Luquillo EF, Puerto Rico. The succession of multimillion-dollar, multiyear grants to LTER sites was a leading cause for the saw-toothed appearance of the Environmental Biology program's line in Figure 5. Competitive grants for wood-related research from NSF have also grown over time. These investments have occurred outside the Biology Directorate, in Engineering and others (Figure 6). Together, these awards ranged annually from US$5 to US$10 million, roughly half the annual total amount awarded in the Biology Directorate. Most recently, there was a substantial uptick in awards by the Geosciences Directorate for landscape-scale studies that include forests.

Overall, NSF awards for forest and forest-related research fluctuate annually, in part because of the nature of multiyear awards, but also because there is no strategic, sustained support specifically for forests. Considering the long-term funding trends, it does seem that NSF program leaders have at least a midrange tactical view of basic science needs in the forest sector, for instance when a grantee is awarded funding for additional phases to an initial award. Nevertheless, strategic direction for forest- and wood-related research by NSF generally emerges after the fact from some blend of the winning proposals' statements of importance and from the peer reviewers' sense of near-term priorities as they sifted and sorted proposals based on their merits.

NASA

NASA has in-house research programs, as well as an external research grants program. Although we did not have access to information on internal funding for forest-related research, we gathered recent data on NASA awards for forest research from 2007 to 2014 (Figure 3). The total amount of funding awarded for forest research germane to the US fluctuated over the period examined, averaging US$2.46 million annually, with a high of US$3.91 million in 2011 and a low of

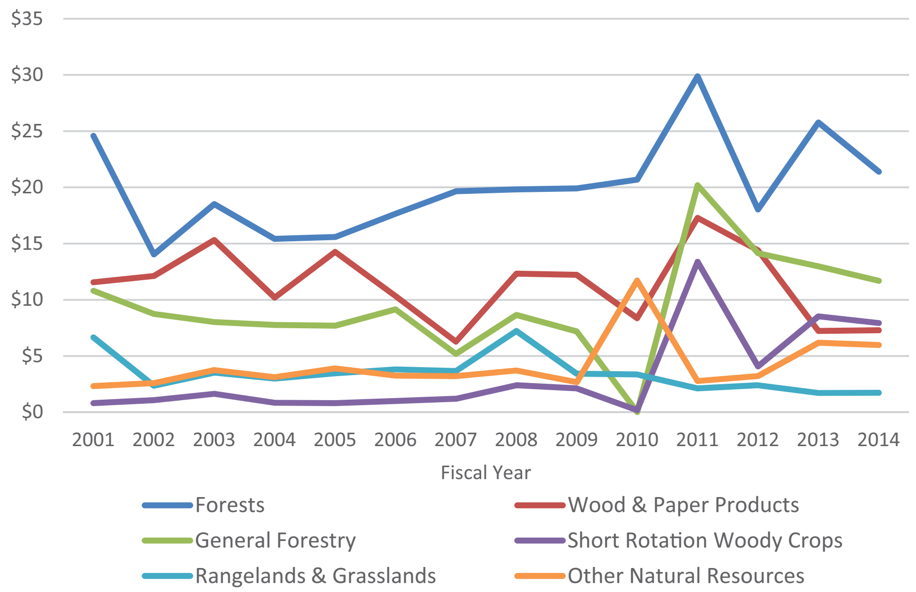

Figure 4. National Institute of Food and Agriculture program funding trends by "subject of investigation" categories, (million constant dollars, 2015 base year). From US Endowment (2017), appendix IV. "Other Natural Resources" includes research on soil, water and watersheds, atmospheric conditions and climate, wildlife and fish, and recreation and wilderness.

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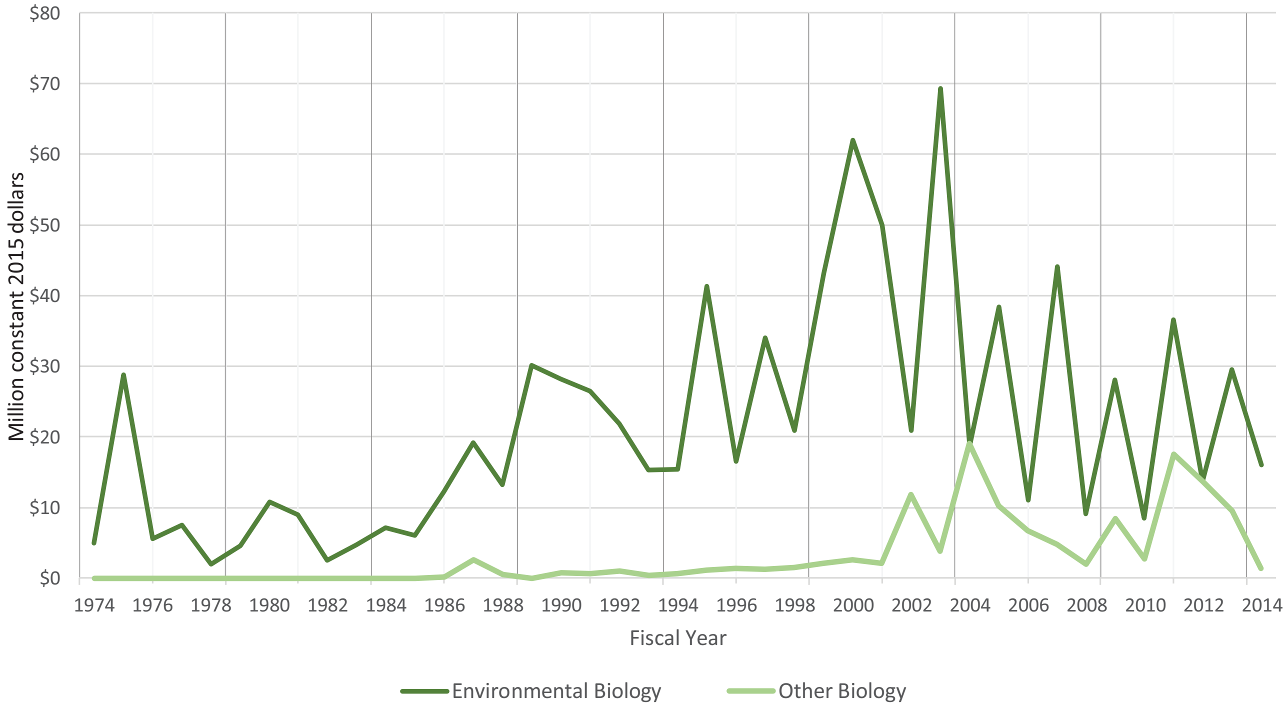

Figure 5. National Science Foundation grants for forest and wood-related research in the Biology Directorate (million constant dollars, 2015 base year).

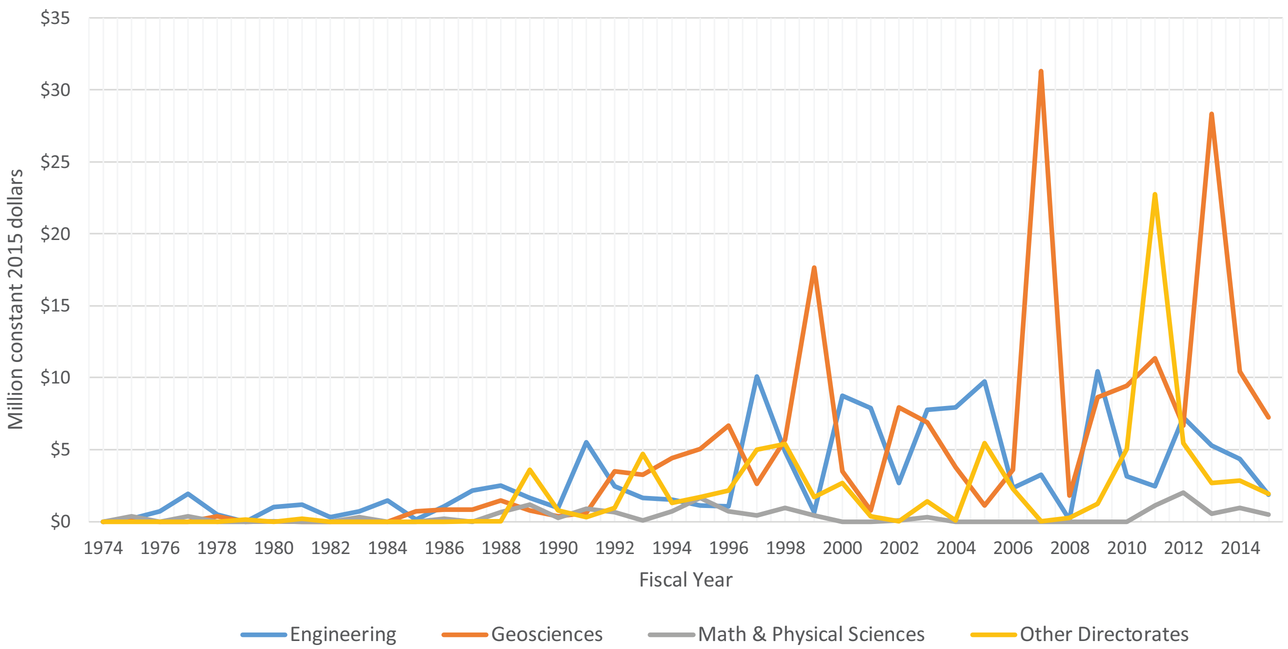

Figure 6. National Science Foundation grants for forest and wood-related research in directorates other than the Biology Directorate (million constant dollars, 2015 base year).

US$1.15 million in 2013 (i.e., in constant 2015 dollars, mean = US$2.62 million, 2011 = US$4.15 million, 2013 = US$1.18 million) (Table 3). These NASA awards largely went to research on remote-sensing applications associated with forests, their distribution, their response to climate change, and their role in the carbon cycle. NASA also funded forest-related research in the tropics and in other areas outside the US or with a global perspective that were not included here. Similar to NSF, fluctuating funding from NASA for

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forest research is closely tied to the nature of multiyear grants and the lack of specific strategic direction for forests.

DoE

Although DoE has a substantial grants program, and its national laboratories do in-house research that includes forest ecosystems, there were no available data to determine how much of DoE research falls within the forestry or forest products parts of the forest sector (US Endowment 2017, Appendix VI). Budget documents from DoE for 2010–15 stated that US$110–$150 million was invested annually in research on terrestrial ecosystem and carbon science, and climate and earth systems modeling (Table 3). Yet, no budget breakdowns were provided or available—online or from the Department's Office of Science—describing the portion devoted to forests vis-à-vis other land covers.

Regarding biomass and bioenergy, DoE and USDA started a joint program in 2006 focused on plant feedstock genomics for bioenergy. An analysis of grant awards from 2006 to 2017 (US Department of Energy 2018) showed that of the US$104.7 million awarded over 12 years[9], US$27.2 million (26 percent) was for research associated with tree species and US$77.5 million (74 percent) associated with nontree species. However, the purposes of that joint program are very limited, tightly focused on basic research to understand how plant genes/alleles influence crop yields and quality, and plant resistance and tolerance of pathogens. The program has funded little applied research or development work on sustainable management of crops for cellulosic biomass production or conversion processes. Further, it was not possible from DoE budget documents to tease out how much of the US$75 million/year devoted to biofuels research was actually spent on sustainable production and conversion of tree-based lignocellulosic biomass versus production and conversion of perennial grasses, nonfood oilseeds, row crop residues, or woody shrubs.

Forest Industry

Historically, private-sector forest-industry firms invested in forestry and forest products research and participated in research cooperatives (NRC 1990, 2002, Hickman 2007, Lönnstedt and Sedjo 2012). However, most of the large vertically integrated forest products firms have been eliminated with the sale or ownership restructuring of industry forest lands into timberland investment and management organizations (TIMOs) and real estate investment trusts (REITs). With restructuring and spinoffs, in-house research programs mostly were eliminated, and ties between industry operations and regional and state research organizations decreased. Additionally, the Great Recession that started about 2008, led to the near collapse of the housing market and other shifts in core forest-sector market segments—all of which added to waning industry support for R&D.

According to Kellison (2014), data from the mid-2000s (prior to the 2008 recession) showed that the wood products industry invested 0.6 percent of total sales in R&D, and the pulp and paper segment invested 0.5 percent (of which one company accounts for half). Our discussions with some forest-sector industry leaders indicated that the current level of industry support for research is now even lower than it was 10–15 years ago. In comparison, other manufacturing sectors, such as the automobile industry, spend 3.4–3.5 percent of sales on R&D. Leading sectors spend more. The biomedicine and health care sector spends 12 percent of revenue on research; the computers and electronics sector spends 9 percent of revenue; software and applications developers spend more than 16 percent of revenue on research (Guldin and Barnwell 2017).

Some remaining integrated forestry firms, along with some TIMOs and REITs, have maintained modest research programs or invest in external programs, as noted in informal discussions with industry leaders and monitored by SFI as a component of its certification standard. SFI requires its certified members to conduct or support forest research to enhance forest health, conservation, productivity, and sustainable management. Associated research investments are recorded and tracked by SFI. In 2015, actual research investments by SFI-certified forest organizations totaled US$57 million; 35 percent (US$20 million) of which was invested in internal research programs, and the other 65 percent (US$37 million) supported external research programs. This was down from US$102 million in 2007 (i.e., US$115 million in constant 2015 dollars) (Table 3). Since the early 2000s at least, SFI-certified organizations generally invested more in forest-related research on their own lands using their own employees and operating funds (internal funding) than they invested in external research organizations or contributed to SFI's competitive grants program (external funding). However, in 2015, SFI-certified organizations invested more in external research (US$37.54 million, 65 percent) than they spent on internal programs (US$19.9 million, 35 percent) (US Endowment 2017).

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Conclusions

Whether capacity is measured using numbers of scientists or total funding available for forestry and forest products research in the forest sector, the nation's forest resource research capacity has declined measurably since 2002. The total number of full-time university professors and FS scientists has declined approximately 15 percent since 2002, and industry research programs have been reduced more substantially. University research personnel in SAF-accredited programs decreased 10 percent from 2002 to 2016. The number of FS researchers decreased 19 percent from 2002 to 2016, but the agency has retained significant capacity for research in terms of laboratories and EFs, as well as technical staff and support for field research—resources that often go unrecognized or underrated and could be used more fully and effectively. Funding for forestry and forest-related research from public and private sources also declined. This trend is in sharp contrast to other forest-rich developed countries, like Canada and Finland, who invest comparatively more in forest and forest products research, providing their forest sectors a significant advantage over the US.

Because we have assembled data that extend many of the trends reported in National Research Council (1990) and (2002), we believe that our results accurately portray long-term trends in the nation's R&D capacity for the forest sector. To us, the human capital metrics—number of researchers and scientists in agencies and at universities—are the most concerning for the forest sector and reflect the declines in overall funding for forests and forestry R&D. Moreover, a wave of retirements of "baby boomers" at the end of 40+ year careers in academia and public service has hit research institutions, with limited investment in their replacements, due in part to the declines in related federal and state budgets. These fiscal and human-capacity constraints will continue to wear away at forest-sector research capacity, while the resulting impacts are mostly going to be felt a decade or two from now, when it is too late to recover quickly. Further, because the costs of doing research continue to grow, outpacing conventional measures of cost inflation, the appropriated dollars available today mean real declines in actual funding, in personnel, and in R&D capacity.

Shifts in forestry and forest-sector research away from applied research on production and commodities toward more basic research on forest factors, conditions, goods, and services reflects, in part at least, expanding societal and stakeholder goals for forests and their uses. These shifts toward more fundamental forest research also reflect trends in scientific research overall and related funding, since rigorous and refereed peer review processes for grants and publications increasingly favor innovative theory and methods, and measurable scholarly contributions, giving comparatively less weight to applied or practical research. The university promotion and tenure processes, and FS scientist panel processes do so as well. Another factor in the shift away from applied and forest products research is the wave of retirements without replacement in these specialties.

Since the 2008 recession, timber prices have fallen to modern-era lows, leaving a glut of sawtimber across much of the country and affecting a wide range of forest landowners. As a result, there may not be much perceived need to invest more research resources in increasing forest productivity. Nevertheless, this trend underscores the need for more research aimed at developing new markets for smaller-diameter wood products; nontimber products, such as high-performance fibers, films, plastics, and natural chemicals from cellulose to replace petrochemical products; and ecosystem services that may prove more profitable for these landowners. Likewise, investments in wood use and product development are critical for the innovation required to increase or even sustain the sector's competitiveness in global markets (Ellefson et al. 2010).

Overall, we maintain that decreased staff and budgets for forest research will result in less research innovation and commercial product development of forest-based commodities and services. This is particularly troubling in the context of increasingly complex issues affecting forests, such as advancing age and increasing occurrence and susceptibility to fire, insects, and disease, which are compounded by the effects from competing objectives for forest goods and services, shrinking forest incomes, declining markets for timber and nontimber commodities, and even weaker markets for ecosystem services (Siry et al. 2018). Given the current and ever-increasingly complex context for forests, sustained if not enhanced research investments seem most appropriate and justified, not less.

Forest research organizations, interest groups, and stakeholders will need to continue their cooperation and advocacy for adequate levels of funding and desired research priorities just to maintain stable research funding. And, they will have to find new and creative ways for increasing funding beyond current levels, while competing with a host of other national and state priorities that garner priority over forest resource

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research, development, and management. Systematic monitoring and reporting on forest research capacity across the range of public and private institutions will continue to be critical for informed decisionmaking. Regularly updating this information would provide a stronger foundation on which to base decisions, and will require a concerted effort to make information on forest research funding, personnel, and other capacity measures available and consistent across agencies and institutions.

Acknowledgments

This project was partially supported by the US Endowment for Forests and Communities, Inc. and the USDA Forest Service National Sustainability Assessment Program. The authors also thank Felipe Sanchez and Guy Robertson (USDA Forest Service), Ali Mohamed and Eric Norland (NIFA), and Rocco Saracino and Paul Trianosky (Sustainable Forestry Initiative) for providing data essential to our analyses.

Endnotes

1. Indicators have been renumbered sequentially in the forthcoming US national report. Thus, what the Montréal Process documents and website call indicator 7.4.b is referred to as indicator 7.51 in the US report. (https://www.montrealprocess.org/Resources/Criteria_and_Indicators/index.shtml).
2. https://www.faeis.ahnrit.vt.edu/
3. The National Association of University Forest Resource Programs (NAUFRP) now includes 67 schools that have some forestry or natural resource programs, but we only tallied faculty at accredited forestry programs in order to be consistent with prior research capacity studies and to keep the same core forestry focus.
4. SFI is a sustainability organization that works with members and partners on forest-based conservation and community initiatives, including supply-chain assurances through its certification programs.
5. Personal email communication of February 20, 2018 by Catherine Ronning, DoE Office of Biological and Environmental Research, who wrote to Guldin: "The US$75 million you refer to involves multidisciplinary, multi-institutional programs, and as such it would be very difficult if not impossible to break out amounts for individual crops."
6. Personal communications between Guldin and members of the NAUFRP at annual meetings of the deans and department heads, November 1, 2016 in Madison, WI and November 2, 2015 in Baton Rouge, LA.
7. http://www.ncasi.org/About-NCASI/Index.aspx
8. The actual appropriations annual totals include all appropriated dollars available to the R&D mission area in a fiscal year, including funds appropriated to the Joint Fire Sciences Program and National Fire Plan in the Fire strategic program area and funds appropriated to the State and Private Forestry mission area for the Forest Inventory & Analysis program, which are included in the Inventory and Monitoring strategic program area.
9. DoE contributed US$80.6 million and USDA–NIFA US$24.1 million. A mean of US$9.2 million was awarded annually, ±$2.6 million.

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