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NATIONAL COUNCIL FOR AIR AND STREAM IMPROVEMENT

FOREST GROWTH TRENDS
IN THE UNITED STATES AND CANADA

TECHNICAL BULLETIN NO. 1045

JANUARY 2018

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Cite this report as:

National Council for Air and Stream Improvement, Inc. (NCASI). 2018. *Forest growth trends in the United States and Canada*. Technical Bulletin No. 1045. Cary, N.C.: National Council for Air and Stream Improvement, Inc.

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PRESIDENT'S NOTE

Forest ecosystems are a source of wood and fiber, clean water, recreational opportunities, habitat for wildlife, and other ecosystem services. Over the past century, various studies have reported changes in environmental factors such as CO_2 concentrations, temperature, and precipitation, and in factors such as ozone, nitrogen deposition, and other pollutants. Changes in factors such as these have implications for forest ecosystems and the services derived from them.

Forest certification standards ask their participants to consider the potential for climate factors to affect forests. For example, the 2015-19 Sustainable Forestry Initiative (SFI) Forest Management Standard and Fiber Sourcing Standard ask participants to broaden awareness of climate change impacts on forests, wildlife, and biological diversity. SFI participants who manage forests are also asked to consider the potential for climate factors to influence forest growth, estimates of forest inventory, and planned harvests.

Thus, NCASI conducted this literature review to evaluate reported trends in historical forest growth. The authors identified 62 publications that quantified forest growth trends over periods ranging from 10 years to 300+ years. Reviewed papers used multiple sources of data, including remote sensing, permanent plots, growth models, tree ring analysis, and historical photography, to evaluate forest growth trends.

The net conclusion from the reviewed studies is that, over the past century, forest growth has increased by over 40-60% in some cases. In some regions such as western Canada and Alaska, however, forest growth trends were mixed, with some forest types (e.g., aspen [*Populus tremuloides*]) experiencing dieback in certain locations due to recent droughts. Factors cited in the reviewed literature as causing enhanced growth varied by region but included reduced fire frequency, rising CO_2 concentrations, N deposition, warming temperatures, and changes in other environmental factors.

Dirk Krouskop

January 2018

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NOTE DU PRÉSIDENT

Les écosystèmes forestiers sont des sources de bois et de fibres, d'eau propre, de possibilités récréatives, d'habitats pour la faune et d'autres services écosystémiques. Au cours du siècle dernier, diverses études rapportent des changements dans certains facteurs écologiques tels que la concentration de CO_2, la température et les précipitations et dans des facteurs tels que l'ozone, les dépôts d'azote et d'autres polluants. Des changements dans des facteurs comme ceux-ci ont des répercussions sur les écosystèmes forestiers et sur les services offerts par ces écosystèmes.

Dans les normes de certification forestière, on demande aux participants de tenir compte de la possibilité que des facteurs climatiques puissent avoir un effet sur les forêts. Par exemple, dans la norme sur l'aménagement forestier et dans la norme sur l'approvisionnement en fibre de la *Sustainable Forestry Initiative* (SFI) 2015-19, on demande aux participants d'accroître la sensibilisation aux incidences du changement climatique sur les forêts, la faune et la biodiversité. On demande également aux participants SFI responsables de l'aménagement de forêts de tenir compte de la possibilité que les facteurs climatiques puissent influencer la croissance forestière, les estimations d'inventaire forestier et les récoltes planifiées.

C'est pourquoi NCASI a réalisé la présente revue de littérature pour évaluer les tendances rapportées dans la littérature en matière de croissance forestière au cours des années. Les auteurs ont identifié 62 publications ayant quantifié ces tendances au cours de périodes variant de 10 ans à 300+ années. Les articles qui ont fait l'objet de la présente revue ont fait appel à de multiples sources de données pour évaluer ces tendances, notamment la télédétection, des placettes-échantillons permanentes, des modèles de croissance, l'analyse des anneaux de croissance et des photos historiques.

La conclusion qui se dégage nettement des études passées en revue est que, dans certains cas, la croissance forestière a connu une augmentation de plus de 40-60% au cours du siècle dernier. Par contre, dans certaines régions telles que l'Ouest du Canada et l'Alaska, les tendances de croissance forestière sont variables, alors qu'on note une mort en cime dans certains types de forêts (p. ex. peuplements de tremble [*Populus tremuloides*]) à certains endroits en raison de sécheresses récentes. Les facteurs cités dans ces études pour expliquer l'augmentation de croissance forestière varient d'une région à une autre, mais incluent notamment une diminution du nombre de feux de forêt, une augmentation de la concentration de CO_2, des dépôts de N, un réchauffement des températures et des changements dans d'autres facteurs écologiques.

Dirk Krouskop

Janvier 2018

FOREST GROWTH TRENDS IN THE UNITED STATES AND CANADA

TECHNICAL BULLETIN NO. 1045
JANUARY 2018

ABSTRACT

Reports of changes over the past century in factors such as temperature, precipitation, fire regimes, ozone, atmospheric CO_2, and nitrogen deposition have led to questions about forest growth over this same time period. Determining changes in forest growth over long intervals is complicated by constantly changing growth conditions due to tree maturation, stand self-thinning, disturbance, fires, and other factors. Because a comprehensive review is lacking, results from publications examining forest growth trends in the United States and Canada over the past 100 years were evaluated. Reviewed papers used multiple sources of data, including remote sensing, permanent plots, growth models, tree ring analysis, and historical photography, to evaluate forest growth trends. In the Pacific Northwest (including British Columbia), the entire eastern US, and eastern Canada, reviewed publications report medium to strong growth enhancement based on a variety of data types over periods exceeding 100 years in some cases. For the inland West, historical photography shows clear densification and expansion of Ponderosa pine (*Pinus ponderosa*) forest across the region. However, a recent drought, probably linked to ocean cycles, has caused a growth setback, especially in the Southwest. In western Canada and Alaska, results are mixed. Studies have found forest expansion both upslope and down into grassland in many areas of the boreal zone. On the other hand, aspen (*Populus tremuloides*) dieback has been noted due to recent drought in these same forests. Studies using remote sensing and inventory data present mixed results in this region, with disagreement between studies and methods as well as probable heterogeneous responses. Factors identified as the cause of enhanced growth varied by region, but included reduced fire incidence, rising CO_2 concentrations, N deposition, increased precipitation, and warming temperatures.

KEYWORDS

climate change, environmental factors, forest growth and yield, forest growth trends, inventory data, remote sensing

ANALYSE DES TENDANCES DANS LA CROISSANCE FORESTIÈRE AUX ÉTATS-UNIS ET AU CANADA

BULLETIN TECHNIQUE N^O 1045
JANVIER 2018

RÉSUMÉ

Des rapports sur des changements dans des facteurs tels que la température, les précipitations, le régime des feux, l'ozone, le CO_2 dans l'atmosphère et les dépôts d'azote survenus au cours du siècle dernier ont conduit NCASI à s'interroger sur la croissance forestière pendant cette même période de temps. Mesurer les changements dans la croissance forestière durant une aussi longue période de temps est d'autant plus difficile que les conditions de croissance changent constamment en raison de la maturation des arbres, de l'éclaircissement naturel des peuplements, des perturbations, des feux et d'autres facteurs. NCASI a évalué les résultats d'études sur les tendances dans la croissance forestière aux États-Unis et au Canada au cours des 100 dernières années parce qu'il n'existait aucune analyse complète sur ce sujet. Les articles qui ont fait l'objet de la présente revue ont fait appel à de multiples sources de données pour évaluer ces tendances, notamment la télédétection, des placettes-échantillons permanentes, des modèles de croissance, l'analyse des anneaux de croissance et des photos historiques. Les publications portant sur les régions du Pacifique Nord-Ouest (incluant la Colombie-Britannique), sur tout l'Est des États-Unis et sur l'Est du Canada rapportent une augmentation de croissance moyenne à significative en se basant sur divers types de données couvrant, dans certains cas, une période de plus de 100 ans. Dans les forêts intérieures de l'Ouest, une photo historique montre clairement une densification et une expansion des peuplements de pin ponderosa (*Pinus ponderosa*) dans l'ensemble de la région. Par contre, une sécheresse survenue récemment, probablement reliée aux cycles des océans, a causé un ralentissement de la croissance, particulièrement dans le Sud-Ouest. Dans l'Ouest du Canada et en Alaska, les résultats sont variables. Des études constatent une expansion des forêts à la fois en contre-haut et vers le bas jusque dans les prairies à bien des endroits de la zone boréale. Par contre, on note une mort en cime de peuplements de tremble (*Populus tremuloides*) causée par une sécheresse survenue récemment dans ces mêmes forêts. Les études qui ont fait appel à la télédétection et à des données d'inventaire donnent des résultats variables, incluant des divergences entre des études et des méthodes et probablement des réponses hétérogènes. Les facteurs cités dans ces études pour expliquer l'augmentation de croissance forestière varient d'une région à une autre, mais incluent notamment une diminution du nombre de feux de forêt, une augmentation de la concentration de CO_2, les dépôts de N, une augmentation des précipitations et un réchauffement des températures.

MOTS-CLÉS

changement climatique, croissance forestière, données d'inventaire, facteurs écologiques, rendement forestier, télédétection, tendances dans la croissance forestière

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FOREST GROWTH TRENDS IN THE UNITED STATES AND CANADA

1.0   INTRODUCTION

The health of forests is of critical interest to forest landowners and the forest products industry. Many studies have reported changes over the past century in climate-related and other environmental factors that have potential to influence forest health and growth, such as fire frequency, ozone levels, nitrogen deposition, atmospheric CO_2 concentrations, temperature, and precipitation. The magnitude and pattern of reported changes in some of these factors have varied regionally. For example, Pederson et al. (2015) reported that the 20th century has been anomalously wet in the eastern US. Kim et al. (2012) detected increasing Northern Hemisphere soil non-frozen seasons over 1979 to 2008. As a result, various authors (Anderegg et al. 2015; McDowell and Allen 2015; McDowell et al. 2016) have predicted that changing conditions will lead to widespread forest mortality and/or dieback and may already be doing so. Because of the multiplicity of potential causal pathways and interactions, general discussions of changing condition impacts on forests (e.g., Peñuelas et al. 2013) have been unable to reach specific conclusions.

There is some evidence that forest growth may have increased over the last 100 years. Campbell et al. (2017) provided a global estimate of gross primary productivity (GPP) over the 20th century using carbonyl sulfide (COS) records in ice cores and atmospheric measurements. COS is produced naturally in the ocean, by biomass burning, and by industrial processes, and terrestrial plants take up COS as a side effect of photosynthesis. Atmospheric COS concentrations were stable before the industrial period. Taking all uncertainties into account, the authors found that a best-fit model balancing sources and sinks was quite explanatory and showed a 31% ±5% global gross primary productivity (GPP) growth enhancement over 1900 to 2000. Because forests dominate terrestrial photosynthesis, this suggests that a strong signal of increased forest growth should be evident, especially after 1950 (by their Figure 2d). Global surveys combining various types of data also suggest that on average forest growth is increasing (e.g., Boisvenue and Running 2006).

The contradiction between predictions that changing conditions should be having adverse effects on forests and evidence to the contrary needs resolution. It clearly affects determination of forest resource health, near-term trends for forest resources (e.g., lumber), and influences on wildlife habitat and other ecosystem services. This report sets out to synthesize information on historical trends in forest growth to help resolve this uncertainty.

Various methods exist for estimating tree growth, including remote sensing methods, models based on measured leaf area, long-term plots, and tree ring analysis. Estimating growth over large areas and long spans of time, however, is not simple and is complicated by changes in tree geometry with age (Johnson and Abrams 2009; Loehle 2009), changes in stand density and hence, competition (Cherubini, Dobbertin, and Innes 1998), tree death, and other factors. For example, as a tree grows, annual increment is spread over a wider diameter, which results in narrower rings. For an open-growing tree, the use of basal area increment (BAI) can compensate for this geometric effect and may produce relatively constant values for mature trees (Loehle 2009). However, most trees occur in stands and are not open grown. As stands age, crowding can lead to reduced individual tree BAI. In addition, Johnson and Abrams (2009) found that for long-lived, shade-tolerant species, individual tree basal area increment (and thus wood accumulation) continues to increase over time even for the oldest (300+ years old) trees, though this does not mean that entire stands continue to grow faster with age. They also found that tree ring standardization masks this effect, though Peters et al. (2015) found standardization to be reliable.

Stand dynamics also affect the reconstruction of historical growth trends. Trees constantly die in a growing stand due to disturbance and pathogens and because dominant trees increasingly take up more space and crowd subordinate trees which may die, thereby affecting estimates of past productivity and standing biomass. These interactions will differ depending on stand history and management. Thus, the competitive rank of individual trees (Cherubini, Dobbertin, and Innes 1998) and correlations of individual tree growth with environmental conditions (Carrer 2011) can change over time, largely due to changes in competition, which can create a bias.

For trees with pulsed establishment, such as following a disturbance, the largest trees may have been the fastest growing during stand development (Brienen, Gloor, and Ziv 2017), and if compared to smaller trees, may give the appearance of reduced growth in recent years. This problem is greatest in tropical forests where tree age may not be reliably measurable. Nehrbass-Ahles et al. (2014) further showed that slower-growing trees may have better survival (see also Loehle 1988), and thus the oldest trees will have likely grown slower than average when young and give the appearance of accelerating recent growth when older and younger trees are compared. Other complications arising when using tree-ring data are discussed by Peters et al. (2015).

Based on these considerations, several valid approaches can be used to determine long-term trends in forest growth. Long-term plot data can be used to assess aboveground net primary productivity (aNPP). Measurements of all trees can be converted to individual tree total biomass using allometric equations and differences over time ascribed to aNPP (Dye et al. 2016). Trees that died during an interval can be taken into account if data are available, for example from repeated measurements of plots. Tree ring methods can replicate such long-term plot studies (Dye et al. 2016) but, because trees that died in the past are not quantifiable from current live trees, this approach can only extend back a few decades and not in cases with rapid self-thinning. If plots do not have large dead trees (or logs) indicating that all trees on the plots in the past are still living, this approach might be extendable back farther (e.g., see Graumlich, Brubaker, and Grier 1989). Nehrbass-Ahles et al. (2014) showed that tree ring studies based on dominant individuals and several other sampling designs can lead to large over-estimates of growth trends over time. They also showed, however, that fixed-plot designs that use all trees in a plot are nearly unbiased as long as plots are not small (i.e., $\geq$ 22.5 m in radius (circular plot) in their study).

Tree height growth rate for dominant trees, commonly used to construct site index metrics, is less affected by competition (Bontemps et al. 2011) and could provide a useful approach for estimating growth trends. For plantations where spacing and age are uniform, height at a given age for older and younger stands could be compared either from inventory data or from tree dissections, although similar sites should be compared. For plantations on similar sites, yield tables from past harvests or tree sizes (height or biomass) at given ages can be validly compared. Planting density must be the same as should treatments (e.g., thinning, fertilization) for such comparisons to be valid. Genetic improvement of planting stock over time could also confound results.

There are, then, certain approaches for estimating forest growth trends that are not valid or are subject to confounding. The use of tree ring data to infer growth rates is subject to complications from changes in tree geometry and competition over time. Tree ring standardization to account for these issues can remove the information being sought (Johnson and Abrams 2009; but see Peters et al. 2015). Relationships to environmental conditions based on tree rings and changes in these relationships over time also are affected when individual trees do not exhibit constant correlations of growth with environmental conditions over time (Carrer 2011). The use of rising mortality as an indicator of worsening conditions might seem obvious, but is in reality fraught with complications. As an example, dieback of entire stands of aspen (*Populus tremuloides*) in the Rocky Mountains has been observed (Anderegg et al. 2012), with an implication that climate is involved. However, aspen is

not a long-lived species and many of these stands were quite old. A senescent stand subject to a modest stress (e.g., drought or insects) could show rapid mortality.

A widespread phenomenon is the strong positive correlation between NPP and mortality (Stephenson et al. 2011). One reason for this is that competition for light is spatially constrained. To grow larger, a tree must expand its crown, but this is necessarily at the expense of neighboring trees. Those individuals that are overtopped will show decreased growth and may eventually die (Stephenson et al. 2011). Fertilization can speed up the self-thinning process (e.g., Yang 2006) by exaggerating initial height differences. To the extent that nitrogen fertilization, rising CO_2 and climate factors act to increase growth, this could lead to more rapid self-thinning and thus increased mortality, primarily in subordinate trees. Thus, any study that estimates total mortality, for example from forest inventory data, may come to the opposite conclusion in terms of impacts and trends from data on NPP, height growth, stand basal area, or other more appropriate measures.

An example of complications inherent in assessing forest responses to climate factors can be seen by examining several assessments of forest growth rates cited by the IPCC (Settele et al. 2014). Silva and Anand (2013) and Silva, Anand, and Leithead (2010) used individual tree BAI as a metric of growth and found a recent downturn in growth in several forests, but individual tree BAI can decline with tree age due to increasing competition (crowding) as trees get larger or due to age. Thus, recent declines in BAI of individual trees can result from factors other than climate.

Further complications arise from natural stand aging. For short-lived trees, a stand that is over-mature will exhibit a rise in mortality of even dominant individuals, especially with the imposition of stress (e.g., Worrall et al. 2013). Many early successional species which form even-aged cohorts after a disturbance could thus exhibit increased mortality after a certain age. NPP also declines for older stands (Girardin, Bernier, and Gauthier 2011). The increasingly large amount of respiration required for support tissue inevitably causes reduced carbon accumulation with age (Gray, Whittier, and Harmon 2016). Comparing NPP decades ago to today for older stands could be misleading if a reduction in growth results from maturation rather than changes in environmental conditions. Stand age-matching (e.g., Bontemps, Hervé, and Dhôte 2009) and growth models can be used to minimize this confounding.

Finally, short- versus long-term data may show different trends. A region that is experiencing increased growth over the past 100 years due to changing climate factors (e.g., precipitation, temperature) and/or rising CO_2 might nevertheless show a short-term recent decline in growth due to drought, pests, or stand aging. Thus, longer-term data (100 years) are likely more informative than short-term (e.g., decadal-scale) data.

Remote sensing data can provide spatially extensive indicators of plant growth, though the oldest data typically available date back only to 1982. While it is tempting to view these data as a direct measure of plant growth, this is not the case. Satellite sensors actually measure the intensities of various wavelengths of light reflected back to space. After corrections are made for incidence angle, clouds, nonvegetated pixels, orbital decay, etc., metrics are computed, such as light use efficiency (LUE), vegetation optical depth (VOD), and fraction of absorbed photosynthetically active radiation (fPAR), which is closely related to leaf area index (LAI). Several different assumptions and models are then used to compute variables such as normalized difference vegetation index (NDVI), LAI, and NPP, which can be compared over time. While these models are based on free-air CO_2 exchange (FACE) experiments, for estimation of NPP (but not LAI) De Kauwe et al. (2016) indicated that these computations do not properly account for how rising CO_2 enhances NPP, with an underestimate due to current methods of up to 43% (estimate from their graph) over the satellite era. This effect would likely be greater for broadleaf and lesser for conifer species. This possible bias compounds with time as atmospheric CO_2 concentration rises and will tend to reduce estimated NPP trends compared to true values. An additional consideration is that above full canopy coverage, reflected light saturates. It

can thus be difficult to detect changes in LAI above or near 100% crown cover. Estimated NPP trends based on satellite data should thus be compared to other types of data, as in the following discussion.

An additional indictor of forest response is change in forest area or density. A complicating factor in understanding forest area change is that multiple processes can produce observed changes, and these processes have not changed uniformly in space. Fire has historically been an important governing force determining forest/shrub or forest/grassland ecotone boundaries. Decreased fire frequency or intensity can allow forest to expand at the dry range limit and become denser. Historically, fires in North America were more common 100 years or so ago due to human ignitions in the past and recent fire suppression (Doerr and Santín 2016; Addington et al. 2017; Taylor et al. 2016), but with no overall century scale trend globally (Doerr and Santín 2016). For the western US over recent decades, there is no overall trend in acres burned, but a decline in acres burned at high severity (Doerr and Santín 2016). Initially, areas recently burned with high-intensity fire may be difficult to distinguish from forest loss, particularly with satellite imagery, even though forest regeneration may be ongoing (Martinez-Vilalta and Loret 2016). Many wildland acres that burn are not forest or have variable tree mortality.

Precipitation trends also can influence forest area and density, and are highly variable in time and space (Pederson et al. 2015). Rising CO_2, by increasing growth rates and water use efficiency (Loehle, Idso, and Wigley 2016), may mimic the effects of rising precipitation and favors broadleaf species more than conifers. Rising temperature can lead to drought stress but has additive effects when combined with rising precipitation that would favor tree growth. At higher elevations, rising temperature could cause tree lines to rise. In the far north, it could allow the boreal forest ecotone to expand into what is now tundra.

Because of changes in precipitation, fire regimes, CO_2, and other factors, attribution of forest area changes can be complex and often requires evaluation of several types of evidence. In the studies described next, more than one environmental factor often could have caused the observed changes in forest area. In such cases, authors sometimes made inferences from historical data on climate (e.g., seasonal/annual changes in temperature/precipitation) and/or fires to help clarify causation. A historical reconstruction of trends is needed because there are both positive and negative factors at work, without an obvious net effect. A more intensive historical survey of forest productivity for the US and Canada would be useful and is undertaken here. This region has various long-term data sets that may enable useful elucidation of whether and how forest growth has changed in response to climate factors.

2.0   METHODS

The scientific literature was searched for references to long-term growth trends of forests in the US and Canada. As an initial entry to the literature, the complete contents of *Forest Science* (2015-2017), *Canadian Journal of Forest Research* (2015-2017), *Global and Planetary Change* (2014-2017), and *Global Change Biology* (2012-2017) were searched, and then Google Scholar was searched using "forest history" and "forest growth trends" as keywords. The cited literature in each publication identified through the journal and Google Scholar searches were then searched. Key abbreviations are noted in Table 2.1.

Table 2.1 List of Abbreviations Used

Term	Definition
AMO	Atlantic multidecadal oscillation
aNPP	Aboveground net primary productivity
BAI	Basal area increment
COS	Carbonyl sulfide
FIA	Forest inventory system (US)
fPAR	Photosynthetically active radiation
GPP	Gross primary productivity
LAI	Leaf area index
LUE	Light use efficiency
NDVI	Normalized difference vegetation index
NEP	Net ecosystem productivity
NPP	Net primary productivity
PDO	Pacific decadal oscillation
TNPP	Total net primary productivity (may equal NPP)

3.0   RESULTS

Sixty-two publications that quantified forest growth trends over time were found (Table 3.1), plus numerous supporting references. Reviewed studies estimated forest growth rates over periods ranging from 10 years to 300+ years. Twenty-one studies estimated forest growth for large geographic areas (e.g., continental scale) using remote sensing, ensuring overlap of results for multiple regions. Studies used a variety of approaches including remote sensing estimates (21), plot-based reconstructions (29), model-based reconstructions (4), long-term photographic evidence of areal extent changes (7), and height growth rate changes (1). Results are organized by study type.

Table 3.1 Summary of Growth Trend Results[a]

Reference	Years	Region	Methods	Trend
Addington et al. (2017)	1896-2000	Colorado Front Range	Compared historical to modern photos	Widespread pine expansion, densification
Beck et al. (2011)	1982-2008	Alaska	Tree ring data	Growth declines in interior forest
Brown et al. (2015)	1667-2012	Colorado Front Range	Fire history and stand density reconstruction using tree cores	Pine expansion, densification, increase in Douglas-fir
Buma and Barrett (2015)	2004-2010	Southeast Alaska	FIA data	Net gain biomass especially in north
Conway and Danby (2014)	Recent decades	SW Yukon	Evaluated ecotone movement using tree sizes and ages on 28 sites	Aspen & spruce invasion downslope into grassland/tundra
De Grosso et al. (2008)	1901-2000	US & Canada	Simulated NPP with fixed CO_2	TNPP increased 12% to 50% over most of Canada, central & western US (but not S. Rockies)
Dial et al. (2015)	≈ 50 years	South-Central Alaska	Historical aerial photos at 2 study areas	1.2 to 2.8 m/yr upslope woody ecotone advance
Dragoni et al. (2015)	1998-2008	South-Central Indiana	Flux tower measurements	38% NEP increase

(Continued on next page. See note at end of table.)

Table 3.1 Continued

Reference	Years	Region	Methods	Trend
Dye et al. (2016)	1970-2010	Three sites in ME, MA, WV	Permanent plots & tree ring data	No trend but data highly variable
Gamache and Payette (2004)	1800-2000	Quebec, Canada	Black spruce stem dissections on a 300 km transect	Height growth progressively increased since 1970s, especially for northern sites.
Girardin et al. (2011)	1901-1999	Canada S. Boreal east of Great Lakes	Combined fire history, tree ring records, inventory data with model for jack pine growth	$\approx$12% NEP increase due to climate, almost 12% decrease due to stand aging
Girardin et al. (2014)	~300 yr	SE of Hudson's Bay, Canada	Tree ring analysis black spruce	BAI decline all ages after 1960s
Girardin et al. (2016)	1950-2002	Canada	Tree ring chronologies from 598 localities across Canada	Areas with enhanced and reduced growth about equal. No CO_2 signal detected
Graumlich et al. (1989)	1880-1979	Western Washington	Tree ring analysis of 4 study areas on plots with no obvious mortality, converted by allometric models to biomass	Regional increase of 60% growth increment
Hogg et al. (2005)	1951-2000	Western Canada	Evaluated aspen stand dynamics at 25 sites	General increase in stand BAI with high variability and dieback events due to drought, insects

(Continued on next page. See note at end of table.)

Table 3.1 Continued

Reference	Years	Region	Methods	Trend
Jackson et al. (2016)	1962-2005	Mount Albert Edward British Columbia, Canada	Historical aerial photos	Woody cover at upper ecotone increased from 75% to 81%
Lloyd and Fastie (2003)	≈past 200 yr	Central Alaska	Tree aging and mapping	Elevational expansion of spruce
Masek (2001)	Recent decades	Boreal Canada ecotones	General summary of studies	Slow ecotone expansion
McMahon et al. (2010)	100+ years	Maryland	Compared resurvey periodic increment on stands of multiple ages to expected trend from biomass vs age curve	All ages were growing faster than predicted, up to twice as fast
Millar et al. (2015)	1963-2000 1955-1978	Western Great Basin	Compared ecotone tree ages	Found recruitment pulses (expansion up and into grassland) for limber pines, bristlecone pine).
Multiple authors	Recent decades	US & Canada	Documented events	Periodic to recent tree dieback, no trend proven
Pan et al. (2009)	1895-2000	US Mid-Atlantic	Used simulated climate, N deposition, CO_2 histories to model NPP	NPP increased 29% due to net N, CO_2, O_3 effects, +4% due to simulated climate change

(Continued on next page. See note at end of table.)

Table 3.1 Continued

Reference	Years	Region	Methods	Trend
Pontius et al. (2016)	1931–2001	New Hampshire	Long-term plot data	90% higher 10-year growth increments for most recent survey
Pretzsch et al. (2017)	≈past 200 yr	World-wide	Tree ring data	Enhanced growth since ≈1960
Searle et al. (2017)	1958–2013	Western Canada	1797 permanent plots, all species	Broadleaf and early successional species increasing, some evidence of recent drought stress
Soulé and Knapp (2006)	1950–2000	US West	Tree ring analysis of Ponderosa pine	Attributed increased growth rates to CO_2
Suarez et al. (1999)	Past ~200 year	NW Alaska	Age distribution at ecotone from tree rings	Past 150 yr forest spread 80-100 m into tundra
Thomas et al. (2009)	Pre-industrial vs recent	Midwest & NE US	Based on FIA data & N deposition, estimated N effect on growth	Estimated 40% growth enhancement but CO_2 effect could not be separated
Twine and Kucharik (2009)	1950–2002	Eastern US	Modeled forest growth by vegetation type (CO_2 constant)	Positive trends NPP in deciduous forest
Wu et al. (2014)	1956–2001	British Columbia, Canada	Growth model with climate, N deposition, CO_2 effects	24% to 36% NPP growth increase

[a] Due to conflicting results, remote sensing studies are not included.

3.1   Changes in Forest Ecotones, Area, and Density

The most common response of forests over the past 100+ years has been expansion and/or densification (Nelson and Reams 2017). Expansion of forest into grassland/shrubland types or tundra/alpine areas as well as increased tree density indicate that conditions for tree growth are improving. Expansion has not been reported in the eastern half of the US or in the southern forests of Canada, where land not in forest is often already developed or in agricultural use, although densification is possible.

Jackson et al. (2016) used historical aerial photography from 1962 and 2005 (43 years) on Mount Albert Edward in British Columbia, Canada to evaluate ecotone shifts. They found that woody cover increased from 75% to 81% of the area, largely by infilling of gaps. Change in tree abundance was difficult to detect from the photographs. Lloyd and Fastie (2003) also detected spruce (*Picea* spp.) expansion upward in central Alaska, especially after 1950. Dial et al. (2016) found similar rates of forest upward movement into tundra in south-central Alaska. They found tall shrub upward expansion over ~50 years, based on aerial photography, to match rates of warming, with rates of 2.8 and 1.2 m y^{-1} in two study areas. Due to slow growth rates, tree expansion lagged tall shrub expansion. Over such long periods, all three studies reported very small changes that were consistent with observed slow rates of boreal forest ecotone movement in Canada (Masek 2001).

Millar, Westfall, and Delany (2015) found that at multiple sites across four mountain ranges in the western Great Basin, upper elevation pines had experienced a pulse of expansion between 1963 and 2000 for limber pine (*Pinus flexilis*) and between 1955 and 1978 for bristlecone pine (*Pinus longaeva*). Pines were found to have expanded above the current timberline, downslope into grass or shrub communities, and laterally at mid-slope into treeless zones. Average extension over all cases was 225m. These recruitment pulses were correlated with complex, lagged increases in precipitation at those times. Examining only upper tree line response could have led to a conclusion of temperature causing an elevational rise.

Conway and Danby (2014) measured tree size and age on forest ecotone transects in southwestern Yukon, Canada across 28 sites in two regions. They found that trembling aspen and some white spruce (*Picea glauca*) were encroaching into grassland at nearly every location on flat terrain and south-facing slopes. Aspen spread was positively associated with rising spring temperatures and precipitation. There was no spread on white spruce-dominated north-facing slopes. On slopes, this expansion was downhill rather than uphill, which was the opposite of expected patterns. Similarly, Suarez et al. (1999) found, based on age distribution data from tree rings, that forest had expanded 80 to 100 m into tundra over the past 150 years in the Noatak National Preserve in northwest Alaska. Increased growth, based on a detrended growth index, was correlated with rising temperatures.

Buma and Barrett (2015) used high resolution remote sensing data to assess forest area change in the rainforests of southeast Alaska over 2000 to 2012. Managed lands were excluded. Forest gain by expansion or ingrowth of shrub areas was 25% greater than losses by tree death or blowdown, with more gains in the north.

Brown et al. (2015) reconstructed forest age structure in the northern Front Range, Colorado, using tree ring analysis. Fire history was reconstructed from 1667 to 2012. Fires were recorded in two or more plots from 1667-1859 (the date of the last such fire) on average every 8-15 years. In 1860 (the earliest that stand structures could be reconstructed), all trees were Ponderosa pine (*Pinus ponderosa*) and stand density was highly variable. Forests in 2012 were denser, had higher basal area, more smaller trees, and more Douglas fir (*Pseudotsuga menziesii*) and Rocky Mountain juniper (*Juniperus scopulorum*). These changes are what would be expected from reduced fire frequency. Stine et al. (2014) presented photographs documenting similar changes in the Okanogan-Wenatchee National Forest in Oregon over 1934 to 2010.

Addington et al. (2017) conducted a detailed study of Ponderosa pine forests of the Colorado Front Range using historical photography. They concluded that historical fire frequency and intensity were likely much higher before the mid- to late-1800s. A comparison of photographs from 1896, 1899, and 1905 to recent photography (past 20 years) showed ubiquitous and dramatic increases in tree density. Extensive historical photographs supporting these conclusions can be found in Veblen and Lorenz (1991). This trend was spatially extensive and agrees with trends in the Southwest, according to the authors (and see Brown and Wu 2005). They noted that, in addition to fewer fires, a history of extensive grazing since settlement would have favored pine establishment over the study period by reducing grass competition with pine seedlings. Soulé and Knapp (2006) also documented increased growth in Ponderosa pine after 1950 attributable to CO_2 enrichment. The effect was greatest on drier sites and during drought years.

3.2   Large Extent Estimates of Growth

Remote sensing and models were used by 21 of the reviewed studies to infer temporal trends in productivity over large areas. However, remote sensing data are only available from the early 1980s forward, depending on the data type, and complications arise when interpreting results due to the influence of factors such as wildfire, disease, insects, and human activities (e.g., silviculture) on forest productivity.

Girardin et al. (2016) combined remote sensing data (1982-2002) with tree ring chronologies developed from dominant and co-dominant trees on long-term (1950-2002) forest inventory plots from 598 localities across Canada. This plot-based design and the slow growth of these forests largely overcomes issues pointed out by Nehrbass-Ahles et al. (2014), though more so for the 20-year analysis than the 52-year analysis. For the 1982-2002 timeframe, most of the Canadian forest showed a positive growth trend from plot data, except for the northern third of the western-most provinces, which showed decline. These data did not correlate well with the NDVI trends over the same period. For the 52-year plot data, areas with enhanced and reduced growth were about equal. They did not detect a CO_2 signal and found most of the variability in growth to result from summer heat (negative) and moisture (positive) fluctuations.

Nowacki and Abrams (2015) used remote sensing and historical land survey data to study the interacting effects of changes in environmental factors and forest disturbances such as land clearing and logging from 1500 to the second half of the 20th century on forests of the eastern United States (including the Midwest). They ranked tree species for warmth preference and shade tolerance based on physiological growth studies and predicted that warm-adapted species would have increased in abundance. This did not occur in general. Instead, persistent changes due to past human disturbance appeared to override a climate signal in terms of species abundance. In the north, early disturbance resulted in reductions of conifers and increases of *Acer*, *Populus*, and *Quercus*. Fire suppression by mid-20th century led to increased abundance of mesophytic species such as *Acer saccharum*, which are cooler types, thus confounding expectations. They concluded that these forests will remain in climate disequilibrium for some time. These changes have likely affected forest productivity and the commercial value of forests because species differ in their growth rates, but the study did not quantify these factors.

Zhu et al. (2016) studied three leaf area index-based satellite metrics over 1982-2009 using 10 ecosystem models to integrate results. They reported that 25% to 50% of the globe evinced increased LAI over the period and <4% a decrease. They attributed 70% of the greening, mostly in the tropics, to changes in CO_2 and 8% to changes in ambient temperatures, mostly at higher latitudes. All three LAI data sets showed greening in the eastern half of the US, with one showing the entirety of Canada and the US except Alaska to be greening. The other two LAI products showed most or all of Canada to be losing leaf area. The inconsistencies across Canada were not explained.

Mao et al. (2016) used two satellite LAI data sets over 1982-2011 (30 years) to estimate northern hemisphere changes in vegetation. The mean of the two data sets showed strong increases in LAI over the eastern US and eastern Canada, and increases everywhere else except for decreases across arctic Canada, British Columbia, and Alaska.

Ju and Masek (2016) evaluated NDVI trends in Canada and Alaska over 1984-2012, masking out recently burned areas. They found 29.4% of the study area to be greening and 2.9% to be browning. In contrast to Mao et al. (2016), they found far northern regions to be mostly greening. The belt across central Canada showed neutral to mixed responses. Strong greening was evident in the agricultural belt of Manitoba west through Alberta, with much greening also in British Columbia.

De Jong et al. (2013) evaluated NDVI from satellite data over 1982-2008. They found a strong greening effect across the US and Canada except for the western boreal forest zone of Canada, west into British Columbia and eastern and southwestern Alaska. A narrow band along the west coast of the US also showed declines. They estimated 50% of the changes to be due to altered climate.

Kimball et al. (2007) estimated plant productivity over 1982 to 2000 for the western Arctic (western Canada and Alaska). The NOAA AVHRR Pathfinder data set provided LAI and absorbed photosynthetically active radiation (fPAR) for computation of NPP using the TEM model and regional climate data. They found no areas with decreasing NPP trends. The eastern, more forested half of the study region showed strong positive NPP trends of 10-20% over the period. The correlation of NPP with summer air temperature was 0.66.

Beck et al. (2011) and Verbyla (2008) both report growth declines in Alaska. Beck et al. (2011) used NDVI data over 1982-2008 combined with tree ring data from 839 mature, dominant trees. They found growth declines in most interior forests and greening across coastal zones in the North and West. Verbyla (2008) developed NDVI trends over 1982-2003 and found the same pattern, except for no greening on the west coastal zone.

Girardin et al. (2014) used NDVI data for 1979-2008 to estimate NPP for a region in Canada southeast of Hudson's Bay. They also obtained tree ring data back to 1688 for 724 black spruce (*Picea mariana*) trees, for which they analyzed BAI. They found a gradual decline in NPP over the full 30 years and a decline in BAI after the 1960s for trees of all ages. Their study did not appear to account for stand aging or competition effects.

Cohen et al. (2016) used Landsat imagery to evaluate forest disturbance for the conterminous US from 1985-2012. The TimeSync software was used to visually interpret 7200 plots. Decline, defined in terms of reduced cover over time as an indicator of mortality caused by drought, insects, disease, or other agents, could be drawn out across years for the same plot. Fire, harvest, and other disturbances were generally single-year events. Forest cover for decline plots declined an average of 1.5%/yr. An increase in US disturbance rates after 1995 was dominated by the mountain West region and to a lesser extent the lowland West region. However, shifts in the PDO have caused a decadal-scale drought in this region that matches the increased rate of decline (see Johnstone and Mantua 2014). Thus, this increase in disturbance may not portend a long-term shift.

Zhao and Running (2010) used remote sensing data to evaluate NPP globally over 2000 through 2009. They reported a slight upward trend in the northern hemisphere, a decline in the southern hemisphere, and a small decline globally. They found a positive trend across Canada and Alaska except for south and west of Hudson's Bay. There was a negative trend in the western US and Texas, consistent with drought during this period, and in the Northeast, with a positive trend elsewhere.

The work of Guay et al. (2014) throws some light on vegetation trend discrepancies identified from remote sensing data. They compared the updated GIMMS-NDVI version G to the earlier GIMMS as well as to shorter records from the more modern SeaWiFS, SPOT-VGT, and MODIS sensors over

1982-2008 and over the periods of sensor overlap for northern high latitudes. Less than half (46.1%) of the area had a greening or browning trend that all the sensors agreed on. NDVI also differed between sensors, ranging from about 0.53 to 0.71 in 2008, a 34% difference. Four of five sensors reported a rising trend in NDVI, with quite different slopes. GIMMS and MODIS both showed about half the area to be greening and half browning, with more greening in tundra and more browning in conifer forests. They suggested that these data products be calibrated against ground-truth measurements and that a bias toward detecting greening with SPOT may result from differences in the VGT1 and VGT2 sensors. A bias toward browning in SeaWiFS may be related to sensor degradation that has not been adequately accounted for. They concluded that GIMMSg and MODIS are the most reliable. Berner et al. (2011) further showed that, across northeast Russia and northwest Canada, correlations between ring width index and NDVI were highly variable and weak (r=0.43).

Using a 30-year (1982-2011) NDVI record, Gonsamo, Chen, and Lombardozzi (2016) found that NDVI trends were strongly positive in the US South and East, the Arctic, and in the southern boreal zone of Canada. However, the northern boreal zone into British Columbia was negative to strongly negative. The US West was positive to mixed, with a negative patch just southwest of the Great Lakes. They also estimated correlations of vegetation change with long-term cyclic aspects of climate and found that the patterns they detected were mostly coherent with both the Atlantic Multidecadal Oscillation (AMO) and Pacific Decadal oscillation (PDO), with greening areas positively related to AMO and PDO phases and browning areas negatively related. The US Rockies and Southwest were strongly positively related to precipitation deviations and negatively related to temperature. Much of Canada and Alaska responded positively to temperature. Other long-term patterns in climate factors were also related to spatial patterns of vegetation response. Peterson and Peterson (2001) and Peterson, Peterson, and Ettl (2002) also found effects of the PDO on 100-year-long time series for two species in the Pacific Northwest. These results indicated that past and possible future changes in vegetation are likely to have complex spatial and temporal structures. Thus, forest growth has likely not continuously declined or increased over the last 100 years in any region of North America, and growth trends over this period likely differ among regions.

De Jong et al. (2012) analyzed global NDVI trends over the period 1982-2008 (27 years). Overall, they detected net global greening. Most of the US and Canada was greening except for the far western US from California northward through the forested parts of Alaska, the northern boreal region south of the Arctic tundra, and west of Hudson's Bay, which were browning.

Potter, Li, and Hiatt (2012) derived trends in enhanced vegetation index (EVI) derived from MODIS data over 2000-2010 for the eastern US. They masked out agricultural and recently burned areas. Greening was detected in the far Northeast, west of the Mississippi River, and west of Lake Superior. Browning was seen in most of the remaining area. This result contrasts with all other studies. The short timeframe and natural forest aging could explain some natural decreases in estimated growth rates but not the large deviation from all other remote sensing studies described here previously. The authors stated that a small portion of observed declines could have resulted from sensor degradation but did not explain the differences from prior studies.

Some early studies using satellite imagery have now been superseded by longer records and better calibration, but are briefly mentioned here for completeness. Nemani et al. (2003) estimated NPP over 1982-1999 using fPAR and LAI derived from GIMMS and PAL data sets. They found positive NPP trends over most of North America except the US Southwest. Slayback et al. (2003) developed trends in NDVI over 1982-1999. Most of Canada had a nonsignificant trend in NPP compared to sensor noise, but the trend for significant pixels tended to be positive. The NPP trend for all of the eastern US above 35° latitude was positive.

Hicke et al. (2002a) found a net 8% increase in NPP for North America over 1982-1998, with decreases mainly in boreal Canada and the US Southwest (west Texas across to the California

border). The analysis of Hicke et al. (2002b), which overlaps with Hicke et al. (2002a), used NDVI data over 1982-1998 (17 years) in conjunction with the CASA carbon cycle model to estimate NPP changes across the US and Canada. They found a large increase in NPP across the Southeast, which they attributed to intensive silviculture. Large NPP increases in the forests of eastern Canada were attributed to rising precipitation and recovery from insect damage. British Columbia, Yukon, and Alaska reported increased NPP due to warmer spring temperatures. The area of western Texas across to the border of California and the farthest northeast of Canada were the only regions with large declines.

3.3   Tree Height Growth Rate Studies

Height growth of dominant trees is not as much affected by crowding as diameter growth and, therefore, is a useful metric for detecting changes in growth (Bontemps, Hervé, and Dhôte 2009). For example, in France, Bontemps, Hervé, and Dhôte (2009) used paired stands of European beech, one 50 to 75 years old and a neighboring one 100 to 175 years old, to estimate a century of change. The stands were dissected to obtain height/age curves. The authors found that the younger stands were up to 50% taller at the same age. Further comparison allowed them to determine that most of the increase in height growth took place after 1960. While this study took place in France, the advantages of their methods in terms of reduced confounding compared to tree ring analyses suggest this study as a model for future work. One caution, however, is that some prior work (e.g., Loehle 1988, 2000) suggests that longer-lived individual trees might grow slower than average due to growth-defense tradeoffs. An older stand might thus contain more slow-growing individuals. This was countered somewhat by Bontemps, Hervé, and Dhôte (2009), who selected trees that were canopy dominants in even-aged plantations.

The only study found for North America that used height growth was Gamache and Payette (2004). They studied a 300 km latitudinal transect in Quebec from the southern forest-tundra to the shrub-tundra. Sampled in 1999, stem dissections allowed height (and thus height growth) to be determined back over 200 years for the oldest trees. Height growth rates for black spruce since the 1970s progressively increased over the study period, especially in the 1990s. Tree line trees had increased growth the most, becoming comparable to more southerly trees. Topography played a complex role and growth changes could not be quantified from their analysis.

3.4   Mortality Events

Mass mortality is an obvious sign that forest growth has been negatively affected. Aspen is one species that has exhibited extensive mortality in some locations (see citations below). A complicating factor, however, is that aspen is a short-lived, disturbance-dependent species and thus, older stands will be inherently more subject to mortality events. Hogg, Brandt, and Kochtubajda (2005) studied aspen stand dynamics at 25 sites across western Canada over 1951 to 2000. They found stand-level BAI to have generally increased over the period, but this did not account for trees that died before their sampling date. They found that BAI was strongly affected by moisture availability and episodic widespread defoliation and other damage by insects, with growth varying up to 50% over several-year intervals. This high variability combined with stand aging complicates interpretation of dieback events. A severe drought, for example, in interior western Canada in 2000-2002 caused severe mortality, especially in drier aspen parkland (Hogg, Brandt, and Michaelian 2008; Michaelian et al. 2011). A severe drought over 2002-2008 caused extensive aspen mortality in Colorado (Anderegg et al. 2013; Worrall et al. 2008, 2010). Worrall et al. (2013) concluded that across its range, aspen dieback was typically preceded by drought, tended to occur on marginal (i.e., drier) sites, and was exacerbated by insect and pathogen attack. While aspen appears to be sensitive to drought, there is also evidence that sucker regeneration is common in the understory of stands experiencing dieback (Frey et al. 2004). A key factor in aspen decline may be the influence of ungulate browsing on aspen regeneration. Beschta et al. (2016) found that historical data on exclosures in Yellowstone National

Park and recent fluctuations in Rocky Mountain elk populations both point to herbivory as a limiting factor for aspen sucker success. In the northern part of the park, where elk abundance had declined, aspen stands were recovering. The following thus seems plausible: all aspen, but particularly old aspen stands or those on dry sites, are prone to dieback, and when there is excessive herbivory, are unable to recover.

Millar, Westfall, and Delany (2007) documented a mortality event in lower elevation, young limber pine stands in the eastern Sierra Nevada range over 1985 to 1995. This was a period of high temperature and persistent drought in the region, according to their data. They note that thinning caused by the drought led to increased resilience and no mortality during the subsequent 1999-2004 drought.

Yellow birch (*Betula alleghaniensis* Britt.) suffers episodic dieback across its range. Bourque et al. (2005) documented that dieback events are most likely to occur after a prolonged winter thaw followed by a severe freeze. Such events can cause cavitation, bark damage, and root damage. However, the authors did not document any trend over time.

Palik et al. (2011) documented dieback of black ash (*Fraxinus migra* Marsh) in Minnesota. Older trees on wetland sites appeared to be the most impacted. They speculated that hydrologic fluctuations and, because this species is not particularly long-lived, stand senescence could have played a role. Mortality was higher adjacent to roads where local hydrology was altered and road salt was potentially damaging roadside trees. They noted that the frequent dead trees near roads may give the impression of more widespread dieback than was the case based on their data.

Ouimet et al. (2013) concluded that white spruce decline in south central Quebec was due to potassium (K) deficiency on certain soils lacking exchangeable clays. They noted that budworm attack, which preceded the decline, tends to cause K leakage on these sites. Excess N from atmospheric deposition causes a nutrient imbalance that aggravates K deficiency. They reported that NDVI, an indicator of leaf area, went up sharply over 1982-1991, perhaps resulting in too much leaf area for the available K supply.

Regional droughts can be extensive and have large impacts, though they do not necessarily indicate a permanent condition. Droughts have been ongoing in California (Guarín and Taylor 2005) and the American West (van Mantgem et al. 2009) for the past 10 years. Even on sites experiencing drought, however, tree mortality rates should be interpreted cautiously. Thorpe and Daniels (2012) noted that self-thinning and succession accounted for most of the mortality trends in their study in Alberta, Canada. A closer look at the rising western mortality rates found by van Mantgem et al. (2009) for the American West and attributed to drought, shows that basal area, a reliable measure of live biomass and forest health, declined only about 5% (from their Figure S1) over 36 years. These forests are known to be aging due to restrictions on logging and fire suppression (e.g., Addington et al. 2017; Brown and Wu 2005), and this could account for much of the mortality they found, which was not consistent with the reported basal area trends. The modest decrease in stand density was also consistent with stand aging and again does not match the rapid increase in mortality if forest decline was truly the cause.

Of the papers reviewed, several documented growth declines or drought stress across western Canada (e.g., Peng et al. 2011; Walker, Mack, and Johnstone 2015). These studies exhibit some of the biases noted before, such as counting all mortality while ignoring stand aging (e.g., Peng et al. 2011), and thus provide ambiguous indicators.

In southeast Alaska and into British Columbia, yellow cedar (*Callitropis nootkatenis* (D. Don) Örsted ex D.P. Little) has been in decline for about 130 years (Wiles et al. 2012). The cause of this decline appears to be warming (Wiles et al. 2012), in contrast to the 1800s when growth and temperature

were positively correlated. On the other hand, Barrett and Pattison (2017) found stable basal area and low mortality over 1995-2013 and no range shrinkage for this species. Beier et al. (2008) found yellow cedar mortality events to result from warmer winters with thaw-freeze events. Thus, the current picture for this species is not entirely clear.

3.5   Model-Based Reconstructions of Historical Growth

Given historical climate data for a region and an ecosystem or tree growth model, it is possible to reconstruct potential vegetation histories. Twine and Kucharik (2009) reconstructed vegetation growth for the eastern US (Texas north to Canada and all east of this) over 1950-2002 by vegetation type. They held atmospheric CO_2 constant at 365 ppm and excluded management interventions. Their simulation yielded positive NPP trends in deciduous forest purely due to historical changes in climate factors across the region, especially over 1982-2002, and negligible change for coniferous forest. Del Grosso et al. (2008) simulated global NPP trends over 1901-2000, with fixed CO_2. They found that total NPP (TNPP) increased from 12% to 50% over virtually all of Canada, central and western US (but not the US Rockies region from New Mexico up through Colorado) over the 100 years, and 13% globally. Results from simulations such as these depend critically on the reliability of interpolated older weather station records, realism of the growth models used, and whether CO_2 enhancement is included.

Pan et al. (2009) simulated forest NPP using the PnET-CN model for the Mid-Atlantic US states (Virginia and West Virginia northward through New York) over 1895-2000. They used a factorial design, and historical climate and other data, to evaluate contributions to forest growth. They reported a 29% growth enhancement due to changes in atmospheric composition (+14% from rising CO_2, +17% from N deposition, +6% from N/CO_2 interactions, and -8% from ozone). Changing temperatures based on historical data caused only a +4% increase in NPP. Regrowth of forests also contributed positively to carbon gain.

Girardin, Bernier, and Gauthier (2011) combined tree ring records, forest inventory data, fire extent records, and a productivity model to estimate historical patterns of NEP over 1830 to 1999 in jack pine (*Pinus banksiana*) forests of the Canadian southern boreal zone just east of the Great Lakes. They found that over this period, annual fire extent declined, leading to a mean age shift in jack pine from 87 years in the 1920s to 131 years in 1999. They found a significant upward trend in NEP due to increased precipitation and longer growing seasons of 0.39 g C m^{-2} y^{-1} over 1901-2009. At the same time, because older stands of jack pine are less productive, forest aging after the 1930s reduced carbon assimilation 12%, enough to offset the climate effect (mainly warming) in 75% of their ensemble of simulations. They noted that forest age structure can complicate interpretations of historical trends.

3.6   Plot-Based Reconstructions

Historical reconstructions based on permanent plots and/or tree ring records have the potential to provide reliable data, although ongoing tree mortality should be considered in such studies. Searle and Chen (2017) examined 1797 permanent sample plots across western Canada (Alberta, Saskatchewan, and Manitoba) spanning 1958 to 2013. Over the period, broadleaf trees and early-successional conifers increased in relative abundance and late-successional conifers decreased. Late-successional conifers were predominantly older (>150 yr) and broadleaf trees and early-successional conifers were mainly younger (<100 yr). They concluded that broadleaf species and early successional conifers have been favored by rising CO_2, and that rising temperatures favored early- vs. late-successional conifers. They did not find moisture to explain the compositional changes. The observed increase in relative abundance of younger, faster-growing trees could have increased self-thinning mortality and moisture stress. Luo and Chen (2013) studied a subset of 887 of these same inventory plots for Alberta and Saskatchewan over 1958 to 2007. They found that both self-thinning

and warming increased mortality over the period, with moist-site, late successional species, including white spruce, suffering more mortality. Similarly, Jiang et al. (2016) found drought stress in Alberta to have increased over 1985 to 2010, with white spruce suffering more than aspen.

Pretzsch et al. (2017) used tree ring analysis to evaluate growth at 10 urban and nearby rural sites around the world. They evaluated only healthy trees free from competition using basal area vs. age as the metric of response. There was one site in the US (Houston) and one in Canada (Prince George). At all sites, they detected a significant growth enhancement since 1960, which they attributed to change in climate factors. Tree size was 2% greater at age 50, 11% greater at age 100, and 17% greater at age 150 for periods after 1960 compared to before 1960 (age as of the sampling date and from the tree cores). Of particular interest, urban trees at high latitudes grew much faster than rural trees, which they attributed to the urban heat island effect. Dye et al. (2016) evaluated aNPP at three sites in Maine, Massachusetts, and West Virginia, using both permanent plots and tree ring data. Results based on the two methods agreed reasonably well, but in neither case was a trend evident in the three study areas from 1990, 1970, and 1980, respectively, to about 2010, though large confidence intervals may have obscured any trends.

Buma and Barrett (2015) used data from the US Forest Service's Forest Inventory and Analysis Program (FIA), collected in the rainforests of southeast Alaska, to evaluate forest growth trends for remeasurement dates between 2004 and 2010. Considering only forested stands (not areas of forest expansion that they also detected), they found a net accumulation of biomass of 0.24 Mg/ha/yr. Most of this accumulation was in the north, where rates were 0.79 Mg/ha/yr. Lower latitudes had a rough balance between gains and mortality. Due to topography, patterns of loss and gain were complex and fine-scaled.

Thomas et al. (2009) sought to evaluate the impact of anthropogenic nitrogen deposition on forest growth. They used the 19-state region from Wisconsin east to Maine and Kentucky east to Virginia, with FIA and N deposition data as inputs. They excluded heavily disturbed plots, but could not remove confounding by CO_2 effects. They found that species associated with arbuscular mycorrhizae especially benefited from N deposition, because this fungus cannot help the tree obtain N. Some species showed reduced growth, either due to loss of cations on certain soils or increased competition. Given actual recent N deposition rates, they estimated an overall 40% increase in aboveground forest growth compared to pre-industrial conditions (including CO_2 effects), even accounting for reduced growth of some species and changes in climate factors.

McMahon, Parker, and Miller (2010) studied tree biomass changes at a site with 55 census plots in Maryland. As a baseline, they determined the expected stand biomass as a function of age using the Monod function, which smoothly approaches an asymptote for older stands. This graph based on age, up to 250 years, represented historical growth trends. Actual measurements of these plots for a range of remeasurement intervals showed faster growth at all ages than expected compared to the baseline. Most plots showed up to twice the periodic growth vs expected, with a few up to four times. The authors attributed enhanced growth to local warming, longer growing seasons, and rising CO_2 but did not determine effects statistically.

In a study at the Bartlett Experimental Forest in northern New Hampshire, Pontius, Halman, and Schaberg (2016) found, based on plot data from 1931 and 2001, that the aging forest was continuing to accrue biomass at rates greater than expected based on age. Selected stands had a mean age of 170 years in 1931. They attributed the increased growth (90% higher 10-year growth increments) to increased dominance of larger trees, nitrogen deposition, and changes in climate factors (qualitative analysis). These stands had not experienced storm or insect damage and thus showed upper bounds on growth. They did not account for CO_2 fertilization effects.

Dragoni et al. (2011), using flux tower measurements at a site in south-central Indiana, estimated an approximate 38% increase in NEP over 1998-2008. They attributed this increase to warming and longer growing seasons, but made only a qualitative attribution.

Wu et al. (2014) evaluated data from 3432 long-term plots in British Columbia over 1956 to 2001. They calibrated the InTECC growth model to NPP determined by flux tower data to remove stand age effects (decreasing NPP with age) and to estimate CO_2 and N deposition effects. They found a roughly 24% increase in NPP for maritime areas and 36% increase for inland (higher, cooler) areas. After correcting for forest age effects, the relative ranking (maritime vs. inland) flipped and growth enhancements increased, but percent increases could not be determined from their age-corrected plots which were on an anomaly basis. The authors found that ≈70% of the NPP increase was due to warming and most of the remaining increase was due to rising CO_2 and N deposition.

Graumlich, Brubaker, and Grier (1989) found a large growth enhancement based on four sites in western Washington. Using reconstructions for stands without any obvious mortality (evident due to the slow decay of large trees in that locality), they inferred a regional increase in growth of 60% over 1880 to 1979. They ruled out a significant CO_2 effect and attributed most of the enhancement to warming, with precipitation having mainly short-term effects.

McIntyre et al. (2015) used US Forest Service forest inventory data from surveys in the 1930s vs. the 2000s to study changes in California forests. Over this time period, they found a 30% increase in tree density, fewer large trees, and a 19% reduction in basal area (an indicator of biomass). However, Roesch and Van Deusen (2010) showed that a change in survey methods across the two time periods has the effect of making large trees less observable. In addition, forest harvesting since the 1930s could produce these same changes in structure by creating a younger forest.

McKenzie, Hessl, and Peterson (2001) used tree ring records from across the West to evaluate growth trends over 1880 to 1980. They found a periodic signal in the Southwest, as discussed previously in the section on mortality. They found large positive growth trends at a subset of sites and no declines. However, Nehrbass-Ahles et al. (2014) concluded that the data selection method used by McKenzie, Hessl, and Peterson (2001) was likely to yield a positive bias to growth trends.

4.0   SUMMARY BY REGION

In the following section, results are summarized by region. Inconsistencies between remote sensing study results are discussed at the end of this section.

4.1   Alaska

Evidence concerning ecotone and elevational shifts in Alaska generally represents long-term trends (50 to 200 years). All reviewed studies reported expanding forest, consistent with trends in Canada (see below). Forest expansion was reported by Dial et al. (2015) and Suarez et al. (1999), with the latter also reporting more rapid tree growth over the past 150 years. However, the reported forest expansion was quite slow. The exception was in the rainforests of southeast Alaska, where Buma and Barrett (2015) found rapid forest expansion and increased growth.

In distinct contrast, results from studies based on remote sensing methods conflicted. Declines were reported by Beck et al. (2011), de Jong et al. (2012, 2013), Mao et al. (2016), and Verbyla (2008). Positive trends were reported by Guay et al. (2014), Hicke et al. (2002b), and Nemani et al. (2003). Ju and Masek (2016) reported 29.4% of the area greening and only 3.0% browning, Buma and Barrett (2015) found a 0.24 Mg/ha/yr biomass gain in southeast Alaska, and Kimball et al. (2007) found a 10-20% increase in NPP. These contradictions, perhaps due to remote sensing methods, are discussed below.

4.2   Western Canada

Western Canada has been well-studied but, as in Alaska, contradictions exist. Some studies have reported forest expanding over long periods into grassland or tundra (Conway and Danby 2014; Jackson et al. 2016; Masek 2001), but slowly. De Jong et al. (2012) found net greening in Canada but de Jong et al. (2013) found browning in western Canada including British Columbia. Other observations include a 12 to 50% TNPP increase (Del Grosso et al. 2008), a positive trend in NPP since 1982 (Girardin et al. 2016) except in the upper western provinces but no trend since 1950, mixed results for NPP (southern boreal strongly positive, northern boreal negative) since 1982 (Gonsamo, Chen, and Lombardozzi 2016), rising NDVI (Guay et al. 2014), large NPP gains in British Columbia but small declines elsewhere in this region (Hicke et al. 2002b), and increasing BAI since 1951 but dieback events (Hogg, Brandt, and Kochtubajda 2005). Girardin et al (2014) found recent declines south of Hudson's Bay using two methods, in concordance with Zhao and Running (2010). Ju and Masek (2016) found a strong net number of greening pixels. Kimball et al. (2007) found a 10 to 20% NPP increase. Mao et al. (2016) detected NPP decreases in British Columbia. Zhao and Running (2010) found increased NPP in western regions. Nemani et al. (2003) found net positive changes across Canada, and a 30% NPP increase was found in British Columbia (Wu et al. 2014). Zhu et al. found mixed results that depended on the LAI data set used.

As is the case for Alaska, it is not possible to reconcile these contrasting results except to speculate that the various remote sensing data products are not yet mature for these forest types. When compared to growth, mortality, and water stress data, there is evidence that the western boreal forest (excluding British Columbia) is currently under moisture stress and showing reduced growth. However, even here, some results may be confounded by natural stand dynamics (e.g., succession, aging) or may be short-term trends (due to recent drought).

4.3   Eastern Canada

Results for eastern Canada are more consistent than those for Alaska and western Canada. Greening has been reported by de Jong et al. (2012, 2013), Del Grosso et al. (2008), and Girardin et al. (2016) since 1982 but others have found no net productivity trend since 1950 based on plot and satellite data (Gonsamo, Chen, and Lombardozzi 2016, Guay et al. 2014, Hicke et al. 2002a, Ju and Masek 2016, Nemani et al. 2003, Zhao and Running 2010). Girardin, Bernier, and Gauthier (2011) estimated NEP gains of about 12% over the past 100 years due to local warming but an almost equal reduction due to stand aging for jack pine stands. Strong increases in productivity were reported by Gamache and Payette (2004), Hicke et al. (2002b), and Mao et al. (2016). Only Zhu et al. (2016) showed mixed results. Thus, the weight of evidence suggests that growth increases in this region have been reliably detected, though probably not on every site.

4.4   Southwest and Inland West

Multiple lines of evidence point to expansion and densification of Ponderosa pine stands over long timeframes (Addington et al. 2017; Brown et al. 2015; Millar, Westfall, and Delany 2015) as well as increased growth of Ponderosa pine due to rising CO_2 (Soulé and Knapp 2006). Several studies documented increased greenness or productivity or mixed results (e.g., de Jong et al. 2013; Del Grosso et al. 2008; Gonsamo, Chen, and Lombardozzi 2016; Hicke et al. 2002a; Mao et al. 2016), but other studies showed declines in this region (Cohen et al. 2016; de Jong et al. 2012; Hicke et al. 2002b; Nemani 2003; Zhao and Running 2010).

The consistent spatial trend of expanding forests over the past 100 years indicates increased growth due to reduced fire, rising CO_2, grazing, and perhaps changes in climate factors. In this region, forests tended to show rising levels of more moisture-demanding and fire-intolerant species, such as Douglas-fir (*Pseudotsuga menziesii*) and true firs (*Abies* spp.), suggesting both reduced fire and rising

precipitation as causes. On the other hand, more recent negative trends probably reflect recent droughts. Some of the disagreement across studies no doubt also reflects methodological differences.

4.5   Pacific Northwest (Coastal)

Some large-extent remote sensing studies indicate increased growth in this region during the satellite era (de Jong et al. 2012, 2013; Gonsamo, Chen, and Lombardozzi 2016; Hicke et al 2002a; Mao et al. 2016; Nemani et al. 2003). Studies conducted using other methods also suggest increased growth. A large increase since 1901 in productivity for the US as a whole, including this region, was indicated by Del Grosso et al. (2008). Graumlich, Brubaker, and Grier (1989) found a 60% increase in NPP over 1880 to 1979 in Washington although small declines were reported by Hicke et al. (2002b) and Zhao and Running (2010) over 1982-1998 and 2000 to 2009, respectively. Except for these last two studies, increased growth seems to be a consistent diagnosis, with two studies spanning 100 years.

4.6   Eastern US

This region spans from the Great Plains eastward, including the Midwest and South. Remote sensing studies show the entire region, with local exceptions, to be neutral to greening (Cohen et al. 2016; de Jong et al. 2012, 2013; Dye et al. 2016; Gonsamo, Chen, and Lombardozzi 2016; Hicke et al. 2002a, 2002b; Nemani et al. 2003; Twine and Kucharik 2009; Zhao and Running 2010; Zhu et al. 2016). Multiple studies found very strong positive local to regional trends, including a 12 to 50% TNPP increase over the whole US since 1901 (Del Grosso et al. 2008), a large NPP gain in the Southeast (Hicke et al. 2002b), a strong increase in the East (Mao et al. 2016), an approximate doubling of growth in Maryland over 100 years (McMahon, Parker, and Miller 2010), a +29% NPP increase due to atmospheric change and +4% NPP increase due to local warming (by simulation) over 1895-2000 (Pan et al. 2009), an almost doubling of periodic aboveground biomass increment in New Hampshire since 1930 (Pontius, Halman, and Schaberg 2016), and a 40% NPP increase compared to preindustrial times in the North Central to Northeast regions (Thomas et al. 2009). Only Potter, Li, and Hiatt (2012) reported mostly a browning vegetation index across this region based on remote sensing data. This provides strong support for a conclusion of greatly enhanced forest growth over a century or more, especially in the Northeast where more studies have been done.

5.0   DISCUSSION

In the studies evaluated, there were some inconsistencies, and some of these relate to methods. For example, Song (2013) notes, "At present, mapping biomass remains predominantly empirical because there is no direct physical relationship between reflected energy in visible, near or mid infrared wavelengths and biomass… Although optical images have been successfully used in mapping biomass in low biomass areas, it remains a challenge to map biomass in forested areas with high biomass density due to signal saturation." Signal saturation applies to LAI estimates as well, which are used to estimate NPP. The omission of CO_2 effects on NPP from remote sensing products (De Kauwe et al. 2016) could also resolve some of the inconsistencies noted between browning estimates from satellite data and rising growth estimated from forest expansion and other methods. Finally, the study of Buma and Barrett (2015) in southeast Alaska reported that losses and gains were happening at very fine, patchy scales, which may be evaluated differently depending on remote sensing method and map scale. We may thus be forced to accept the inconsistencies in estimated trends from remote sensing until these issues are resolved.

Several other aspects of methods and data used in the reviewed studies warrant consideration when interpreting results. As discussed earlier, factors such as changes over time in stand density and age can influence analyses based on tree rings and it is not always possible to determine from the description in a publication exactly how the analysis was performed. Unusual events in a region, such

as uncharacteristically high or low levels of disturbance or insect damage, can make extrapolation to wider areas problematic. Finally, in a few studies, forcings could be partitioned to some extent, but in most reviewed papers, the authors could only infer the causes of trends.

Overall, quantifiable growth enhancements, some large, over up to 100-year timeframes are evident in the eastern half of the continent and the Pacific Northwest. In the Mountain West and the Southwest, forest has been spreading and getting denser, but periodic drought obscures current trends. Alaska and western Canada show slow forest expansion over long time horizons, but recent (over the last 30 years) trends are ambiguous, with some evidence of drought stress.

An assumption underlying the use of yield tables and site index curves in forestry is that short-term weather fluctuations will average out over the life of a stand, making growth projections mostly reliable. If conditions change radically over decades, however, such relations could be altered. Numerous studies cited here (e.g., Dragoni et al. 2011; McMahon, Parker, and Miller 2010) found major increases in productivity over just the past few decades. Thus, yield tables and site index curves, even from the 1980s, might significantly underestimate growth. Conversely, in areas such as western Canada or the Southwest where recent growth reductions may exist due to drought, projections will over-estimate growth. A general ongoing effect is rising CO_2 which accelerates early tree growth (LaDeau and Clark 2001; Loehle 1995) thus potentially distorting yield tables and site index curves, and favoring some species more than others. Also, as CO_2 rises, trees become more fecund at an earlier age (LaDeau and Clark 2001), with implications for seed orchards and recovery after large fires. Thus, the weight of evidence from reviewed studies indicates that, in many regions, growth relations have been changing over time.

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