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The case for stand management guidelines as dynamic as global change: Aspen forest stockings of the western Great Lakes

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ABSTRACT

Since the development of contemporary stocking techniques a century ago, the combination of climatic, atmospheric, financial, and social factors that determine forest management strategies have changed, altering aspen stand dynamics in the western Great Lakes, USA. Despite this, aspen management is still informed by 1970s management guides that are based on 1920s inventories; hence, a century exists between the data that underlie current management guidelines and current stand conditions. We hypothesized that current aspen stands may support higher stocking and height growth than nearly a century ago at relatively similar age and site indices, due to increased atmospheric CO_2 concentrations and fertilization, intensive coppice harvests, and other factors. To explore this question, we compared historic aspen observations with comparable contemporary data from the USDA Forest Service's Forest Inventory and Analysis program. The results show increased stand stocking levels as well as increased height growth of aspen throughout the region over the historic inventory data. Although other controlled experimental studies support the hypothesis of increased carbon fertilization altering aspen size-density relationships, our study is the first to examine an empirical application to forest management guides. Our results suggest a comprehensive reevaluation of aspen growth dynamics under contemporary environmental conditions is warranted. We highlight the need to assess the value of current stocking standards in an era of increasingly variable environmental conditions and to reimagine a more dynamic, responsive, and predictive approach to guide forest management for future application as global change may accelerate.

1. Introduction

Today, aspen (*Populus* sp.) forests are circumpolar and, in Canada and the conterminous United States, comprise over 47 million hectares and represent 11.2% and 2.9%, respectively, of each nation's total forest cover (NFI, 2013; Miles, 2019). Aspen play an important role in the pulp and paper industry globally and provide early successional habitat to various species (e.g., ruffed grouse [*Bonasa umbellus*], woodcock [*Scolopax minor*], masked shrew [*Sorex cinereus*], and moose [*Alces alces*]) (Weber et al., 2006). In the United States (US), annual aspen removals amount to 77.3 million m^3, making it the seventh ranked forest products species and serves as a keystone resource in the forest industry for several northern states including Minnesota, Wisconsin, Michigan, and Maine (Miles, 2019). As an ephemeral transitional forest type, disturbance or management is necessary to maintain the aspen covertype in the landscape and meet objectives to achieve the provisioning of many ecosystem services (e.g., habitat and fiber production). In the western Great Lakes region of the U.S. (henceforth Lake States), substantial efforts have been invested in the advanced planning, proper silvicultural treatments, and an accurate understanding of potential future outcomes associated with trembling aspen (*P. tremuloides*) forest management. Yet, the impact of numerous environmental, climatic, and silvicultural factors on the growth of aspen are not well understood and, therefore, information available to aspen land managers may not be adequate to achieve management objectives.

Climate change factors alter several physiologic mechanisms in aspen that result in shifting growth patterns that may not be considered in current management guides. Studies of free-air CO_2 enrichment

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(FACE) sites suggested that aspen trees may now be growing faster and at greater densities than previously expected due to CO_2 fertilization allowing for increased photosynthetic rates (Kubiske et al., 2019; Dickson et al., 2000; Norby et al., 2005; Curtis and Wang, 1998). Longer growing seasons may extend annual growth opportunities and allow more total growth to occur in the entire stand (Schimel et al., 2015). Hydrologic changes of precipitation quantity, intensity, and timing also result in varying degrees of impact to individual and stand growth rates (Reich et al., 2018). Additionally, global change also affects tree physiology and stand dynamics that can dramatically affect the growth, composition, and resiliency of the entire forest. It is unclear to what degree current aspen growth and yield tools integrate global change factors, and to what extent that uncertainty plays a role in the management of such an economically and ecologically important forest type.

In addition to the environmental and climatic change factors, the approach to aspen management has changed in response to increased economic utilization due to evolving wood markets (Balatinecz and Kretschmann, 2001), improved harvesting methods (Rittenhouse et al., 2012), and new regeneration and thinning strategies (Cleland et al., 2001). Historically, aspen was not always considered commercially valuable. For instance, an excerpt from *Forest Possibilities of Aspen Lands in the Lake States* (Kittredge and Gevorkiantz, 1929, p. 7) reads, "A desirable solution of the problem of the use of aspen lands would be the replacement of aspen by other more valuable species, as spruce or pine." The emergence of aspen as a desirable feedstock for the pulp and paper industry during the 1940s brought aspen management to the forefront (Stearns, 1997), and by the 1970s the objective for aspen management was to "improve yields of timber, water, and wildlife by clearcutting and regenerating pure, fully stocked aspen stands" (Perala, 1977, p. 1). Over the last 40 years, management objectives have shifted to encompass multiple goals including wood volume production, wildlife habitat, old growth and aesthetics, and ecosystem services (Domke et al., 2008). Thus, the degree to which currently available guides provide accurate information to today's managers is unclear, because outdated guides may not include consideration for modern aspen management objectives, contemporary silviculture techniques, or impacts of CO_2 enriched environments.

One of the seminal references for aspen management in the Lake States is the Manager's Handbook for Aspen in the North Central States (Perala, 1977; "1977 Handbook" hereafter) (e.g., Neumann, 2015). Our

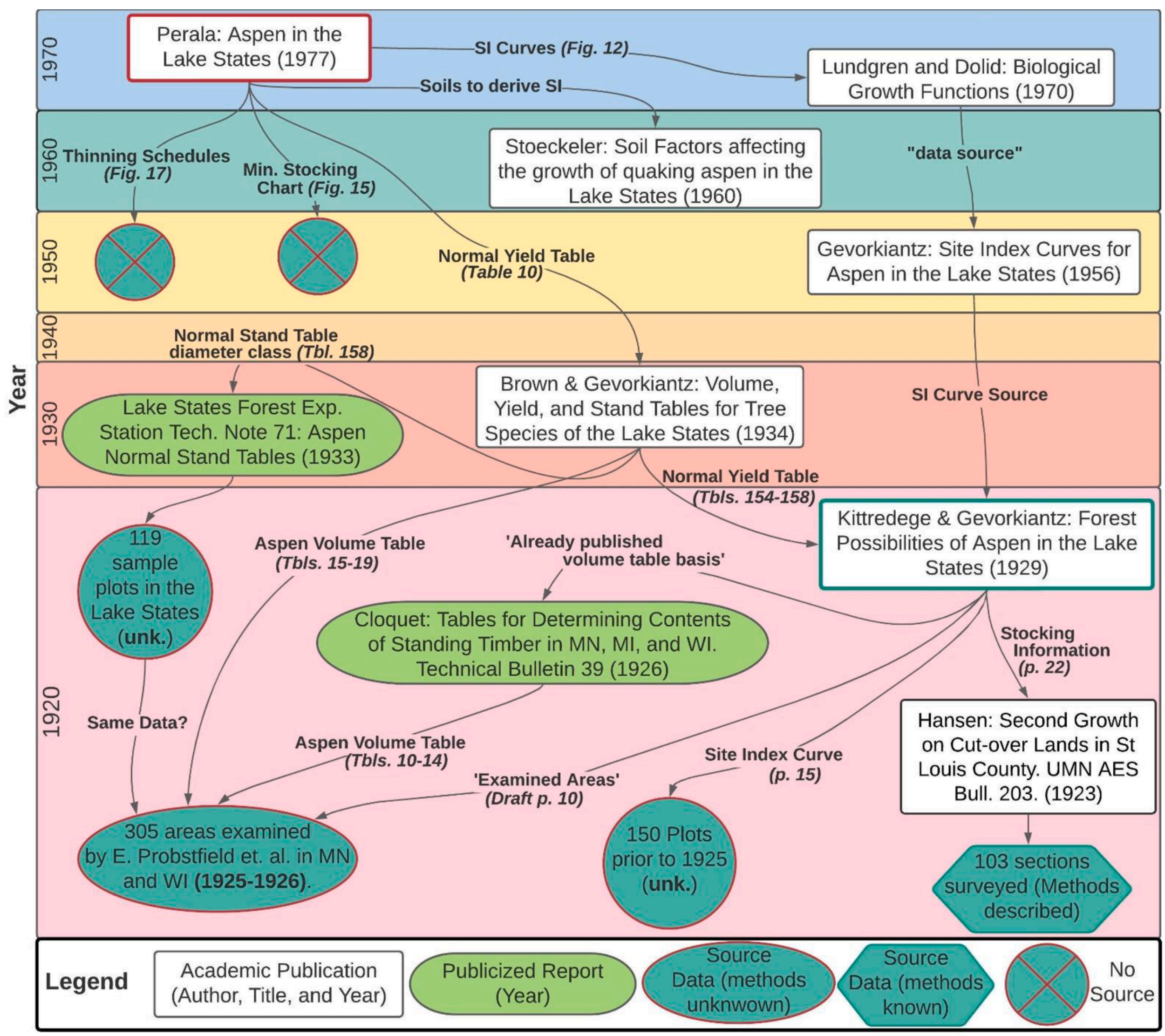

Fig. 1. Aspen management research history diagram. Years are displayed on the y-axis. The diagram displays the data sources used to develop Perala's (1977) publication (top) that is still used for management today. Perala's *Thinning Schedule* and *Minimum Stocking Chart* do not have any directly cited data sources. The *Normal Yield Table* comes from published data from the Brown and Gevorkiantz (1934) publication. Perala's *Site Index Curves* use Lundgren and Dolids' (1970) functions that, in turn, cited Gevorkiantz (1956) that was a republication of the original Kittredge and Gevorkiantz (1929) work.

literature review of the information used in the 1977 Handbook indicates that the empirical data are decades older than the publication itself. The 1977 Handbook inventory data sources and associated inventories date back to field measurements taken in 1925 and 1926 (Kittredge and Gevorkiantz, 1929) (Fig. 1). The site index curves that were parameterized by Lundgren and Dolid (1970), which are still being used today for forest planning, management, and yield estimation (Carmean et al., 1989; USDA Forest Service, 2008), have no direct antecedent prior to Kittredge and Gevorkiantz (1929). Additionally, many of the yield tables used in the 1977 Handbook originate from similar historic data.

Updating management guides is not a new idea, and aspen management particularly benefits from updates due to its relatively short biological rotation age and role as one of the key economic species in the Lake States. However, dynamic management guides that are responsive to changing conditions are currently uncommon and difficult to implement. The opportunity costs of management decisions made using inappropriate or outdated growth and yield data include loss of revenue, time, ecosystem services, plant and wildlife diversity, and flexibility to identify and react to shifts in growth patterns (Kangas, 2010).

Many of the management guides for various Lake States forest types are decades old and formulated using even older measurement data (Kubiske et al., 2019). In this paper, our goal was to review a long-standing management guide and its suitability to inform contemporary forest management by comparing the underlying stand data used to develop the guidelines to similar contemporary data. In order to broadly evaluate this topic, we used the aspen forest type and associated empirical data in the 1977 Handbook (Perala, 1977) compared with contemporary observations to assess potential discrepancies/divergences of stocking levels and dominant tree heights. Such analysis might serve as a foundational assessment to justify future work within the forestry sector that focuses on constructing management guides that are dynamic and inclusive of emerging datasets and models to enable adaptive management (i.e., evolving silvicultural techniques in response to changing conditions).

2. Material and methods

2.1. Data sources

Data used for the study came from two sources: Kittredge and Gevorkiantz (1929) (henceforth KG29) provided tabulated historic data from the 1920s, while contemporary data was derived from the Forest Inventory and Analysis (FIA) program (USDA, 2021).

KG29 aggregated their findings into multiple tables for their publication. The first table includes trees per acre and basal area (BA) per acre, providing the earliest stocking information in the Lake States (Fig. 1). Gevorkiantz used data surveyed from 106 different aspen stands with unknown inventory protocols and developed a Normal Yield Table with smoothed stocking information. Exact details and extent of their statistical methods were not documented in the 1929 publication or personal notes.

The FIA program, administrated by the United States Department of Agriculture Forest Service, encompasses the nation's largest continuous and congruous forest inventory system. Historically, FIA utilized a periodic inventory to procure forest estimations. In 1999, it was converted to an annual inventory system with recurrent sampling based on a state-determined standardized cycle. Nationally, plots are comprised of four 0.0169-hectare circular plots where all stems $\geq$ 12.7 cm diameter-breast-height (dbh; 1.37 m above ground) are measured and four 0.0013-hectare microplots where all stems $\geq$ 2.54 cm dbh are assessed (Bechtold and Patterson, 2005). In addition to stem counts and tree data, various other observations are recorded at the plot level including disturbances, treatments, slope angle, field call of covertype, and other vital plot data. Data from 2012 to 2018 were used for this analysis and represents the most recent complete measurement of the Lake States (USDA, 2021; Burrill et al., 2021).

2.2. Contemporary FIA matching and replication

2.2.1. FIA filtering for contemporary FIA matching

All KG29 data are used as originally published in their *Table I*. We selected and filtered recent FIA data to best match the listed criteria for plot selection in KG29 (Fig. 2). Representative 'sample plots' were made using FIA plot and forest condition data filtered by aspen covertypes and reported in per-hectare estimates. Recently disturbed, recently treated, and sliver plots (plots where the forest condition exists on less than 25% of the full FIA plot) were removed from the dataset to better resemble the plot-based data within KG29. To further model KG29 plot selection and reporting, records with <69% stocking (considered understocked by KG29) were removed, and all sample plots were categorized into 10-year age and 3.048 m site index classes. Presumably, KG29 would have used plots primarily composed of aspen. To mimic this, records with <50% aspen by BA (m^2 ha^{-1}) were removed, resulting in 1,106 samples. A second subset of recent FIA data with higher aspen purity was selected using the same process defined above, but only including records with $\geq$80% aspen by BA, resulting in 530 samples (Fig. 3). Finally, KG29 used a minimum tagging limit of 2.54 cm at dbh, and therefore we used subplot and microplot data from FIA samples that matched the 2.54 cm limit used in the historic dataset.

2.2.2. Selection and replication for stocking and self-thinning

Kubiske et al. (2015) suggested that atmospheric CO_2 enrichment allows greater carrying capacity within aspen stands, resulting in a higher self-thinning line than in traditional stocking charts. To examine for similar changes in the self-thinning line at the landscape level, individual FIA records were randomly selected from the Contemporary FIA dataset to replicate the plot count as reported in KG29 (Fig. 1). To recognize the likelihood of past forest management emphasizing only monoculture settings and the potential that KG29 may have selected only pure aspen plots, we conducted the Contemporary FIA matching process with both the mixed ($\geq$50% aspen BA) and pure ($\geq$80% aspen BA) aspen datasets.

To match the KG29 data, we drew with replacement a corresponding number of records within each age class and site index category to replicate the plot distribution in KG29 (Table 1). Contemporary FIA matches were not conducted for age/site index class combinations that had no original KG29 plots ($n = 0$). Thus, 106 FIA sample plots were selected to match the 106 plots used within KG29. Once the records were selected, the average BA (m^2 ha^{-1}) and tree density (count ha^{-1}) were calculated within the combination of each age class and site class category. The Contemporary FIA matching selection process was then repeated for 1,000 iterations, and results of all selections compared and averaged. We used the averaged BA m^2 ha^{-1} and density values to create a traditional stocking chart for comparing the self-thinning line or carrying capacity from the recent data to that found in KG29 (after Kubiske et al. (2015)).

2.2.3. Selection and replication for site index and height growth

Kubiske et al. (2015) also observed increased aspen height growth under increased atmospheric CO_2. To investigate this effect at the landscape level, aspen dominant canopy heights (m) and ages (years) were selected from the same FIA datasets used to examine stocking ($\geq$50% aspen by BA and $\geq$80% aspen by BA). The same random selection approach with replacement was used to match the plot counts from KG29, with the exception of subsetting both historic and modern data solely by age class. This allowed us to observe differences in dominant height growth by age between KG29 and the present without relying on previous definitions or models of site index. Records were aggregated into seven age groups in 10-year age class intervals from 20 to 80 years. Again, 106 records were used in each match and ran for 1,000 iterations. The average dominant heights in each age class were averaged across all

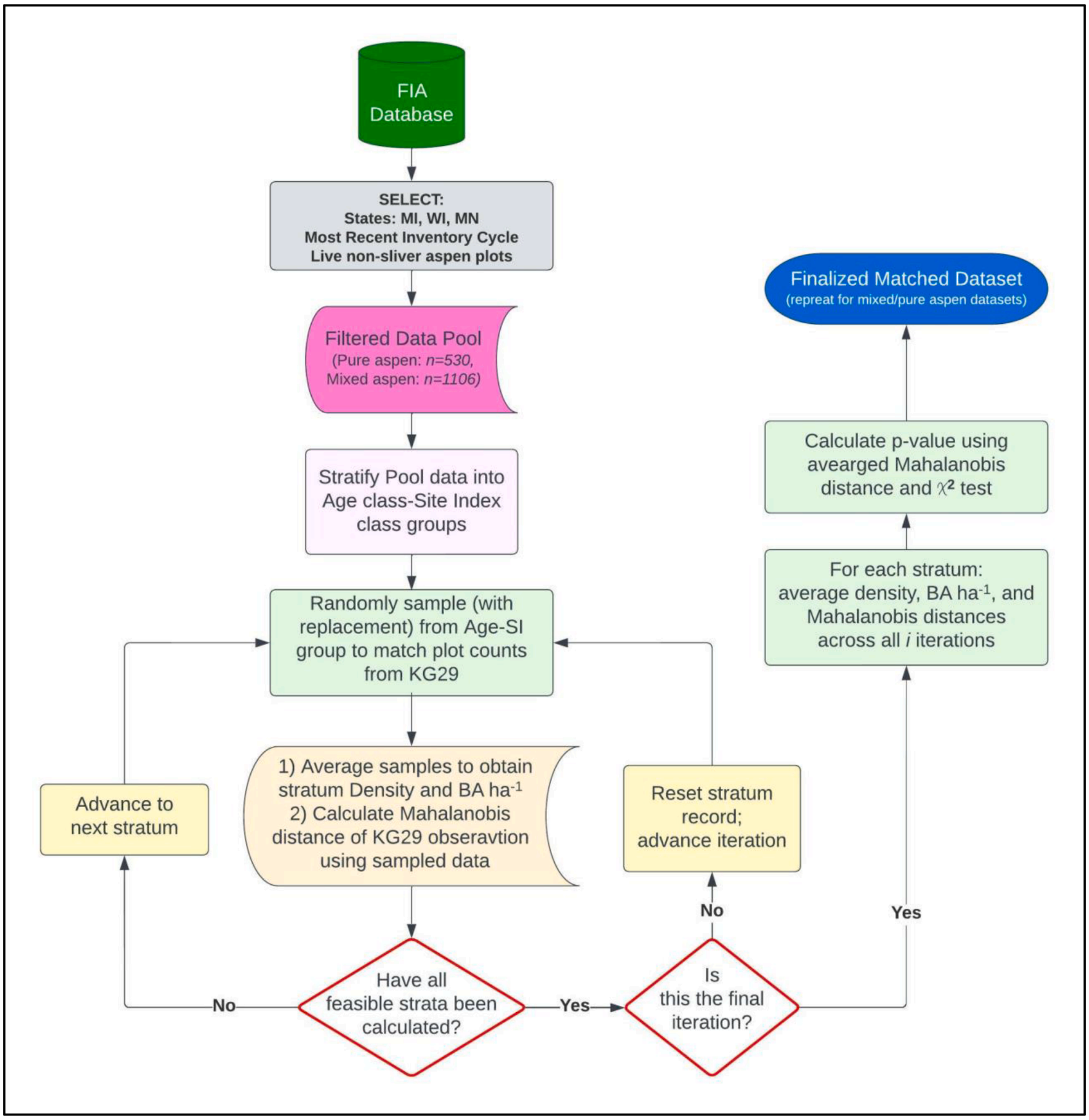

Fig. 2. Forest Inventory and Analysis (FIA) data selection and Contemporary FIA matching process flow model. FIA data were filtered based on similar stand classification criteria and locations (Lake States) used to compare aspen stocking levels in the Lake States. Filtered FIA data were stratified into common site index and age class categories, then sampled with replacement at the same plot frequency as the Kittredge and Gevorkiantz (1929) dataset.

iterations, and the entire process was completed for both pure and mixed aspen datasets.

2.2.4. Statistical analysis and data management

Since we compared results of two variables (BA m^2 ha^{-1} and density^{-1}) within a preselected category, we used a multivariate statistical approach to determine strength of the differences using the matched data within each iteration. Each age/site class category in the stocking analysis or each age category in the dominant height analysis was used as a training dataset to estimate the multivariate centralization and statistical variation of the two variables. We then calculated a Mahalanobis statistical distance for the comparative multi-dimensional KG29 value (Mahalanobis, 1936). Mahalanobis distances are a widely used statistical generalization of the vectorized disparity from the mean used in various data science applications of cluster analysis and classification including machine learning, remote sensing, biometrics, and other ecological applications (Crookston and Finley, 2008; Dasgupta and Mahalanobis, 2018; Etherington, 2021). Distances for categories with less than two observations were not calculated due to procedural requirements. We then averaged the multivariate Mahalanobis distances for all 1,000 iterations in both analyses and calculated the comparative p-value using a chi-squared test (Table 1) (Elfadaly et al., 2016). This method requires multivariate normality, so quantile-quantile (Q-Q) plots were created and reviewed for each age/site class category using Mahalanobis distances for all available FIA data points. Note that Mahalanobis distances are susceptible to bias when there is a lack of sufficient learning samples (Kabayashi, 2020), so p-values associated with categories with few samples should be interpreted with caution.

All database management, matching, and statistical analyses were completed using the sqldf (Grothendieck, 2017) and car (Fox and Weisberg, 2019) packages, in addition to base functions using the R statistical program version 4.0.4. (R Core Team, 2015).

3. Results

3.1. Stocking and self-thinning

Contemporary FIA results showed an increase in either BA m^2 ha^{-1}, tree density, or both variables in the mixed and pure aspen datasets (Fig. 4, Supplementary Fig. 1a and 1b, respectively). Although not all

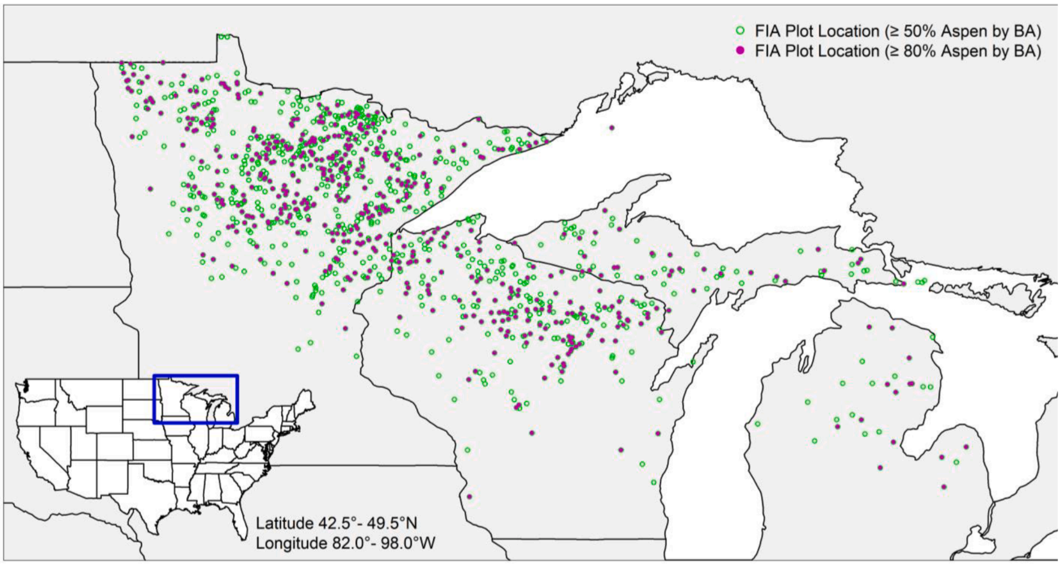

Fig. 3. Map of inventory locations of Forest Inventory and Analysis plots of the western Great Lakes (Lake States) used in this study for Contemporary FIA match selection. Solid purple points locate 530 plots that are pure aspen (≥80% aspen by basal area). Hollow green points locate 576 plots between 50% and 80% aspen by basal area. The Contemporary FIA match process for pure aspen plots used only the 530 solid points; the Contemporary FIA match process for mixed aspen plots used both sets of points (1,106 total). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

changes were significant, the Contemporary FIA results (Table 1) from both the mixed aspen and pure aspen datasets demonstrated an overall increase in stand stocking capacity compared to KG29 (Fig. 4). A spline curve of tree density versus BA m^2 ha^{-1} shows a distinct shift upward and to the right, implying that modern stands grow more, larger aspen trees. Note that all data in the analysis except for the *age class 30 - site index 21.3 m* category exhibited multivariate normality.

3.2. Site index and height growth

The second Contemporary FIA matching of age class only (omitting site index categorizations) tended to show a quadratic trend in the Contemporary FIA results between dominant height and age classes with a maximum height around age class 50, or the rotation age (commonly used in the Lake States) (Fig. 5). Both the pure aspen and mixed aspen datasets showed the largest dominant height increase of 27% and 25%, respectively, over the historic KG29 data at age 20, with relative height gains slowly reducing to an increase of 10% and 2%, respectively, at age 50. The historic trend in KG29 deviated from the Contemporary FIA results after age 50, showing a positive linear relationship where average dominant height increases with stand age class.

4. Discussion

We observe, through our analysis of representative FIA data, that the self-thinning line of aspen has increased relative to stand data published in KG29. Since the average dominant tree height is higher in young FIA plots (≤50 years old) than historically reported in KG29, aspen growth rates appear to have increased, and thereby site indices have changed as well. Data that underlie contemporary management guidelines, nearly a century old at the time of this publication, most likely do not correctly represent the present status of aspen growth and management in the Lake States, with serious implications against a backdrop of increasing global change. Observed changes in growth patterns for this key covertype in the Lake States were likely driven by climatic factors (e.g., CO_2 fertilization), differences in contemporary management, and other factors.

Previous research has alluded to some of the contributing factors of these results, but none have fully addressed the changes that modern aspen has undergone. Kubiske et al. (2019) and other FACE studies described the impacts of increased CO_2 fertilization on young aspen stands and predicted the long-term increase of self-thinning lines (Norby et al., 2005; Kubiske et al., 2015). Their observations from controlled studies were echoed by our results where data were obtained from uncontrolled, natural systems. Atmospheric CO_2 fertilization likely plays a critical role in this shift; however, the changes are likely a combination of multiple factors over the past century. Parsing out the specific elements were beyond the scope of the paper, but climatic, environmental, forest dynamics, and forest management changes all likely contributed to the increased stocking levels shown by our research.

Historic data and growth assumptions fail to provide accurate representations of current growing conditions in the Lake States. Most aspen stands will have an increase in growth under increased CO_2 concentrations, longer growing seasons, and warmer temperatures. Stands that will not directly benefit from the enriched atmospheric CO_2 due to other limiting resource constraints (such as boreal bogs or other poor-quality sites) will undergo other alterations that are not well understood. Moreover, existing and extensive root systems provide significant growth advantages for modern second- and third-generation aspen stands relative to the pioneer stands that defined much of the post-cutover era (1850–1930) in the Lake States (Domke et al., 2008).

We attempted to select a subset of FIA plots that resembled those available in the 1920s. However, the absence of historic descriptions detailing what constituted an aspen plot of interest, along with the large sample sizes and diverse stand histories within FIA data, led our Contemporary FIA data to have varying levels of statistically significant change. Although not all of the site index-age class combinations were statistically significant between KG29 and the Contemporary FIA data, when viewed holistically, the self-thinning splines in Fig. 4 have strong indications that stocking and height growth have increased over the last century. In addition, KG29 likely biased their plot selection towards the best aspen stands available, whereas the Contemporary FIA data unbiasedly includes all stands that met the basic selection criteria. If FIA included a variable that could identify a stand as managed or intensively managed (they do not), these plots would likely provide a better comparison to KG29. As is, this 'best' versus 'all' comparison attenuates the real differences. Nonetheless, our analysis still shows relative, and in cases significant, increases in stocking for 'all' modern FIA stands over the 'best' historic stands of KG29.

The dominant height growth analysis used age class to produce the

Table 1
Kittredge and Gevorkiantz (1929) (KG29) original stocking data[1] (trees ha^{-1} and BA m^2 ha^{-1}) compared with Contemporary Forest Inventory and Analysis (FIA) matched results at two aspen purity levels. Metrics are broken out by 10-year age classes and 3.048 m site index classes. 'Plots' denote to the initial number of plots measured and used in KG29 and replicated in the contemporary analysis. Contemporary FIA Matches were not conducted for age/site index class combinations that had no original plots ($n = 0$). Records with a p-value of <0.05 are bolded, and those with a p-value of *NA* did not have sufficient plot observations to determine a Mahalanobis distance.

Age	Plots	Kittredge and Gevorkiantz 1929		Contemporary FIA Mixed Aspen Stands (≥50% aspen by BA)			Contemporary FIA Pure Aspen Stands (≥80% aspen by BA)		
		Trees ha^{-1}	BA (m^2 ha^{-1})	Trees ha^{-1}	BA (m^2 ha^{-1})	p-value	Trees ha^{-1}	BA (m^2 ha^{-1})	p-value
		Site Index 24.4 m (80 ft)							
20	0	3,682	20.2	–	–	–	–	–	–
30	1	2,174	25.3	2,625	27.1	*NA*	2,551	27.0	*NA*
40	0	1,483	29.6	–	–	–	–	–	–
50	1	988	32.8	2,222	37.0	*NA*	1,201	35.5	*NA*
60	0	655	35.1	–	–	–	–	–	–
70	0	457	37.0	–	–	–	–	–	–
80	0	366	37.9	–	–	–	–	–	–
		Site Index 21.3 m (70 ft)							
20	7	4,448	19.1	4,236	20.5	0.095	4,198	20.6	0.073
30	5	2,632	23.4	3,228	27.2	0.063[2]	2,631	24.1	**0.035**[2]
40	4	1,878	27.5	2,203	29.8	**0.000**	2,019	30.8	**0.000**
50	2	1,223	30.5	1,990	39.0	*NA*	2,760	47.0	*NA*
60	3	815	33.1	1,802	39.1	**0.000**	707	39.5	**0.000**
70	3	581	34.7	4,811	37.1	**0.000**	3,119	35.3	*NA*
80	1	445	35.6	1,669	37.9	*NA*	2,206	40.3	*NA*
		Site Index 18.3 m (60 ft)							
20	6	5,683	17.4	4,368	20.2	**0.015**	4,187	20.3	**0.001**
30	17	3,459	21.6	3,538	29.8	0.078	3,388	30.1	0.072
40	8	2,422	25.3	3,080	25.5	0.124	2,588	21.3	**0.037**
50	12	1,594	28.0	2,350	36.5	0.131	2,447	42.5	**0.000**
60	13	1,043	30.5	1,762	33.7	0.115	1,118	31.1	0.117
70	0	729	31.9	–	–	–	–	–	–
80	0	578	32.8	–	–	–	–	–	–
		Site Index 15.2 m (50 ft)							
20	5	7,907	13.8	4,861	21.6	**0.000**	5,072	24.5	**0.000**
30	4	4,720	17.2	3,791	25.8	**0.000**	2,546	23.9	**0.000**
40	4	3,212	20.2	2,172	29.5	**0.000**	2,229	33.5	**0.000**
50	4	2,115	22.5	1,897	24.2	**0.000**	–	–	–
60	3	1,433	24.1	1,937	37.9	**0.000**	1,425	42.4	*NA*
70	0	988	25.0	–	–	–	–	–	–
		Site Index 12.2 m (40 ft)							
20	0	10,131	8.7	–	–	–	–	–	–
30	1	5,980	10.6	5,537	29.0	*NA*	3,009	20.5	*NA*
40	2	4,102	12.4	3,625	25.1	*NA*	2,668	19.7	*NA*
50	0	2,743	13.8	–	–	–	–	–	–

[1] The Brown and Gevorkiantz (1934) publication of volume, yield, and normal stand tables used a combination of reports and the Kittredge and Gevorkiantz (1929) publication that all likely originated from the same data source of 305 areas measured between 1925 and 1926 by E. Probstfield and an unknown inventory crew. These measurements were collected using an unknown sampling design and all reports only include summarized information without variance statistics. Kittredge and Gevorkiantz (1929) used the same dataset for many of the tables, and the included *Site Index Curve* was created from an independent set of 150 plots that were measured prior to 1925 (exact location and sampling methodology unknown) and normalized into the site index curves still used today (Carmean et al. 1989).
[2] This category did not exhibit multivariate normality, thus the p-value should be viewed with caution.

results displayed in Fig. 5. A limit to this approach is the reduction of high-quality stands at older ages seen in FIA. Due to their economic potential, these stands are harvested closer to rotation age, around 50 years old, while lesser-quality sites may be held from harvest for a decade or two. The Contemporary FIA matching analysis used did not weight probabilities based on harvest levels, thereby including more old, poorer quality sites than old, good quality sites at ages older than 50. This harvest selection bias is a major contributor to the rapid downward trend in FIA plots (present in both mixed and pure aspen stands) after age 60 in Fig. 5, but this represents reality. Alternatively, small sample sizes and probably biased selection of the best stands likely explains the linear (rather than asymptotic) height curve seen in the KG29 data.

Considering the prevalence and critical economic importance of aspen in the Lake States, it would behoove researchers and forest managers to reconsider longstanding management approaches to aspen. Our literature review of the data sources that underly current management guides suggests a need for more dynamic coupling of contemporary forest stand data with management guideline formulations. Perala (1977) offers a modern example of this conundrum: stands that were regenerated within a few years of publication that used the suggested stocking guidelines are just now reaching maturity. Many of these stands display unexpected gains or losses in growth and volume that were not predicted by Perala (1977), as shown in our results. Even if the original guidelines used then-modern data collected in the early 1970s, the climatic conditions of the past 40 years are already different (i.e., global CO_2 atmospheric concentrations; Keeling and Keeling, 2017)) and may have already altered the expected stand volume at maturity. Further, stands that were regenerated recently using guideline-recommended

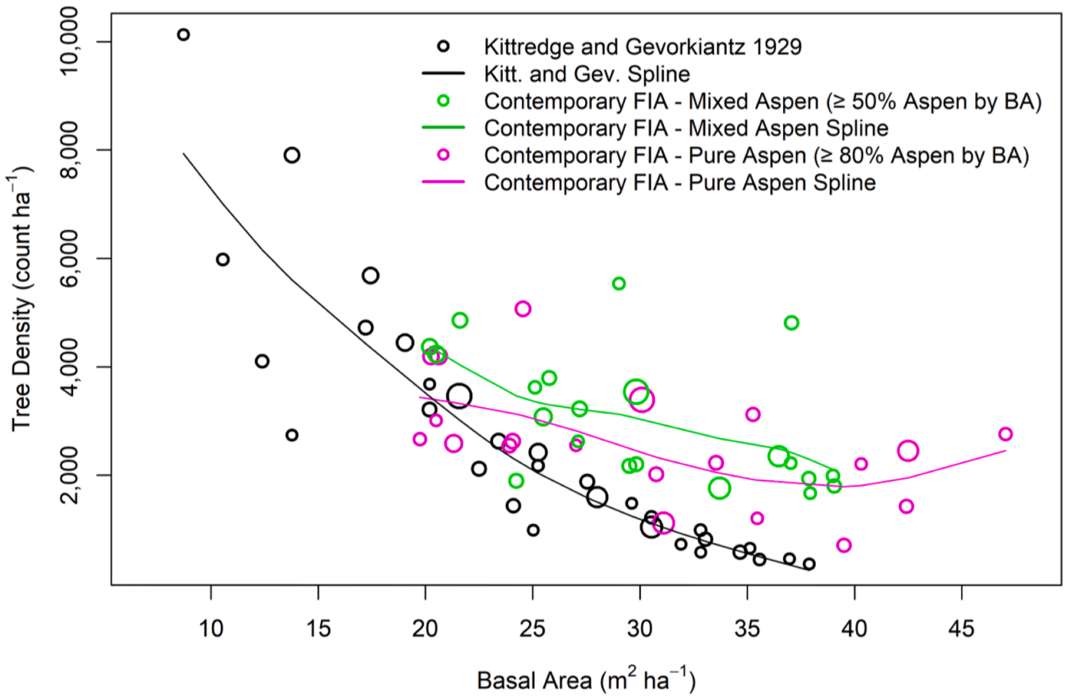

Fig. 4. Tree (≥12.7 cm dbh) density (tree count ha^{-1}) and basal area (m^2 ha^{-1}) relationships for one historic dataset and the two modern datasets, mixed aspen (≥50% aspen by basal area) and pure aspen (≥80% aspen by basal area) matched using Forest Inventory and Analysis data. Plotted points include all site index and age class combinations. Point sizes nonlinearly indicate plot counts, with larger points having more plots than relatively smaller points. Splines displayed have four degrees of freedom. Raw data for each point can be found in Table 1.

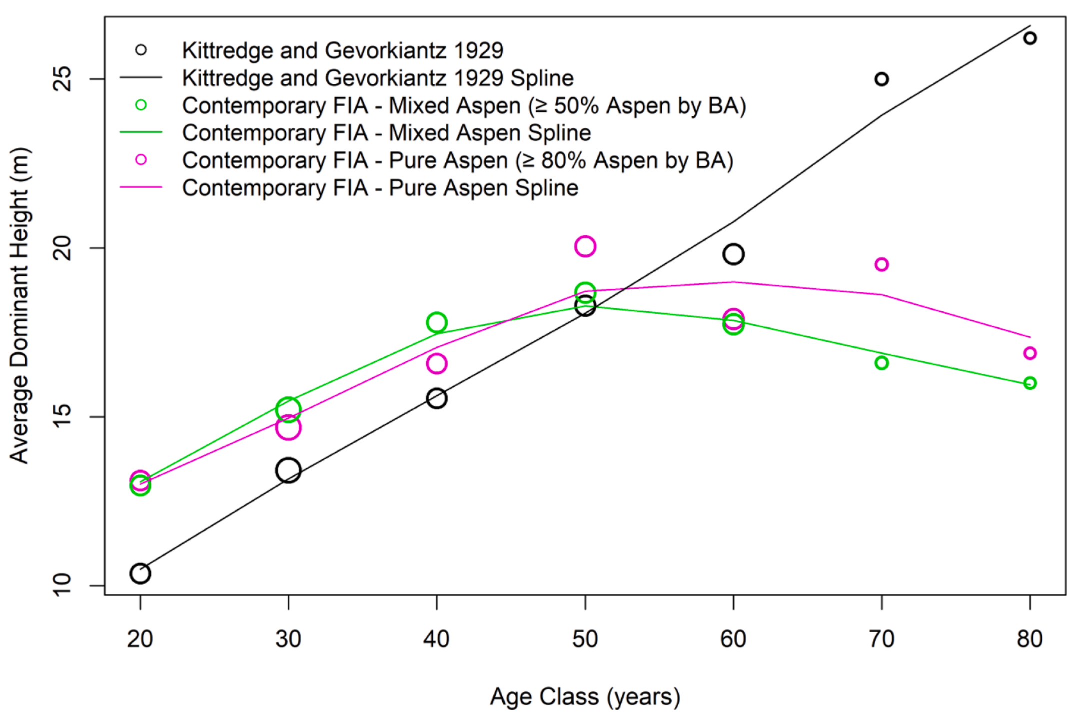

Fig. 5. Age class by average dominant height (m) of KG29 and the two modern datasets matched using Forest Inventory and Analysis data. The analysis grouped plots across site index classes (m) into a single age class category prior to random plot selection. Point sizes nonlinearly indicate plot counts, with larger points having more plots than relatively smaller points (see Table 1 for unaggregated plot counts). Splines displayed have four degrees of freedom. Note that the inflection of the Contemporary FIA points after age 50 reflects the harvest selection bias towards more productive (higher site index) stands than less productive (lower site index) stands, creating a higher forest wide proportion of low-quality sites at older ages than present at young ages.

stand initiation practices have incorrect stand growth assumptions that will be borne out 40–80+ years after the initial guides were published.

At a minimum, a comprehensive revision of aspen management guidelines or the Handbook (Perala, 1977) would provide an updated, accurate, and applicable set of targets and prescriptions that forestland managers can use to better inform forestry practices under modern day conditions. Further studies to assess aspen stand growth characteristics including site index, stocking capacities, volume production, and other vital metrics used in forest management would prove extremely beneficial. However, while an updated revision to the guidelines will provide a more accurate representation of present-day aspen growth, it will not fully encapsulate future growth conditions that a young aspen stand will experience due to global change. Climatic variables such as differing precipitation, warmer winter temperatures, longer growing seasons, increased amounts of available CO_2, and other dynamic factors that can change within a single stand rotation should also be included and attributed for in predictive growth models. An improved approach to stocking standards and stand management guidance appears necessary to empower forest managers and planners with more accurate guidelines. A new method of developing holistic stocking levels will require models that include 1) a dynamic predictive model that not only correlates future growth with present stand conditions, but also includes a time-dependent dimension that makes alterations based on future climates, 2) a model that accounts for multiple climatic futures and makes predictions based on probability and severity of outcomes, and 3) a feedback function that allows for regular revision of the guides using new data that can update model assumptions as required, including changing growth rates, shifting wood markets, and new silvicultural approaches. Currently, an opportunity exists with FIA to provide a sample dataset that can be used to help inform which metrics are the most nascent for aspen growth, providing key variables for further focus by larger and more intentional studies.

As future climate amongst a host of other environmental drivers (e.g., CO_2 concentrations and invasive species) is particularly difficult to predictively model (Toot et al., 2020), high resolution predictive climate models may enable forest researchers to not only study past impacts of climate change but also predict expected future growth patterns. In order to dynamically respond to these trends, researchers might utilize the FIA program as a means to leverage continuously resample inventory plots to develop multiple series of time-dependent data with short sampling intervals to both train and test predictive models (e.g., Woodall and Weiskittel, 2021). The combination of regularly inventoried plots and detailed climate predictions provides the basis of dynamic time-dependent growth models with automated feedback loops leading towards dynamic calibration.

Forest planning research has begun to account for multiple climate futures by building harvest scenarios using probabilities of various climatic futures and analyzing the long-term impacts of particular decisions made in the near future (Llorente et al., 2022). Since the planning horizon for forestry exists in the far future, being able to account for multiple possible futures is a necessity to encompass all potential outcomes of modern decisions. To further improve upon these methodologies, a reimagined approach to stocking and management guidelines would allow managers to build in resiliency into forest plans and thereby limit the consequences of misinformed decisions made in the present. This theoretical guideline model would not be the first attempt to provide robust predictive information for forest management. In the past two decades, many different process-based model approaches have been developed that attempt to synthesize these components into a single comprehensive model (Johnsen et al., 2001). Using a hybrid combination of mechanistic and empirical approaches with machine learning has provided the ability to merge large data with complex algorithms to predict and test future conditions. Unfortunately, most of these models are highly complex and therefore generic due to the requirement of large local data for them to be accurate, and with the sole exception of Forest Vegetation Simulator (FVS; developed and continuously updated by the USDA Forest Service), none have been adopted for wide-scale management purposes (Twery and Weiskittel, 2013). The time has come to invest in and improve these tools to enhance our predictive abilities in forest ecosystems and to understand the management implications that our decisions today will have in the future.

5. Conclusions

A comparison of seminal aspen stand management metrics and contemporary forest conditions demonstrated an increase in self-thinning levels, as well as height growth rates in the western Great Lakes over the last century. Understanding these changes and adapting management strategies accordingly will require a comprehensive revision of associated management guidelines, and perhaps the creation of more versatile stocking guidelines that capture the dynamic nature of global change impacts to forest growth. We have shown that current aspen management guidelines, using data collected nearly 100 years ago when forest/climate conditions differed dramatically from present, may not provide regional forest managers with accurate guidance. Most importantly, we suggest that new paradigms of forest management guideline creation may need to be explored that not only incorporate contemporary data in a dynamic fashion, but also recognizes the influence of global change on tree form, function, and forest product markets (e.g., bioenergy versus long-lived wood product storage) that drive forest management as society seeks to adapt to expected climate change.

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CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2023.120905.

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