Development History and Bibliography of the U.S. Forest Service Crown-Condition Indicator for Forest Health Monitoring

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Abstract Comprehensive assessment of individual-tree crown condition by the US Department of Agriculture, Forest Service, Forest Inventory and Analysis (FIA) Program has its origins in the concerns about widespread forest decline in Europe and North America that developed in the late 1970s and early 1980s. Programs such as the US National Acid Precipitation Assessment Program, US National Vegetation Survey, Canadian Acid Rain National Early Warning System, and joint US–Canadian North American Sugar Maple Decline Project laid the groundwork for the development of the US Forest Service crown-condition indicator. The crown-condition assessment protocols were selected and refined through literature review, peer review, and field studies in several different forest types during the late 1980s and early 1990s. Between 1980 and 2011, 126 publications relating specifically to the crown-condition indicator were added to the literature. The majority of the articles were published by the US Department of Agriculture, Forest Service or other State or Federal government agency, and more than half were published after 2004.

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Abbreviations

ARNEWS	Acid Rain National Early Warning System
EMAP	Environmental Monitoring and Assessment Program
FHM	Forest Health Monitoring
FIA	Forest Inventory and Analysis
ICP-Forests	International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests
NAMP	North American Sugar Maple Decline Project
NAPAP	National Acid Precipitation Assessment Program
NVS	National Vegetation Survey
SE DEMO	Southeast Loblolly/Shortleaf Pine Demonstration
UN-ECE	United Nations Economic Commission for Europe
VDS	Visual Damage Survey

Introduction

Visual assessment of tree crown transparency is included in many forest health inventories currently implemented throughout the world and as such is indeed “an almost universal index of tree health” (Innes 1993, p. 233). As the tree’s principal engine for energy capture, full, vigorous crowns generally are associated with more vigorous growth rates. Since trees undergoing stress often react by slowing growth and shedding parts of the crown (Millers et al. 1989), visually inspecting crowns for damaged or missing foliage provides insight into the overall condition of the tree. Though the modern application of tree crown condition as a forest health indicator has its origins in the concerns about forest decline in Europe and North America that developed in the late 1970s and early 1980s, foresters probably have used visual assessments of crown conditions since the beginning of the profession. Publications document their use in the USA as early as the 1920s (e.g., Ehrlich 1939; Snell 1931); however, it was not until the 1980s that the USA established large-scale monitoring efforts to study forest decline in part through crown condition assessments (Innes 1993).

After their inception, the monitoring programs, as well as the individual crown assessment variables, evolved in response to changing information and programmatic needs. In 2007, Schomaker et al. published a state-of-the-art guide to the crown-condition classification methods recommended by the US Department of Agriculture, Forest Service. The guide outlined the justification for using crown-condition classification to assess forest health alongside the procedures for data collection, data quality control, and data analysis. Their report did not, however, describe the historical development of the crown-condition classification methods from their infancy in the 1980s. Since much of this history lies in internal reports and the institutional memory of those personally involved with the methods’ development, the purpose of this review is to succinctly document the development of the crown-condition classification methods outlined by Schomaker et al. (2007) from the late 1980s through 2010. As with the methodology’s history, much of the crown-assessment research is dispersed throughout the literature, often composing only a small part of a larger forest inventory or forest health study. Such results may be difficult to locate in a standard literature search; therefore, a bibliography of articles related to the Forest Service crown-assessment methodology is included with this review.

Initial development of crown-condition assessment protocols

In 1982, in response to concern about the possibility of widespread damage to forests by air pollution, Germany became the first country to implement a national program to assess crown condition (Redfern and Boswell 2004). Included in the assessments were two primary variables, defoliation (percentage of leaf or needle loss), and discoloration (percentage of discolored foliage in the crown) (Anderson and Belanger 1987). In 1984, Great Britain followed Germany’s example and established a national monitoring program based on the German methodology (Redfern and Boswell 2004). A year later, the United Nations Economic Commission for Europe established an international cooperative program for forest monitoring known as the “International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests” or ICP-Forests (Innes 1993). The need for a large-scale grid of monitoring plots across Europe was agreed upon at the first program task force meeting on October 4, 1985 in Freiburg, Germany (ICP-Forests 2010), and in 1987, annual assessment of forest condition became mandatory throughout the European Union (Redfern and Boswell 2004). Assessments of crown condition, and defoliation in particular, served as the foundation of the ICP-Forests program (Eichhorn et al. 2010).

In North America, the US National Acid Precipitation Assessment Program was created in 1980 to study atmospheric deposition and its effects on aquatic and terrestrial ecosystems (Bechtold et al. 2007). This led to the US Forest Service launching the National Vegetation Survey (NVS) in 1984 with an objective to design a long-term approach to forest health monitoring (Bechtold et al. 2007). That same year, the Canadian Forestry Service established the Acid Rain National Early Warning System (ARNEWS) in order to detect early signs of forest damage (D’Eon et al. 1994). Original ARNEWS field methods were modified in 1985, finalized in 1986, and included assessments of shoots, branches, dieback, live crown width, live crown length, and needle retention (D’Eon et al. 1994).

Development of the US Forest Service crown-condition indicator

Following the initial activities of the early 1980s, a series of events took place in the USA which eventually established the crown-condition assessments currently utilized by the US Forest Service Forest Inventory and Analysis (FIA) Program:

1986 Anderson and Belanger (1987) implemented a study in the Georgia and South Carolina Piedmont to establish a crown rating method for loblolly (*Pinus taeda*) and shortleaf (*Pinus echinata*) pines. Basing their methods on the German methodology, they discovered that needle loss percentage was a sufficient and reliable estimator of tree and stand vigor and that assessing foliage discoloration was unnecessary.

1987 In January, scientists from Canada and the USA met in Burlington, Vermont, to discuss the status of sugar maple (*Acer saccharum*) decline in southeastern Canada and northeastern USA (McFadden 1991). As a result of their meeting, a joint research effort known as the North American Sugar Maple Decline Project (NAMP) was formulated to assess if, and where, decline of sugar maple was occurring. A field manual detailing instructions for plot selection, plot establishment, and data collection included instructions for assessing crown dieback, transparency, discoloration, dwarfed foliage, epicormic branching, and defoliation (Millers et al. 1991).

In November, NVS personnel and the US Atmospheric Impacts Research Program held a Forest Damage Survey Workshop in Chapel Hill, North Carolina, to identify, evaluate, and recommend variables and procedures necessary for assessing the condition of forests in the eastern USA (Alexander et al. 1992).

1988 Initial tree vigor ratings were made on newly established NAMP field plots (McFadden 1991).

The list of variables identified at the 1987 NVS workshop were refined by a committee and compiled with field procedures into a manual for a Visual Damage Survey (VDS). Among the variables included in the VDS were the European ratings of discoloration and defoliation, Anderson and Belanger's (1987) loblolly and shortleaf pine crown ratings, and other assessments of foliage and branch condition (Alexander et al. 1992). In mid-July to mid-September, VDSs were conducted in mixed hardwood stands in the central hardwood region, high elevation spruce-fir (*Picea–Abies*) forests in the northeast, and loblolly pine forests in the Piedmont (Alexander et al. 1992).

The US Environmental Protection Agency established the Environmental Monitoring and Assessment Program (EMAP) to monitor the status and trends in the condition of ecological resources, develop innovative methods for anticipating emerging environmental problems, and provide a greater capacity for assessing and monitoring the condition of the nation's ecological resources (Messer et al. 1991).

1989 NAMP field plots established in 1988 were remeasured (McFadden 1991).

In mid-July to mid-September, NVS personnel implemented a VDS in loblolly pine forests in the Southeastern Coastal Plain (Alexander et al. 1992).

1990 The NVS and forest-related aspects of EMAP were combined to create the US Forest Health Monitoring (FHM) Program (Bechtold et al. 2007), and forest health detection monitoring plots were established in Maine, New Hampshire, Vermont, Massachusetts, Connecticut, and Rhode Island. Among the variables assessed on these plots were crown dieback, foliage transparency, discoloration, and needle retention (Table 1) (Brooks et al. 1992). The FHM Program also initiated a plot design and logistics study known as the "20/20 study" to evaluate the plot design, subsampling procedures, time and resource requirements, and method efficiencies for detection monitoring. The study consisted of 20 field plots in New England northern hardwood forest types and 20 field plots in loblolly pine-hardwood forest types in Virginia (Riitters et al. 1992).

1991 The FHM Program continued establishment of forest health detection monitoring plots by adding plots in New Jersey, Delaware, Maryland, Virginia, Georgia, and Alabama. Pilot studies were initiated in Colorado and California (Alexander and Palmer 1999) (see Fig. 1 for subsequent state entries into the FHM Program).

1992 The FHM Program initiated a 2-year demonstration study known as the Southeast Loblolly/Shortleaf Pine Demonstration (SE DEMO) to evaluate selected indicators across the Atlantic Coastal and Piedmont loblolly shortleaf pine forest type (Lewis and Conkling 1994).

Table 1 Crown-condition variables recorded by the US Forest Health Monitoring Program (1990–1999) and US Forest Inventory and Analysis Program (2000–2010)

Variable	Stem size included	Protocol changes	Field protocol documentation
Crown class	Trees[a] Saplings[b]	Recorded consistently 1990–1996, 2000–2010	Conkling and Byers (1992)
Crown density	Trees	Recorded consistently 1990–2010	Schomaker et al. (2007)
Crown dieback	Trees	Recorded consistently 1990–2010	Schomaker et al. (2007)
Crown diameter	Trees Saplings[c]	Recorded consistently 1990–1999	Schomaker et al. (2007)
Crown form	Trees Saplings[c]	Recorded in the west only, 1992–1993	Conkling and Byers (1992)
Crown light exposure	Trees Saplings	Initially implemented in 1997. Current coding system adopted in 1998 and applied consistently through 2010	Schomaker et al. (2007)
Crown position	Trees Saplings	Recorded consistently 1997–2010	Schomaker et al. (2007)
Discoloration	Trees	Recorded in 1990	Zedaker and Nicholas (1990)
Foliage transparency	Trees	Recorded consistently 1990–2010	Schomaker et al. (2007)
Needle retention	Trees	Recorded for nine coniferous species (*Abies*, *Picea*, and *Pinus*), 1990–1992	Chojnacky (1991)
Seedling vigor	Seedlings[d]	Recorded consistently 1990–1999	Conkling and Byers (1992)
Sapling crown vigor	Saplings	Recorded consistently 1990–2010	Schomaker et al. (2007)
Live crown ratio	Trees Saplings	Recorded in 5 % increments, 1990–2004. Recorded in 1 % increments 2005–2010. In 2005, the tree length in the denominator of the ratio was changed to the actual length as defined by the FIA variable "actual tree length" (USDA 2007)	Schomaker et al. (2007)

[a] Diameter at least 5.0 in. at breast height (4.5 ft) or root collar

[b] Diameter at least 1.0 in. and less than 5.0 in. at breast height (4.5 ft) or root collar

[c] Optional measurement

[d] Single-stemmed tree species at least 1.0 ft in height but less than 1.0 in. in diameter at breast height (4.5 ft) and multistemmed tree species with no stem larger than 1.0 in. at the root collar

2000 The FHM Program detection monitoring plots were integrated into the FIA Program (Riitters and Tkacz 2004). The date of initial crowns data collection by FIA for states not involved originally through the FHM Program is given in Fig. 1.

The initial crown-condition assessment variables included by the FHM Program in 1990 (Table 1) were selected by peer review, expert opinion, and literature review. Selections were influenced by the variables included by Anderson and Belanger (1987) and in the NAMP and to a lesser extent by the European assessments and the VDS. Using the results of the 20/20 study, the SE DEMO, and the inaugural detection monitoring plots established in the eastern USA, the initial variables were refined through an evaluation based on six criteria: unambiguous interpretability, quantification simplicity, signal-to-noise ratio, regional responsiveness, index period stability, and environmental impact (Alexander and Barnard 1992; Lewis and Conkling 1994). Changes to the initial crown-condition assessment variables resulting from this and subsequent evaluations are outlined in Table 1. In general, the US Forest Service crown-condition assessment protocols have been stable since 2000.

Applications of crown-condition assessments

Long-term studies and thorough evaluations of historic patterns of mortality showed that the claims of

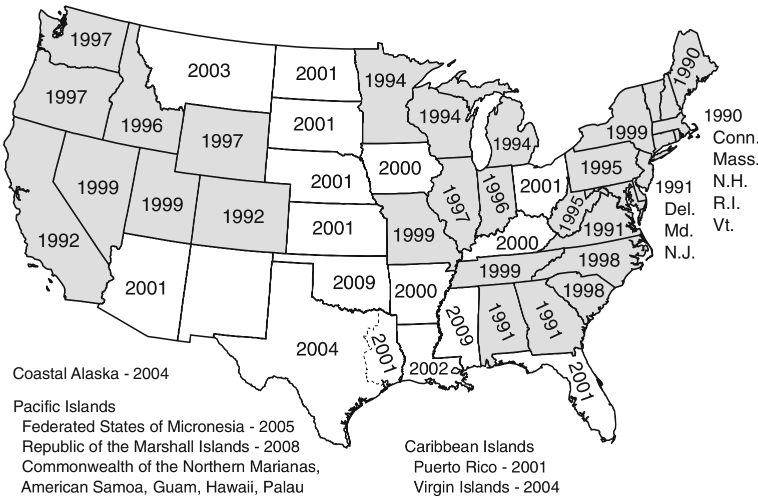

Fig. 1 Year crown-condition data collection was initiated by the US Forest Health Monitoring Program (*gray states*) or US Forest Inventory and Analysis Program, by state, 1990–2010

widespread forest decline due to atmospheric deposition, i.e., the primary motivation behind the initial development of crown-condition assessment protocols, were largely inaccurate (Innes 1993; Allen et al. 1995; Hall 1995). Despite this conclusion, crown-condition assessments have remained a part of forest health monitoring programs and found expanded use in individual research projects.

Crown-condition assessments have been used in a variety of individual research projects, ranging from identifying the effects of military training operations and silvicultural practices on forest stands (Applegate and Steinman 2005; Starkey and Guldin 2004) to describing the effect of insects and diseases on individual species (e.g., Petrillo et al. 2005; Rentch et al. 2009). Such studies, and other general summaries of crown-condition data, provide a wealth of information about individual tree and forest health, but many have been published in conference proceedings or by State or Federal agencies. As a result, they do not always appear in major literature citation databases and may go undiscovered in a standard literature search. The following bibliography compiles the current (2011) literature related to the FHM-FIA crown-condition indicator as a resource for researchers and forest managers who may be considering implementing crown-condition assessments.

Bibliography scope

Four citation databases (CAB Abstracts, AGRICOLA, Scopus, and Web of Science^{SM}) were searched for articles containing the following keywords individually in "all fields" (AGRICOLA and Scopus) or as "terms anywhere" (CAB Abstracts and Web of Science^{SM}): crown condition(s), crown density, foliage or foliar transparency, crown transparency, crown dieback, sapling crown vigor, crown ratio, crown diameter, and crown light exposure. Searches were limited to articles (English-language only) published between January 1, 1980 and December 31, 2011 and that also included the terms "forest inventory and analysis" or "forest health monitoring." The same search was implemented in Treesearch (http://www.treesearch.fs.fed.us), an on-line database housing public domain publications written by US Forest Service Research and Development scientists. All searches were conducted in February 2012. Publications from all of the searches were examined to ensure that the US Forest Service crown-condition indicator was used specifically.

Bibliography organization

All of the references were sorted into categories describing whether the crown-condition data were collected under the administration of the FHM Program, the FIA Program, or other independent individual or organization (Section I), the level of reporting (state, regional, or national) (Section II), the geographic location of the study (Section III), and which crown-condition variables were utilized or reported (Section IV). Special categories were created for quality assurance and quality control discussions (Section V), indicator development and field method guides (Section VI), and allometric modeling, estimation procedures, and other correlation or predictive models (Section

VII). For Section I, the period of FIA Program administration generally began in the year 2000. The composite variables in Section IV-G are crown defoliation index, crown production efficiency, crown shape ratio, crown structure index, crown surface area, crown volume, relative crown amount, total crown losses, visual crown rating, and the ZB index. The "other" crown-condition variables in Section IV-H are crown light exposure, crown position, crown class, discoloration, needle retention, and dwarfed foliage. References may appear in multiple categories.

Bibliography summary

A total of 26 unique references from the citation database search met the required criteria. To this, 33 references were added from the Treesearch database and an additional 67 references from my own personal library, for a total of 126 references ("Appendix"). Theses, dissertations, poster presentations, and articles that may have appeared in newspapers or popular magazines were not included. The majority of the references included in the bibliography were published by the US Forest Service or other State or Federal government agency (Fig. 2). Other sources were conference proceedings (all but two of which were published by the US Forest Service), peer-reviewed journals, and books. The 24 journal articles were distributed across 13 different journals. Slightly more than half of the articles were published after 2004 (Fig. 3).

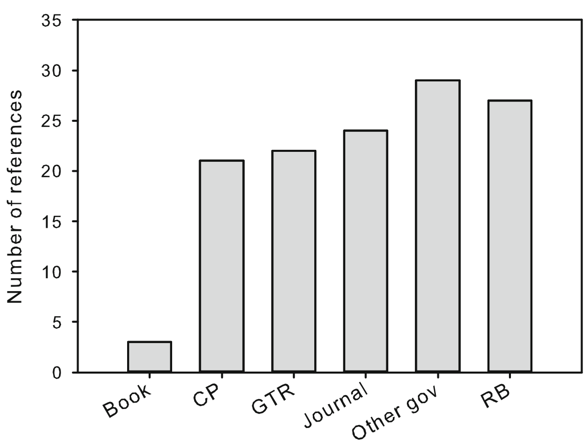

Fig. 2 Number of references in the crown-condition indicator bibliography (Appendix) by publication type. *CP* conference proceedings, *GTR* US Forest Service General Technical Report, *Other gov* State or Federal Government publication (other than GTR or RB), *RB* US Forest Service Resource Bulletin

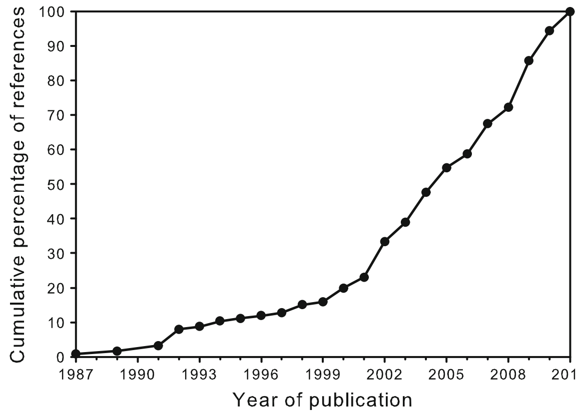

Fig. 3 Cumulative percentage of references in the crown-condition indicator bibliography ("Appendix"), by publication year

Conclusion

A rich history of cooperation and collaboration led to the development of crown-condition assessment protocols in the USA. Those established by the FHM Program and now implemented by the FIA Program have been utilized in a variety of forested conditions both domestically and internationally and provide individual researchers, local communities, and even entire nations options upon which they may develop their own systems to monitor forest health.

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Appendix: Bibliography

I. Administration of data collection

A. US Forest Health Monitoring Program
1, 3, 4, 7, 9, 11, 13, 14, 18, 20, 22, 24, 26, 28, 30, 32, 34, 35, 36, 37, 42, 48, 49, 52, 54, 56, 58, 59, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 82, 84, 86, 97, 98, 100, 108, 110, 111, 112, 113, 126

B. US Forest Inventory and Analysis Program
10, 12, 15, 16, 17, 19, 25, 27, 29, 33, 34, 35, 36, 40, 43, 44, 48, 53, 55, 57, 59, 60, 61, 78, 80, 81, 83, 85, 87, 88, 89, 90, 92, 93, 94,

95, 101, 102, 103, 104, 106, 110, 114, 115, 116, 117, 118, 121, 122, 123, 124

C. Other

6, 23, 38, 39, 41, 45, 46, 47, 50, 51, 79, 91, 96, 99, 105, 107, 109, 119, 120, 125

II. Level of reporting

A. State

15, 16, 19, 25, 27, 29, 33, 38, 39, 40, 43, 44, 49, 53, 55, 57, 60, 61, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 80, 81, 87, 92, 100, 101, 102, 103, 104, 115, 117, 118, 122, 124

B. Regional

1, 7, 13, 18, 22, 26, 42, 54, 84, 88, 89, 90, 95, 98, 110, 113

C. National

4, 7, 34, 35, 36, 37, 83, 116

III. Geographic location

A. Northeastern USA (Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont)

1, 3, 4, 7, 9, 18, 20, 23, 25, 31, 34, 35, 36, 37, 39, 41, 42, 53, 54, 60, 61, 66, 68, 70, 71, 73, 75, 76, 83, 87, 90, 105, 108, 110, 111, 112, 116, 119, 120, 121

B. Mid-Atlantic USA (Delaware, Maryland, New Jersey, Ohio, Pennsylvania, West Virginia)

1, 3, 4, 7, 9, 34, 35, 36, 37, 39, 42, 50, 54, 55, 62, 63, 64, 67, 69, 72, 74, 77, 83, 96, 108, 110, 111, 116, 117, 118, 125

C. Southern USA (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia)

1, 3, 4, 6, 7, 9, 12, 13, 19, 20, 22, 33, 34, 35, 36, 37, 42, 43, 45, 48, 51, 52, 56, 78, 82, 83, 84, 85, 86, 93, 94, 101, 102, 103, 104, 109, 111, 115, 116, 126

D. North Central USA (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, South Dakota, Wisconsin)

3, 4, 7, 9, 31, 34, 35, 36, 37, 38, 57, 65, 79, 80, 81, 83, 87, 89, 91, 92, 110, 111, 113, 116, 122, 124

E. Interior West USA (Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming)

4, 7, 11, 34, 35, 36, 37, 44, 49, 83, 95, 98, 100, 108, 114, 116

F. West Coast USA (Alaska, California, Hawaii, Oregon, Washington)

4, 7, 11, 24, 26, 27, 29, 34, 35, 36, 37, 40, 59, 83, 88, 108, 116, 121

G. Caribbean USA (Puerto Rico, US Virgin Islands)

15, 16, 17

H. International

31, 46, 47, 99, 107

IV. Crown condition variables reported or utilized

A. Crown density

1, 2, 6, 7, 12, 13, 15, 16, 19, 20, 22, 25, 26, 27, 29, 30, 33, 38, 39, 40, 41, 42, 43, 45, 46, 47, 48, 49, 51, 53, 54, 58, 60, 61, 63, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 82, 83,84, 88, 89, 90, 91, 92, 93, 94, 95, 96, 98, 99, 100, 101, 102, 103, 104, 106, 109, 110, 111, 113, 115, 116, 124, 126

B. Crown dieback

2, 3, 4, 6, 7, 13, 15, 16, 18, 19, 20, 21, 22, 24, 25, 26, 27, 29, 30, 31, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 57, 58, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 87, 88, 89, 90, 91, 92, 93, 95, 96, 98, 99, 100, 101, 102, 103, 104, 105, 106, 108, 109, 110, 111, 112, 113, 115, 116, 117, 118, 121, 122, 124, 125, 126

C. Foliage transparency

1, 4, 7, 13, 15, 16, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 29, 30, 31, 34, 35, 36, 37, 38, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 56, 57, 60, 61, 63, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 88, 89, 90, 91, 92, 93, 95, 96, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 115, 116, 122, 125, 126

D. Sapling crown vigor

13, 22, 24, 26, 42, 65, 88, 89, 90, 92, 95, 101, 102, 103, 106, 116, 121, 124

E. Uncompacted live crown ratio

10, 11, 12, 14, 15, 16, 24, 33, 41, 42, 44, 45, 46, 47, 51, 52, 56, 57, 58, 59, 63, 80, 81, 85, 96, 106, 114, 116, 119, 120, 122, 126

F. Crown diameter
9, 11, 12, 14, 17, 30, 33, 46, 47, 51, 52, 56, 58, 86, 106, 120, 126

G. Composite variables
4, 12, 30, 33, 34, 35, 36, 42, 46, 47, 52, 58, 82, 96, 106, 126

H. Other
9, 15, 16, 18, 21, 42, 106, 109, 116, 120, 126

V. Quality assurance/quality control
10, 18, 21, 30, 31, 52, 58, 106, 116

VI. Indicator development and field method guides
2, 5, 7, 8, 14, 28, 30, 32, 52, 58, 106

VII. Modeling and estimation
9, 10, 11, 14, 17, 59, 85, 86, 107, 111, 114, 123, 126

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