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A structured decision making analysis to increase a Red-cockaded Woodpecker population and balance stakeholder objectives for a National Forest

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ABSTRACT

Longleaf pine (*Pinus palustris*) savanna is a biodiverse ecosystem native to the southeastern United States. Due to fire suppression and timber harvest, longleaf pine has declined to 3% of its original range. The extant forest provides habitat for many threatened and endangered species, including the endangered Red-cockaded Woodpecker (*Picoides borealis*; RCW), a cavity-nesting bird that co-evolved with fire-maintained forest, resulting in savanna-like old-growth forest as the bird's preferred habitat. Our study site, the Oakmulgee Ranger District of the Talladega National Forest, harbors the largest RCW population in Alabama and is managed with an emphasis on RCW conservation. The United States Forest Service (USFS) also manages the Oakmulgee for uses such as wildlife conservation, recreation, and timber harvest. Despite efforts to restore RCW habitat and install artificial cavities in the Oakmulgee, the number of RCW groups has not exceeded 123, although the Recovery Plan objective is 394 groups. Our project was motivated by the USFS expressing interest in determining why the RCW population has not exceeded 123 groups. We proposed using structured decision making (SDM) with the USFS and other stakeholders to address this problem. Our goals were to explicitly define management objectives, build a Bayesian belief network with a model of how decision alternatives are believed to affect management objectives, and use a sensitivity analysis to determine the part of the model to which RCW population growth was most sensitive. Therefore, results from the analysis were expected to give insights into 1) ecological factors limiting RCW population growth, 2) how management can overcome these limits, plus 3) the relative expected ability of different decision alternatives to satisfy multiple objectives in addition to increasing RCW group number. We held four SDM workshops with representatives from the USFS, the Animal and Plant Health Inspection Service, the Longleaf Alliance, the Birmingham Audubon Society, and local residents. Stakeholder objectives consisted of maximizing the following: RCW group number, forest health, recreational enjoyment, community economic health, and aesthetics. Cavity insert installation had the greatest probability of increasing the number of RCW groups. The number of RCW groups was most affected by cavity availability, adult survival, reproductive output, food availability, and herbaceous understory. Prescribed burning was most likely to meet the combination of stakeholder objectives, followed by midstory removal. Our findings suggest that cavity installation efforts may need to be increased in the Oakmulgee to increase RCW group number. Also it could be beneficial to investigate how RCWs select cavity tree locations with the goal of increasing the chance that RCWs use artificial cavities to form new groups. The Bayesian belief network provided insights into factors limiting RCW population growth and how management can overcome these limits. The Bayesian belief network also can be used to prioritize management methods in the Oakmulgee given stakeholder objectives and time constraints.

1. Introduction

By 2050 an estimated 70% of the historical extent of tropical and sub-tropical grasslands, savannas, and shrub lands will be gone due to anthropogenic factors (Alcamo & Bennett, 2003). Humans have changed these ecosystems through land clearance and fire suppression, leading to encroachment by woody plants (Ratajczak, Nippert, & Collins, 2012; Swaine, Hawthorne, & Orgle, 1992; Tng et al., 2011; Mitchard & Flintrop, 2013; Honda & Durigan, 2016). In North America, loss of savannas and grasslands to woody plant encroachment has

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reduced species richness of plants by an average of 45% (Ratajczak et al., 2012).

Longleaf pine (*Pinus palustris*) savanna is endemic to the south-eastern United States and is fire-adapted (Outcalt, 2000). The ecosystem is home to 187 rare and 27 federally endangered or threatened plant species as of 2005 (Van Lear, Carroll, Kapeluck, & Johnson, 2005). Grasses and legumes found in the understory provide forage for many small mammal species, 14% of which are also of conservation concern (Engstrom, Kirkman, & Mitchell, 2001; Van Lear et al., 2005). Several species of herpetofauna and birds of conservation concern, including the endangered Red-cockaded Woodpecker (*Picoides borealis*; RCW), also use longleaf pine savanna as their primary habitat (USFWS, 2003; Van Lear et al., 2005).

RCWs have been federally protected as an endangered species since the passing of the Endangered Species Act in 1973 (USFWS, 2003). RCWs are cooperative breeders, living in groups consisting of a monogamous breeding pair and up to four helpers that reside in multiple cavity trees (Walters, Doerr, & Carter, 1988; Walters, Copeyon, & Carter, 1992; USFWS, 2003). RCWs excavate cavities in living old growth pine trees with a preference for pines > 76 years (Hooper, Lennartz, & Muse, 1991; Rudolph & Conner, 1991) that have heart rot, fungus that softens the heartwood they excavate (Conner, Rudolph, Saenz, & Schaefer, 1994; Hooper et al., 1991; Jusino, Linder, Banik, Rose, & Walters, 2016). The RCW's co-evolution with pyrophytic pine forest has led to preferred foraging in frequently burned stands dominated by old growth pine (> 60 years) (Conner et al., 1994; Zwicker & Walters, 1999) with limited pine and hardwood midstory (Jones & Hunt, 1996; Macey, Burt, Saenz, & Conner, 2016; Rudolph, Conner, & Schaefer, 2002) and herbaceous ground cover (James, Hess, & Kufrin, 1997). Despite intensive management, less than 3% of the RCW population remains, and the decline is predominately associated with loss of longleaf pine savanna (USFWS, 2003).

Due to the steep decline in longleaf pine abundance and severe range fragmentation caused by fire suppression, timber harvest, land conversion, and urbanization, the longleaf pine is currently listed as critically endangered on the International Union for Conservation of Nature's (IUCN) Red list (Farjon, 2013). Before European colonization, longleaf pine covered 37 million ha. However, that area has shrunk to 1.2 million ha over the past 300 years, and most patches are 40.47 ha or less in area (Frost, 1993; Outcalt & Sheffield, 1996). High timber harvest pressure, combined with the fact that longleaf pine grows slowly, decimated their populations following European colonization (Outcalt, 2000; Ratajczak et al., 2012). Like other savanna ecosystems in North America, fire suppression is a major factor associated with the decline of longleaf pine savanna. Fire suppression leads to invasion by hardwoods, such as oaks, which compete with longleaf pine (Jose, Merritt, & Ramsey, 2003; Landers, Van Lear, & Boyer, 1995; Samuelson et al., 2014). Today, longleaf pine savanna relies on prescribed burning to promote growth and reduce competition from woody plants (Jose et al., 2003; Outcalt, 2000; Samuelson et al., 2014).

Longleaf pine savanna holds social and economic value for government agencies, private landowners, and the general public as a place for recreational activities such as hunting and hiking, timber harvest, pine straw production, and, potentially, carbon sequestration credits (Alavalapati, Stainback, & Carter, 2002; Brockway, Outcalt, Tomczak, & Johnson, 2005; Lavoie, Kobziar, Long, & Hainds, 2011). Despite the economic and social value of longleaf pine, improving wildlife habitat and maintaining biodiversity were the primary motivations for longleaf pine management according to a survey of private landowners and personnel from state agencies, federal agencies, forest industry, conservation groups, and consulting firms (Lavoie et al., 2011). However, stakeholder groups had different goals for vegetation composition after management. The desired vegetation composition ranged from pure longleaf pine stands to longleaf pine stands with midstory hardwoods (Lavoie et al., 2011). Understanding the values stakeholders place on different outcomes can help managers create effective management plans (Irwin, Wilberg, Jones, & Bence, 2011; O'Donnell et al., 2017). The desire to conserve threatened and endangered species ultimately is driven by human values (Gregory, Long, Colligan, Geiger, & Laser, 2012).

In practice, there are many challenges to effective conservation management. Management plans are often complex and contain vague or inconsistent language, which can make it difficult to identify and achieve desired outcomes. Objectives are often improperly identified under traditional, informal approaches to decision making, reducing the ability of managers to identify effective means to address them and lowering the likelihood of achieving desired outcomes. Additionally, when decision makers do not document their decision making process, it is difficult for future decision makers to build upon previous work during future management or when managing other areas (Conroy & Peterson, 2013).

Structured decision making (SDM) can be used to improve decision making for conservation management. SDM is a formal process that helps decision makers achieve desired outcomes through defining objectives, identifying decision alternatives that can help meet objectives, and building models to predict outcomes (or consequences, using the PrOACT cycle terminology, Hammond, Keeney, & Raiffa, 1999) from the decision alternatives (Conroy & Peterson, 2013; Conroy et al., 2008; Irwin et al., 2011). SDM has been used to address a wide range of natural resource issues such as endangered species management (Conroy et al., 2008; Gregory & Long, 2009; O'Donnell et al., 2017), forest management (Ohlson, McKinnon, & Hirsch, 2005; Ferguson, Chamblee, & Hepinstall-Cymerman, 2015), sports fisheries management (Gregory & Long, 2009; Irwin et al., 2011), wildlife disease risk (Mitchell et al., 2012), and watershed management (Dalyander et al., 2016; Neckles, Lyons, Gutenspergen, Shriver, & Adamowicz, 2015), affecting the interests of a diversity of stakeholders including government agencies, non-profit organizations, the public, and private landowners.

SDM adds rigor and organization to decision making by requiring stakeholders to identify their objectives first and analyzing decision alternatives in a way that is systematic, transparent, and capable of updating (Conroy & Peterson, 2013). Defining objectives first allows decision makers to focus on the fundamental management goals, which increases the likelihood of reaching desired outcomes. Another strength of SDM compared to traditional decision making approaches is that it provides a good framework for involving diverse stakeholders, people from different organizations and with different values and perspectives, in all steps of the decision analysis (Ferguson, Conroy, Chamblee, & Hepinstall-Cymerman, 2015; Gregory & Long, 2009). By facilitating the inclusion of stakeholders, the SDM process helps managers gain community trust, provides an avenue for stakeholders to share local knowledge, increases creativity in the decision-making process, and increases stakeholders' support for conservation decisions because stakeholders have greater understanding and confidence in research results and are more confident that management decisions will reach desired outcomes (Powell & Vagias, 2010; Young et al., 2012; Bernacchi, Ragland, & Peterson, 2015). The transparent and systematic nature of SDM not only fosters trust among stakeholders but makes the resulting management more legally defensible and understandable for future managers. (Gregory & Long, 2009; Gregory et al., 2012; Tear et al., 2005; Young et al., 2012; Conroy & Peterson, 2013). Predictive models are used in SDM to forecast outcomes of decision alternatives. SDM allows these models to be updated over time in the presence of new information (i.e., adaptive management), leading to more effective management in future decision making (Conroy & Peterson, 2013). Altogether, these positive outcomes increase the chance of successful conservation.

In our study, we used SDM to assess management of longleaf pine savanna and RCWs by the United States Forest Service (USFS) in a section of the Oakmulgee Ranger District (referred to hereafter as Oakmulgee) of the Talladega National Forest in Alabama. The

Oakmulgee contains the largest RCW population in Alabama. However, the population has not exceeded 123 groups, despite management by the USFS and a RCW Recovery Plan Goal of 394 groups (USFWS, 2003). Our project was motivated by the USFS expressing interest in determining why the RCW population has not exceeded 123 groups. We proposed using SDM with the USFS and other stakeholders to address this problem. We intended to explicitly define management objectives, build a Bayesian belief network with a model of how decision alternatives are believed to affect management objectives, and use a sensitivity analysis to determine the part of the model to which RCW population growth was most sensitive. Therefore, results from the analysis were expected to give insights into 1) ecological factors limiting RCW population growth, 2) how management can overcome these limits, and 3) the relative expected ability of different decision alternatives to satisfy multiple objectives in addition to increasing RCW group number. The USFS's primary motivation was not to use SDM to select a decision alternative to immediately implement in management. This makes our application of SDM unique, as few studies have used SDM primarily to identify system components that need to be managed in order to meet fundamental objectives (see Brignon, Peterson, Dunham, Schaller, & Schreck, 2018 and Southwell, Tingley, Bode, Nicholson, & Phillips, 2017 for studies where sensitivity analysis featured proximately in the SDM analysis).

2. Methods

2.1. Study context

Our study occurred in the Oakmulgee Ranger District (63,535.6 ha) of the Talladega National Forest in Bibb County, Alabama, USA (32.91982 °N, -87.36132 °W) (USFS, 2004). The Oakmulgee is divided into spatial compartments to organize timing of management activities such as prescribed burning. Our study focused on compartments 45, 48, and 49 (2131 ha, Fig. 1) because USFS staff believe this area should be able to support a larger number of RCW groups than currently occur there. The three compartments contain approximately 1590 ha (74.6% of total area in the 3 focal compartments) of old growth (≥ 30 years old) longleaf and loblolly pine (*Pinus taeda*)-dominated land (Unpublished data; M. Caylor, USFS, Oakmulgee Ranger Station, 2016), but there are only six active RCW groups using approximately 765.4 ha (USFWS, 2003). Because the USFS is interested in why group numbers in the Oakmulgee persistently fall below the Recovery Plan Goal, we are focusing on these compartments that have surprisingly few RCW groups. This focus may give insights into ecological factors limiting RCW population growth and how management can overcome these limits.

The USFS manages the Oakmulgee for RCW conservation, recreation, forest health, and timber harvest objectives as set forth in USFS (2004). Within the Oakmulgee, the USFS regularly conducts prescribed burns and midstory removal to create and maintain RCW habitat (USFS, 2004). The USFS has been working with The Longleaf Alliance to restore 226 ha of mixed pine and hardwood forest to predominantly longleaf pine savanna throughout the Oakmulgee Wildlife Management Area (USFS, 2004). The USFS also has installed artificial nest cavities throughout the Oakmulgee to increase cavity availability for RCWs (Conner, Rudolph, & Bonner, 1995; Copeyon, Walters, & Carter, 1991; Franzreb, 1997). In addition, the USFS conducts southern flying squirrel removal (*Glaucomys volans*) from RCW cavities to reduce competition (USFS, 2004). In our SDM analysis, we used a ten year time frame to align with the USFS's ten year plan for the Oakmulgee (C. Ragland, USFS, personal communication).

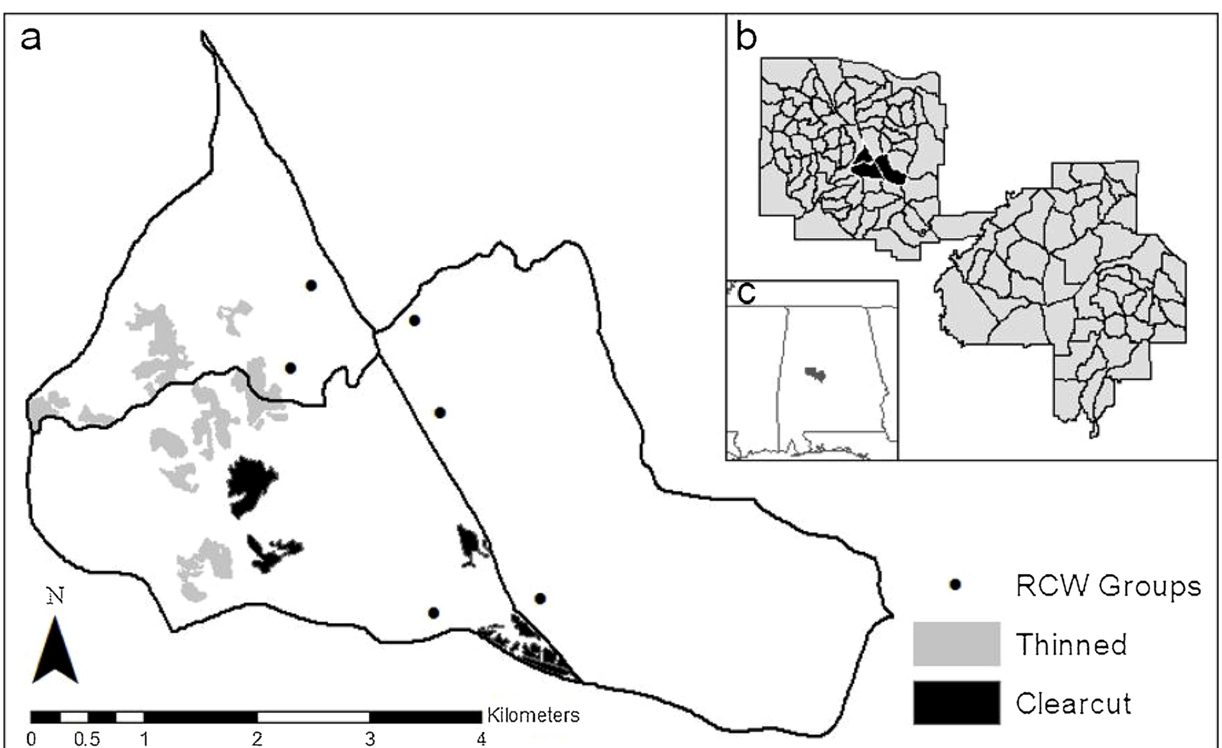

Fig. 1. Study area within the Oakmulgee Ranger District of the Talladega National Forest, Alabama. (a) The black circles indicate the central locations of active Red-cockaded Woodpecker (*Picoides borealis*; RCW) groups within compartments 45, 48, and 49 (polygons with black borders) of the Oakmulgee. Compartments consist of large parcels of land that are used to organize management activities. The grey and black polygons represent areas on which timber was harvested in the last ten years. The clearcut areas were seeded with longleaf pine seedlings in 2011–2012. (b) The compartments (black polygons with white borders) are within the Oakmulgee Ranger District (grey) (c) in central Alabama.

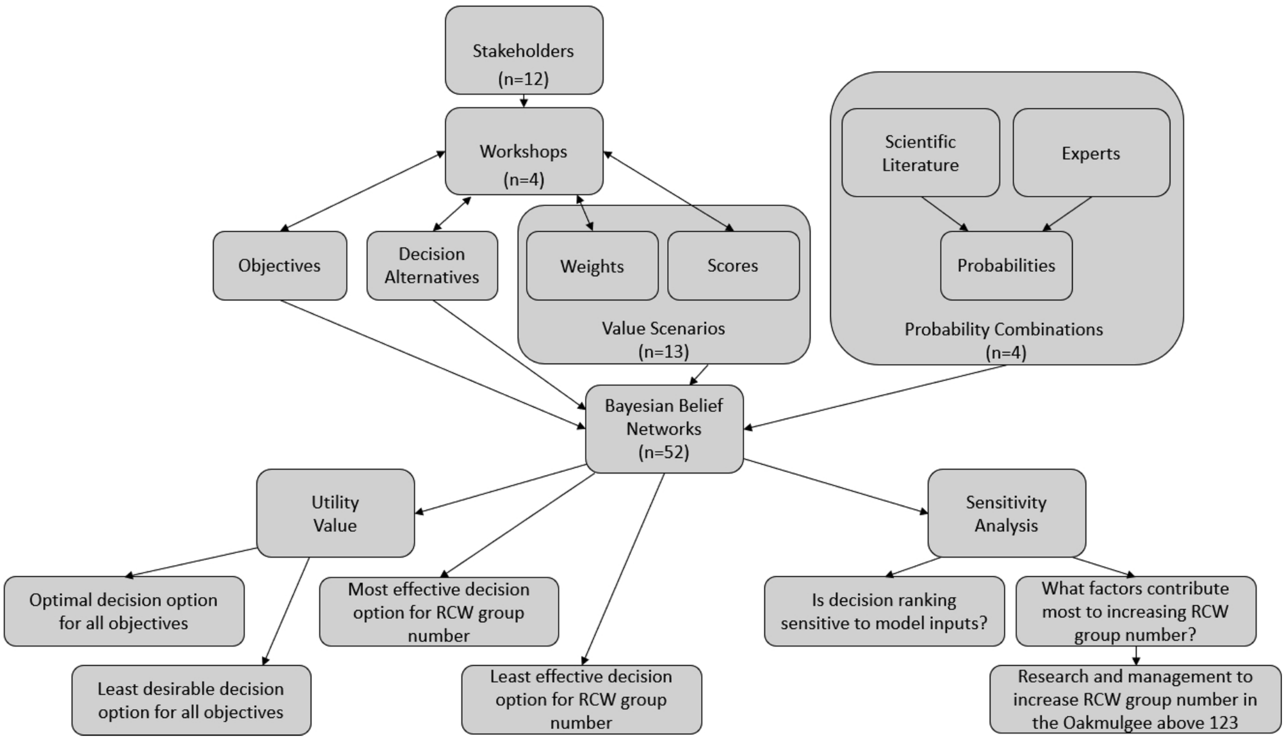

Fig. 2. Components of the structured decision making project. We recruited stakeholders with different perspectives on management of compartments 45, 48, and 49 of the Oakmulgee Ranger District of the Talladega National Forest, Alabama. Stakeholders participated in four workshops where they identified their goals for the management area (objectives), methods that could help meet objectives (decision alternatives), the relative importance of objectives to them (weights), and how satisfied they would be with particular outcomes (scores). The dual pointed arrows between the objectives, decision alternatives, weights, and scores represent feedback from stakeholders during multiple workshops. We used probabilities from the scientific literature and expert opinion in four probability combinations that weighed probabilities from experts and the literature differently. We developed 13 value scenarios comprising the set of weights and scores from each stakeholder (n = 12) plus one aggregate set of weights and scores averaged across stakeholders (*Average*). We analyzed 52 Bayesian belief networks, constructed from all combinations of the 4 probability combinations and the 13 value scenarios. The probabilities, objective weights, and attribute scores were used to calculate utility values for each decision alternative for each version of the Bayesian belief network. The most desirable decision alternatives for all objectives were within 1 point of the highest utility value for each version of the Bayesian belief network, and the least desirable decision alternatives were within 1 point of the lowest utility value. The most effective decision alternative for RCW conservation was the decision alternative with the largest probability of increasing the Red-cockaded Woodpecker (*Picoides borealis*; RCW) group number, and the least effective decision alternative for RCW conservation was the decision alternative with the largest probability of decreasing the RCW group number. Sensitivity analysis was conducted on the Bayesian belief network consisting of the probability combination that was most supported by stakeholders and the *Average* value scenario. Output from the sensitivity analysis was used to assess robustness of the Bayesian belief network and understand limits to Red-cockaded Woodpecker (*Picoides borealis*; RCW) population growth.

2.2. Recruiting stakeholders

The stakeholders consulted in any decision should be representative of those who have influence over the decision, as well as those who are affected by the decision (Freeman, 1984; Reed, 2008). Therefore, we recruited stakeholders with diverse interests in the Oakmulgee to participate in the SDM project (University of Alabama Institutional Review Board #16-OR-286). We used snowball sampling from gateway experts in the USFS to locate stakeholders (Bernard, 2002). Snowball sampling consists of having participants in a study suggest other potential participants. The USFS personnel served as gateway experts by connecting research personnel who were not members of the community surrounding the Oakmulgee (E. Brown and P.F.B. Ferguson) with Oakmulgee stakeholders the USFS personnel knew. Twelve stakeholders were recruited, including USFS employees, a United States Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS) employee, a member of the Birmingham Audubon Society, a member of the Longleaf Alliance, recreationists, and a nearby landowner (Fig. 2).

Stakeholders participated in four workshops moderated by E.B. with assistance from P.F. (Fig. 2). Three workshops were held in the fall of 2016 and one in the spring of 2017. Each workshop was held in the conference room at Brent Centreville Library in Centreville, Alabama, about 2 miles from the Oakmulgee Ranger District office, and lasted approximately three hours. The workshops were cumulative, each building on material from the previous workshop, so the same stakeholders were encouraged to attend all four workshops. Stakeholders were compensated for attending workshops with a small monetary sum ($10-$50 depending on the number of workshops they attended). To collect all the data necessary for the project, stakeholders had to attend or make up all four workshops. If a stakeholder could not attend a workshop, E.B. emailed them the workshop presentation and any worksheets or handouts. E.B. also answered questions about the material and recorded feedback from absent stakeholders over the phone or email.

2.3. Workshop 1: objectives

The goal of the first workshop was to have stakeholders identify their objectives for management of compartments 45, 48, and 49 in the Oakmulgee (Fig. 2). After presenting an overview of SDM and past management in the Oakmulgee, E.B. introduced the following questions to help stakeholders identify their objectives: What do you value about RCWs?, What do you want from RCW management in the study compartments?, How is the Oakmulgee RD important to you?, Are aspects of your community that are important to you affected by the RCW management in our study site?, What are those aspects of your community?, What are some of your resources that are influenced by RCW

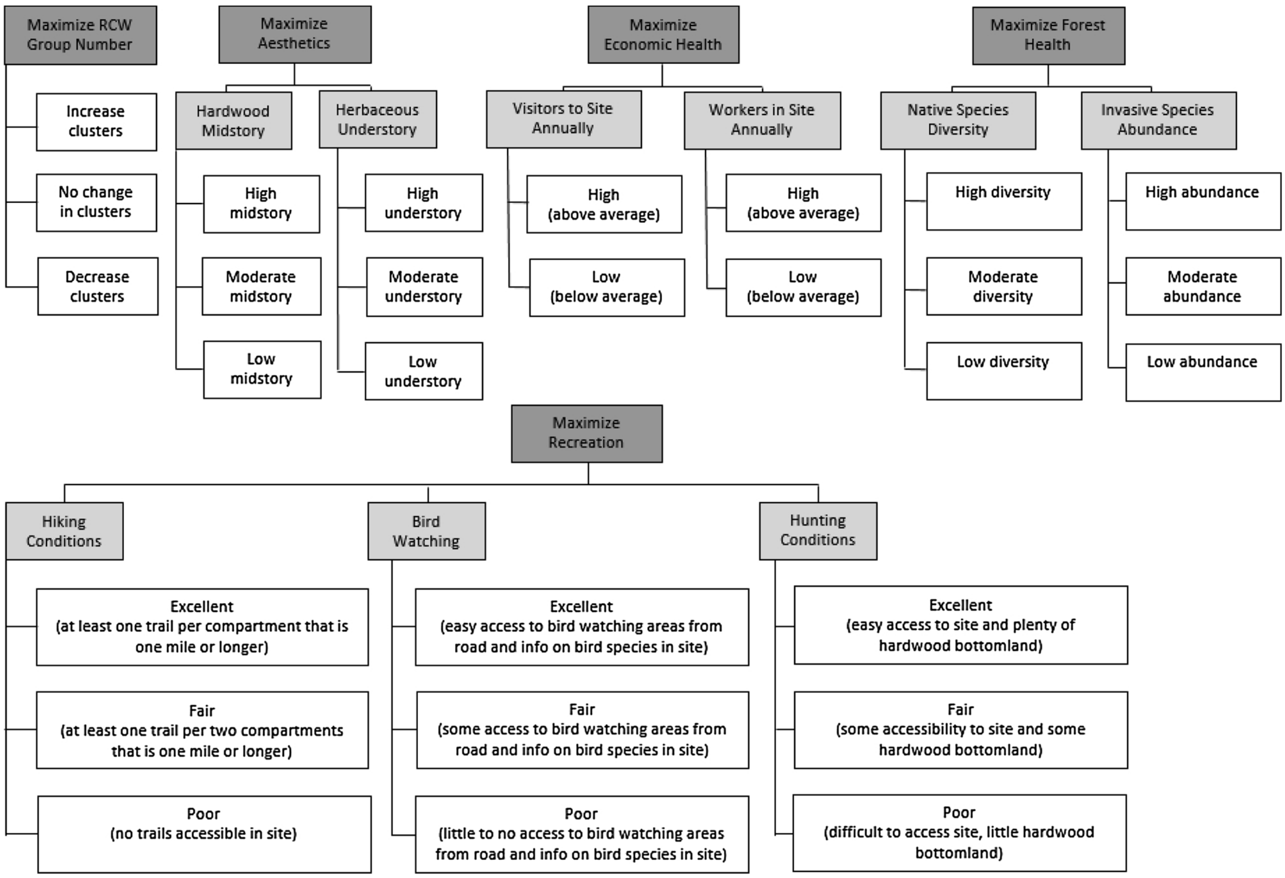

Fig. 3. Stakeholders' first-order fundamental objectives (dark grey), second-order fundamental objectives (light grey), and attribute scales (white). Fundamental objectives are the primary goals for the management area, and second-order fundamental objectives are components that define the first-order fundamental objectives. The management area (site) consisted of compartments 45, 48, and 49 of the Oakmulgee Ranger District in the Talladega National Forest, Alabama. Definitions of attribute levels can be found in Appendix 1, Supplementary material.

management and what about those resources matter to you? E.B. first asked stakeholders to write down any ideas they had individually. E.B. then facilitated a group discussion with the stakeholders in which stakeholders stated their objectives, and through discussion with each other, clarified and refined their description of their objectives. E.B. kept a written record of what stakeholders said about their values and goals for the management area.

We used E.B.'s written notes from the group discussion and the stakeholders' notes to create an objectives network that distinguished between fundamental and means objectives (Keeney, 1992). Fundamental objectives consist of the primary goals that reflect the core values of the stakeholders, whereas means objectives function as a way to attain fundamental objectives (Clemen, 1996; Keeney, 1992). We also identified second-order fundamental objectives as components of first-order fundamental objectives (Ferguson et al., 2015). If a first-order fundamental objective is fairly broad, second-order fundamental objectives can be used to represent components of the first-order fundamental objective that are of importance to stakeholders. We distilled stakeholders' notes and comments to identify potential first-order and second-order fundamental objectives. We presented the first-order and second-order fundamental objectives to the stakeholders at Workshop 2 and asked them for feedback to ensure the network accurately reflected their thoughts.

2.4. Workshop 1: results

Stakeholders identified the following fundamental objectives: Maximize RCW Group Number, Maximize Forest Health, Maximize Recreational Enjoyment, Maximize Community Economic Health, and Maximize Aesthetics. For all except the Maximize RCW Group Number objective, stakeholders identified second-order fundamental objectives to characterize the components of the first-order fundamental objectives (Fig. 3).

2.5. Workshop 2: decision alternatives and attribute scales

The goals of the second workshop were to have stakeholders identify potential decision alternatives to meet fundamental objectives, determine an attribute scale for each fundamental objective, and begin to structure a Bayesian belief network (Fig. 2). Once stakeholders were satisfied with the objectives network, we used consensus-based discussion to identify possible decision alternatives that could fulfill objectives (Miller et al., 2010). As this project is building the first Bayesian belief network and first model of the effects of management in the Oakmulgee, we considered only single management methods as decision alternatives, as opposed to portfolios with different combinations of multiple management methods as decision alternatives. However, we recognize that managers often use more than one management method at a time. Consequently, we expect our results can provide guidance on the relative expected ability of single management methods to satisfy objectives.

Attribute scales allow objectives to be measured. Some objectives have a natural scale, such as number of RCW groups, while scales must be constructed for other objectives that have no clear metric, such as 'landscape beauty.' In those cases, the stakeholders define the meaning of levels such as poor, fair, and excellent in terms of quantifiable metrics. We helped stakeholders define the levels of each attribute scale through consensus-based discussion (Keeney & Gregory, 2005; Miller et al., 2010) (Appendix 1, Supplementary material).

The objectives network provided the framework for a Bayesian belief network, a model that estimates the extent to which fundamental objectives will be met if different decisions are made (Conroy et al., 2008; Irwin et al., 2011; Marcot, Holthausen, Raphael, Rowland, & Wisdom, 2001; Marcot, Steventon, Sutherland, & McCann, 2006; Miller et al., 2010). Bayesian belief networks consist of nodes that represent variables connected by arrows that indicate causal relationships. The decision alternatives are contained in a decision node that can be linked directly or indirectly to the nodes that represent the fundamental objectives. The nodes located between the decision node and the fundamental objective nodes (intermediate nodes) represent variables that influence the fundamental objectives. Intermediate node content and placement were determined through consensus-based discussion (Ferguson et al., 2015; Miller et al., 2010). Before the discussion, we asked stakeholders to write down factors they thought might affect each objective. Then E.B. guided stakeholders through a discussion about these factors and took notes during the discussion. E.B. added the intermediate nodes to the objectives network that was displayed on a projector as the discussion progressed so stakeholders could see the Bayesian belief network being developed. We designed the Bayesian belief network, including the fundamental objectives, intermediate nodes, and possible decision alternatives, in Netica 5.24 (Norsys Software Corp., Vancouver, British Columbia, Canada).

2.6. Workshop 3: objective weights, attribute scores, and Bayesian belief network

The goals of the third workshop were to elicit objective weights and attribute scores from stakeholders and finalize the decision alternatives and nodes (Fig. 2) in the Bayesian belief network. We reviewed the Bayesian belief network with the intermediate nodes at the beginning of the workshop and asked stakeholders to give feedback on node and arrow placement. The definitions for each attribute level within the intermediate nodes were determined according to the scientific literature or by stakeholders via consensus-based discussion. For example, we used the United States Fish and Wildlife Service (USFWS) RCW management plan to define high, moderate, and low RCW breeder survival (USFWS, 2003). When we generated definitions from the literature, we presented them to the stakeholders to get feedback. Attribute level definitions can be found in Appendix 1, Supplementary material. After discussing the structure of the Bayesian belief network, we elicited objective weights and attribute scores, which were later used to determine how satisfied stakeholders would be with different management outcomes.

Objectives with higher weights were more important to stakeholders. We provided stakeholders with worksheets using the swing weighting method to calculate the relative importance of multiple objectives to each stakeholder (Appendix 2, Supplementary material; Clemen, 1996). The swing-weighting protocol reflected the hierarchy of the Bayesian belief network. That is, stakeholders provided first-order fundamental objective weights that summed to one, and the second-order fundamental objectives weights under a first-order fundamental objective summed to one.

Attribute scores represent the level of stakeholder satisfaction associated with the possible level of an outcome (e.g., high, moderate, low) within a node. Higher scores indicated higher satisfaction (Clemen, 1996). The attribute scores were elicited from stakeholders using worksheets where each stakeholder provided a score between 0 and 100 for each possible level of an outcome within a node (Appendix 3, Supplementary material). Stakeholders could choose any value within that range. They were not required to give the preferred outcome level a 100 or the least desired outcome level a 0. We later standardized scores so that the outcome level with the highest score received a 100 and other scores were raised proportionally. For example, if the highest score provided was 80 and another score was 5, they would be standardized to 100 and 6 ((5*100)/80), respectively. This was done to account for occasions where one stakeholder provided a score of 100 for the most desired outcome level in one node and a score of 50 for the most desired outcome level in another node. During the workshop, E.B. and P.F. checked the worksheets and ensured stakeholders corrected any inconsistencies.

Each stakeholder assigned points to potential decision alternatives to indicate their interest in implementing the decision alternative (0–4, with 4 indicating the highest interest). The points were averaged by alternative across stakeholders, and the 10 decision alternatives with the highest scores were included in the Bayesian belief network.

2.7. Workshop 3: results

Stakeholder objective weights varied most noticeably for the *Maximize Aesthetics*, *Maximize Local Economic Health*, and *Maximize Recreational Enjoyment* first-order objectives. Stakeholders ranked these objectives anywhere from being second-most important to least important (Appendix 4, Supplementary material). However, stakeholders consistently placed the most weight on conservation-oriented objectives (*Maximize RCW Group Number*, *Maximize Forest Health*). Nine stakeholders placed the most weight on *Maximize RCW Group Number*, and three stakeholders placed the most weight on *Maximize Forest Health* (Appendix 4, Supplementary material). On average, stakeholders placed the most weight on *Maximize RCW Group Number* followed by the *Maximize Forest Health* (Table 1, Appendix 4, Supplementary material).

Attribute scores indicated, of all objectives, stakeholders' level of satisfaction varied the most over the attribute levels in the conservation-oriented objectives. This was especially true between the lowest and highest attribute levels. For example, stakeholders' attribute score for *Increase in RCW Group Number* was 17.5 times higher on average than for *Decrease in RCW Group Number* (Table 2). Attribute scores had the least variation among stakeholders in the *Maximize Forest Health* second-order objectives and the most variation in the *Maximize Aesthetics* and *Maximize Local Economic Health* second-order objectives (Table 2). Attribute scores from individual stakeholders can be found in Appendix 5, Supplementary material.

There were occasions where the attribute scores provided by a stakeholder followed a pattern contrary to our expectation. For example, one stakeholder assigned a score of 100 to *No Change in RCW Group Number* and a score of 19 to *Increase in RCW Group Number*, indicating higher satisfaction if group number did not change (Appendix 5, Supplementary material). As soon as stakeholders turned in the worksheet where they reported their attribute scores, E.B. and P.F. checked the worksheets for completeness and adherence to directions. When unexpected responses were provided, like the example above, E.B. or P.F. talked to the relevant stakeholder to ensure that they understood directions and their response reflected their belief. Any revisions from the stakeholder were recorded and results reported here include these revisions.

Ten decision alternatives were selected by the stakeholders: RCW cavity installation, bird brochure creation, prescribed burning every 2–3 years, thinning, midstory removal, planting longleaf pine seedlings, frequent herbicide treatment, invasive species education, APHIS hog trapping, and installation of nest boxes near RCW groups in conjunction with removal of flying squirrels from the nest boxes and nearby RCW cavities. Further explanation of the decision alternatives can be found in Appendix 6, Supplementary material.

2.8. Conditional probabilities

Between the third and fourth workshops, we collected conditional probabilities from the scientific literature and experts (Fig. 2). A conditional probability indicates the chance an attribute level in a node will be realized given particular states of the system or actions taken

Table 1
Mean objective weights and the range across 12 stakeholders. The objectives reflected stakeholders' goals for management of compartments 45, 48, and 49 of the Oakmulgee Ranger District (site) within the Talladega National Forest, Alabama. Higher objective weights indicate that stakeholders placed a greater importance on those objectives. First-order fundamental objectives reflect the core goals of the stakeholders, and second-order fundamental objectives define components of first-order fundamental objectives that are of importance to stakeholders. First-order fundamental objective weights sum to one and the second-order objective weights within a first-order objective sum to one. Objectives are further explained in Appendix 1, Supplementary material. RCW stands for Red-cockaded Woodpecker (*Picoides borealis*).

First-order fundamental objectives	Mean	Range	Second-order fundamental objectives	Mean	Range
Maximize number of RCW groups	0.33	0.07-0.65	N/A	N/A	N/A
Maximize forest health	0.22	0.05-0.33	Maximize native species diversity	0.43	0.22-0.67
			Minimize invasive species abundance	0.57	0.33-0.78
Maximize recreational enjoyment	0.17	0.07-0.30	Maximize bird watching opportunities	0.33	0.10-0.53
			Maximize favorable hunting conditions	0.35	0.19-0.50
			Maximize favorable hiking conditions	0.32	0.08-0.51
Maximize local economic health	0.15	0.02-0.25	Maximize number of visitors to site	0.48	0.06-0.67
			Maximize number of workers in site	0.52	0.33-0.94
Maximize aesthetics	0.13	0.02-0.28	Maximize herbaceous understory	0.44	0.11-0.78
			Minimize hardwood midstory	0.56	0.22-0.89

Table 2
Mean and standard deviation (SD) of attribute scores for objectives across 12 stakeholders. The objectives reflected stakeholders' goals for management of compartments 45, 48, and 49 of the Oakmulgee Ranger District within the Talladega National Forest, Alabama. Attribute scores indicate the relative level of satisfaction stakeholders would have if each attribute level occurred. RCW stands for Red-cockaded Woodpecker (*Picoides borealis*).

Objective	Attribute Level	Mean	SD
RCW groups	Increase	93	23.4
	No change	53	22.4
	Decrease	6	10.5
Native species diversity	High	100	0.0
	Moderate	51	20.8
	Low	13	19.1
Invasive species abundance	High	3	7.5
	Moderate	44	16.8
	Low	100	0.0
Bird watching opportunities	Excellent	94	22.5
	Fair	57	17.6
	Poor	25	29.4
Hunting conditions	Excellent	88	18.8
	Fair	72	23.8
	Poor	35	33.6
Hiking conditions	Excellent	85	26.0
	Fair	65	27.0
	Poor	16	17.2
Visitor number	Many	89	26.8
	Few	52	38.6
Worker number	Many	77	28.5
	Few	58	42.0
Herbaceous understory	High	65	39.1
	Moderate	62	24.3
	Low	43	42.9
Hardwood midstory	High	54	44.3
	Moderate	63	21.5
	Low	67	39.9

(Marcot et al., 2001; Oliver & Smith, 1990). The use of probabilities allowed us to predict the outcomes, or consequences, of decision alternatives while including uncertainty associated with changing environmental conditions and the inability to perfectly control implementation of management decisions (Conroy et al., 2008; Irwin et al., 2011).

When possible, we determined conditional probabilities based on peer-reviewed scientific literature (Appendix 7, Supplementary material). However, probabilities are rarely presented in the literature and can be difficult to infer based on the results presented. For this reason, probabilities for Bayesian belief networks are often gathered from experts (Clemen, 1996; Ferguson et al., 2015; Haas, 1991, 2001; Peterson & Evans, 2003). We sent probability elicitation worksheets to 28 experts who were identified based on (1) their authorship (first or second author) of scientific articles that focused on aspects of the Bayesian belief network or (2) suggestions from other experts. Using single management methods as decision alternatives, as opposed to different combinations of multiple management methods, also greatly simplified the conditional probabilities we asked experts to supply. The probabilities elicited via the worksheets are located in Appendix 8, Supplementary material.

If there was more than one expert who provided probabilities for a node, we created an expert node through which we could weigh the conditional probabilities from the experts and scientific literature (Fig. 4; Ferguson et al., 2015). We presented the conditional probabilities we obtained to the stakeholders and asked them to provide feedback on their personal impressions of the probabilities' accuracy. The probabilities were presented anonymously without connecting them to experts.

We generated four probability combinations of the Bayesian belief network in which we weighted conditional probabilities from experts and the scientific literature differently. The first probability combination (*All*) weighted all probabilities from experts and the scientific literature equally. In the second combination (*All 50-50*), we gave the scientific literature probabilities a 0.5 weight and weighted all expert probabilities equally for the other 0.5. The third combination (*Lit Only*) used only the scientific literature probabilities and retained the expert probabilities only for nodes without probabilities in the scientific literature. The fourth combination (*No Lit*) excluded the probabilities we calculated using the scientific literature. We calculated utility values under all 4 probability combinations.

2.9. Conditional probabilities results

We received conditional probabilities from 10 experts (Appendix 8, Supplementary material). Experts consisted of faculty at the University of Alabama and Auburn University, and employees from the USFS, the Joseph Jones Ecological Research Center, Longleaf Alliance, The Nature Conservancy, and Tall Timbers Research Station and Land Conservancy. One of the USFS employees and the Longleaf Alliance employee were also stakeholders in the workshops. Stakeholders unanimously indicated that they felt confident in the probabilities provided by all ten experts. An average of 5 (2 to 9) experts provided probabilities for each

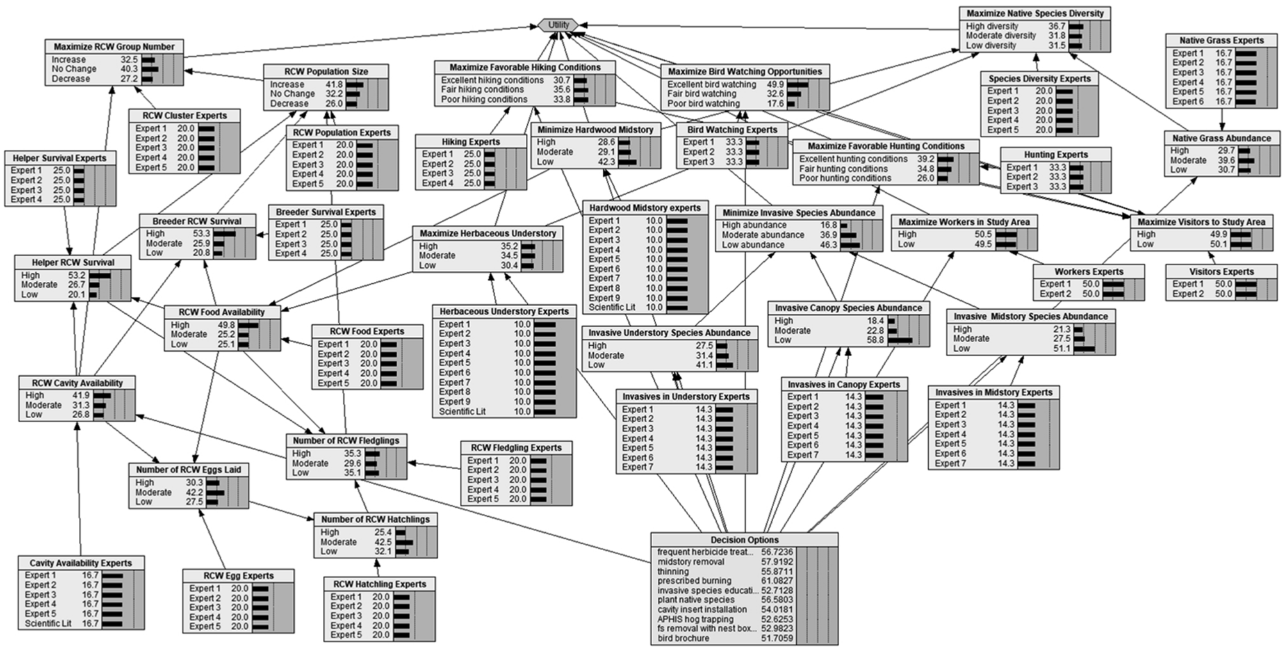

Fig. 4. Bayesian belief network with the *Average* value scenario (used average objective weights and attribute scores across stakeholders) and *All* probability combination (all conditional probabilities from experts and the scientific literature were weighted equally). The Bayesian belief network calculated utility values (in the node labeled decision alternatives) through the utility node (hexagon labeled utility) for each decision alternative. The decision alternative with the highest utility value was most likely to achieve the stakeholders' objectives. Utility values (Appendix 10, Supplementary material) were calculated from objective weights that reflected the importance stakeholders placed on each management objective (Appendix 4, Supplementary material), attribute scores that measured how satisfied stakeholders would be with particular outcomes (Appendix 5, Supplementary material), and conditional probabilities elicited from the scientific literature and experts (Appendix 8, Supplementary material). Arrows between nodes indicate causal relationships. The numbers next to the black bars indicate the percent probability of a level in an attribute scale occurring.

node (Fig. 4). Three nodes contained probabilities from the scientific literature (Appendix 7, Supplementary material).

2.10. Utility values

A utility value measures the degree of satisfaction a stakeholder will attain due to an outcome from a decision alternative (Conroy & Peterson, 2013). The utility value for a decision alternative was calculated based on a stakeholders' objective weights and attribute scores and the probability of an outcome (Fig. 2; Peterson & Evans, 2003) as in equation 1 where W is a first-order fundamental objective weight, U is a second-order fundamental objective weight, and S is an attribute score. For each of the G second-order fundamental objectives ($s = 1, 2, \ldots, G$) within a first-order fundamental objective ($p = 1, 2, \ldots, F$), we weighted the attribute scores for a possible outcome ($v = 1, 2, \ldots, H$) by the probability of that outcome (X_v) given states of influencing nodes (A) (Ferguson et al., 2015). The decision alternative with the highest utility value was most likely to generate outcomes that meet objectives. Utility values were calculated in R version 3.3.2 (Ferguson et al., 2015).

$$U = \sum_{p=1}^{F} W_p \left(\sum_{s=1}^{G} U_s \left(\sum_{v=1}^{H} S_v {*}\Pr(X_v A) \right) \right) \tag{1}$$

We analyzed 13 value scenarios consisting of the objective weights and attribute scores from the 12 stakeholders individually and the mean objective weights and attribute scores across stakeholders (*Average* value scenario). Therefore, we analyzed 52 Bayesian belief networks, all combinations of 13 value scenarios and 4 probability combinations (Fig. 2). In each Bayesian belief network, we noted which decision alternatives were considered the most desirable (highest utility value or within 1 point of the highest) and which were considered least desirable (lowest utility value or within 1 point of the lowest). This procedure (1 point definition) was used in Ferguson et al. (2015), and we found it to be clear and acceptable to stakeholders. However, to test the robustness of this method, we also summarized the results of the 13 value scenarios in the *All* probability combination of the Bayesian belief network defining most desirable as the highest utility value or within 1/3 of the standard deviation of the utility values in that network. Likewise, least desirable was defined as the lowest utility value or within 1/3 of the standard deviation of the utility values in that network. We chose 1/3 of the standard deviation of the utility values because the mean of this value across the scenarios in the *All* probability combination was 1.13 (close to 1, making it comparable to the 1 point definition) but the magnitude of the value for a particular scenario reflected the range of utility values in that network.

Since the USFS was very interested in RCW conservation, we also noted which decision alternatives resulted in the largest probability of increasing the number of RCW groups and the largest probability of decreasing the number of RCW groups. Recall that the probability of different outcomes, such as the number of RCW groups increasing, did not depend on the objective weights or attribute scores in the value scenarios. However, probabilities of outcomes depended on which probability combination was used in the Bayesian belief network.

2.11. Workshop 4: presenting the Bayesian belief network

We presented the most desirable and least desirable decision alternatives under all 52 Bayesian belief networks (every combination of the 4 probability combinations and 13 value scenarios) to the stakeholders (Fig. 2). To determine which Bayesian belief network to focus on for a sensitivity analysis, we had stakeholders vote on the probability combination in which they placed most personal confidence.

2.12. Sensitivity analysis

Sensitivity analysis identifies the parts of a Bayesian belief network where a small change in the input has a large effect on results (Conroy

Table 3
Decision alternative for each probability combination (version of the Bayesian belief network that weighed conditional probabilities differently depending on whether they were elicited from the scientific literature or experts) that was most likely to increase the number of Red-cockaded Woodpecker (*Picoides borealis*; RCW) groups in compartments 45, 48, and 49 of the Oakmulgee Ranger District in the Talladega National Forest, Alabama (most effective decision) and the probabilities of increasing, not changing, or decreasing the number of RCW groups. Probabilities of decision alternatives are influenced by weights placed on conditional probabilities, and therefore can differ across probability combinations. Value scenarios did not influence the probability of each RCW outcome or other management outcomes occurring.

Probability combination	Most effective decision	Increase number of RCW groups	No change in number of groups	Decrease number of RCW groups
All	Cavity insert installation	40.5	37.3	22.2
All 50-50	Cavity insert installation	41.4	37.0	21.6
Lit Only	Cavity insert installation	42.6	36.6	20.8
No Lit	Cavity insert installation	40.2	37.4	22.4

& Peterson, 2013). Reducing uncertainty in the input – in this case, the conditional probabilities that parameterize the model – can then have a large influence on the Bayesian belief network and can contribute to more accurate results (Conroy & Peterson, 2013). For example, if the most desirable decision alternative changes when an input is altered, the decision is sensitive to that input. Field data can be collected to reduce uncertainty in the state of the input node, which can contribute to more accurate results about most desirable decision alternatives.

We used a one-way sensitivity analysis that systematically varied the conditional probabilities of each node in the Bayesian belief network, one at a time, from its highest attribute level to its lowest attribute level. We determined how changing the probability at each attribute level affected the decision alternative ranking, utility values, and probability of the number of RCW groups increasing (Clemen, 1996; Conroy & Peterson, 2013; Fig. 2).

3. Results

The most desirable decision alternative is the decision alternative that is most likely to produce outcomes that fulfill objectives and satisfy stakeholders. Our results were robust to the definition of most and least desirable decision alternative. Recall that we first defined a decision alternative as most desirable if its utility value was within 1 point of the highest utility value and least desirable if its utility value was within 1 point of the lowest utility value in that Bayesian belief network (1 point definition). We also considered defining a decision alternative as most desirable if its utility value was no less than 1/3 of the standard deviation of the utility values in the network away from the highest utility value and least desirable if its utility value was no more than 1/3 of the standard deviation of the utility values in the network away from the lowest utility value (standard deviation definition). We chose to proceed with the 1 point definition because it did not substantially change results, it was easier to communicate, and was consistent with previous work (e.g. Ferguson et al., 2015). The only difference in results using the 1 point definition was that frequent herbicide treatment and thinning were included as most desirable alternatives 1 more time (each 5.6% of all of the most desirable decision alternatives) and invasive species education and APHIS hog trapping were included as least desirable options 1 more time (each 3.2% of all of the least desirable decision alternatives).

3.1. Most effective decision alternative to increase RCW group number

Cavity insert installation was associated with the greatest chance of the RCW group number increasing across probability combinations (Table 3). The decision alternative that was most often associated with the greatest chance of a decrease in RCW group number across probability combinations was planting longleaf pine seedlings (Table 4). Information about how other decision alternatives influenced the number of RCW groups is located in Appendix 9, Supplementary material.

3.2. Most desirable decision alternative for all objectives

In all but 1 of the 52 Bayesian belief networks, prescribed burning was the most desirable decision alternative, meaning it was within 1 point of the highest utility value (Table 5). In the Bayesian belief network that did not have prescribed burning as the most desirable decision alternative, midstory removal had the highest utility value. Midstory removal was the most desirable decision alternative the second most often (21% of Bayesian belief networks) across probability combinations and value scenarios (Table 5). Other decision alternatives that tended to have high utility values (Appendix 10, Supplementary material) included frequent herbicide treatment and planting longleaf pine seedlings, both of which targeted the *Maximize Forest Health* objective, which had the second-highest average objective weight (Table 1). Across probability combinations and stakeholder value scenarios, bird brochure creation was the decision alternative that most frequently (79%, 41 of 52 Bayesian belief networks) was the least desirable decision alternative (Table 5).

Table 4
Decision alternative from each probability combination (version of the Bayesian belief network that weighed conditional probabilities differently depending on whether they were elicited from the scientific literature or experts) that was most likely to decrease the number of Red-cockaded Woodpecker (*Picoides borealis*; RCW) groups in compartments 45, 48, and 49 of the Oakmulgee Ranger District in the Talladega National Forest, Alabama (worst RCW decision) and the probabilities of increasing, not changing, or decreasing the number of RCW groups. Probabilities of decision alternatives are influenced by weights placed on conditional probabilities, and therefore can differ across probability combinations. Value scenarios did not influence the probability of each RCW outcome or other management outcomes occurring. APHIS stands for Animal Plant and Health Inspection Service.

Probability combination	Worst RCW decision	Increase number of RCW groups	No change in number of groups	Decrease number of RCW groups
All	Plant longleaf pine	28.3	41.5	30.2
All 50-50	Plant longleaf pine	29.0	41.3	29.7
Lit Only	Plant longleaf pine	29.9	41.1	29.0
Lit Only	APHIS hog trapping	29.9	41.1	29.0
Lit Only	Create bird brochure	29.9	41.1	29.0
Lit Only	Frequent herbicide treatment	29.9	41.1	29.0
Lit Only	Invasive species education	29.9	41.1	29.0
No Lit	Plant longleaf pine	27.9	41.6	30.5

Table 5
Most and least desirable decision alternatives from 52 Bayesian belief networks – all combinations of 4 probability combinations (versions of the network that weighed conditional probabilities differently depending on whether they were from the scientific literature or experts) and 13 value scenarios (versions of the network with different objective weights and attribute scores from stakeholders) of the Bayesian belief network created in a structured decision making process. One value scenario was created for each of 12 stakeholders' objective weights and attribute scores and one value scenario was created using the mean objective weights and attribute scores across stakeholders. Objective weights indicated the relative importance a stakeholder placed on objectives, and attribute scores indicated the level of satisfaction a stakeholder would experience given particular outcomes. Utility values were calculated using conditional probabilities, objective weights, and attribute scores and were used to assess the expected degree of satisfaction from each decision alternative. Utility values were calculated for each decision alternative in each probability combination and value scenario. The number of times a decision alternative had the highest utility value or was within one point of the highest utility value was recorded as the most desirable decision frequency. The number of times a decision alternative had the lowest utility value or was within one point of the lowest utility value was recorded as the least desirable decision frequency. RCW stands for Red-cockaded Woodpecker (*Picoides borealis*). APHIS stands for Animal and Plant Health Inspection Service.

Decision alternatives	Probability Combination							
	All		All 50-50		Lit Only		No Lit	
	Most desirable decision frequency	Least desirable decision frequency	Most desirable decision frequency	Least desirable decision frequency	Most desirable decision frequency	Least desirable decision frequency	Most desirable decision frequency	Least desirable decision frequency
Frequent herbicide application	1	0	0	0	0	0	1	0
Midstory removal	2	0	2	0	7	0	1	0
Thinning	1	0	0	2	0	3	1	0
Prescribed burning	13	0	13	0	12	0	13	0
Invasive species education	0	6	0	5	0	6	0	5
Plant longleaf pine seedlings	1	0	0	0	1	0	1	0
RCW cavity installation	0	2	0	1	0	1	0	2
APHIS hog removal	0	7	0	7	0	5	0	7
Flying squirrel removal and nest box installation	0	5	0	7	0	7	0	5
Bird brochure creation	0	11	0	10	0	9	0	11

3.3. Sensitivity analysis

Stakeholders unanimously voted to focus sensitivity analysis on the *Average* value scenario of the *All* probability combination, where all expert and scientific literature probabilities were weighted equally. The ranking of decision alternatives was insensitive to changes in node probabilities. No matter which node probabilities were changed, prescribed burning was still considered the most desirable decision alternative. The utility values for the most desirable decision alternative calculated during the sensitivity analysis are located in Appendix 11, Supplementary material.

The number of RCW groups was most influenced by RCW population size, cavity availability, helper survival, breeder survival, and the number of fledglings produced (Fig. 5). For example, when there was a low RCW population size, there was a 5% chance that the RCW group number would increase, and when there was a high RCW population size, there was an almost 60% chance of the RCW group size increasing (Fig. 5). Tornado diagrams that illustrate the sensitivity of all other fundamental objectives to each node in the Bayesian belief network can be found in Appendix 12, Supplementary material.

4. Discussion

4.1. Stakeholder values

Stakeholders tended to give the highest weight to conservation-oriented objectives, and stakeholders, on average, had the highest change in mean satisfaction between the highest and lowest attribute levels for conservation-oriented nodes (Table 2). Further, the least variation in attribute scores among stakeholders occurred for the conservation-oriented objectives. However, the variation in attribute scores was pronounced for the economics and aesthetics objectives, with multiple stakeholders indicating they gained the most satisfaction from different attribute levels (Table 2, Appendix 5, Supplementary material). This was not unexpected since stakeholders represented different interest groups. Despite their different backgrounds, and the differences in values pertaining to economics and aesthetics, our results indicate that stakeholders cared the most about wildlife and plant conservation within the Oakmulgee and generally agreed that an increase in RCW group number, an increase in native species diversity, and a decrease in invasive species abundance would be the outcomes that provide them with the most satisfaction. The tendency we found for stakeholders to most value wildlife and plant conservation is consistent with results from Lavoie et al. (2011). Consequently, we do not think our results are highly sensitive to the stakeholder composition in our study.

4.2. Decision alternative ranking

First, we will discuss the most desirable and least desirable decision alternatives when all objectives were taken into consideration. It is reasonable that prescribed burning had the highest utility value across probability combinations (Table 5), value scenarios (Table 5), and throughout the sensitivity analysis (Appendix 11, Supplementary material) because prescribed burning has been known to positively affect all five of the first-order fundamental objectives. Prescribed fire had a positive effect on the *Maximize RCW Group Number*, *Maximize Forest Health*, and *Maximize Aesthetics* first-order objectives because frequent fire is positively associated with RCW nest success (Ramirez & Ober, 2014), longleaf pine is fire-dependent (Walker 1998; Outcalt, 2000), and fire creates open stand conditions that stakeholders considered aesthetically pleasing (Addington et al., 2015; Outcalt & Brockway, 2010). Prescribed burning also has a positive influence on the *Maximize Local Economic Health* objective because it requires workers to conduct the burn. Lastly, prescribed burning positively influenced the *Maximize Recreational Enjoyment* objective because frequent prescribed burning increases avian biodiversity (Steen et al., 2013), which benefits bird

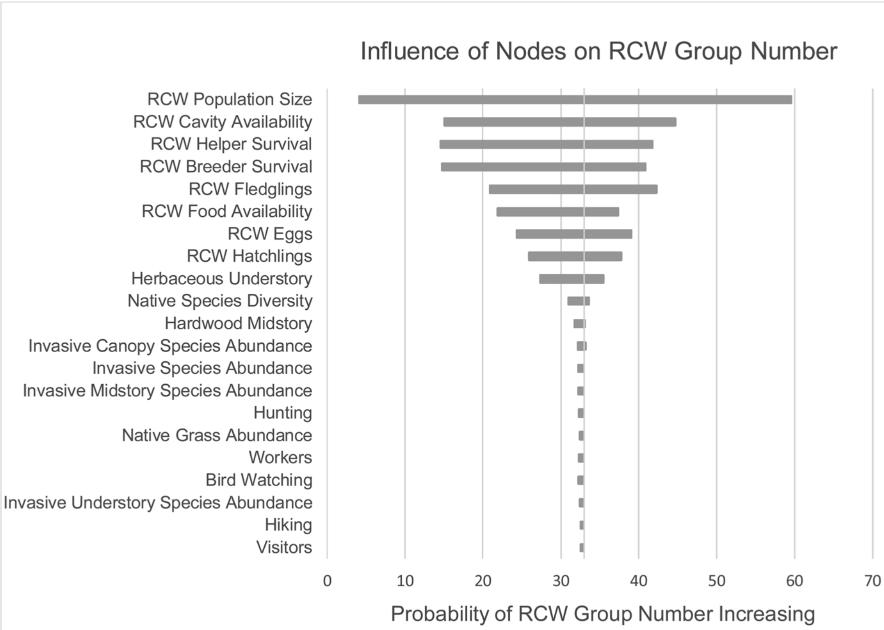

Fig. 5. The influence of different model components (nodes) on the probability of increasing the number of Red-cockaded Woodpecker (*Picoides borealis*; RCW) groups in compartments 45, 48, and 49 of the Oakmulgee Ranger District of the Talladega National Forest, Alabama. The tornado diagram was created from the output of a one-way sensitivity analysis analyzing each component of the Bayesian belief network (node) that affected the probability of increasing the number of RCW groups. The *All* probability combination version of the Bayesian belief network (all conditional probabilities from experts and the scientific literature were weighted equally) was used. Nodes at the top of the diagram had the greatest influence on the probability of increasing the RCW group number, and model components on the bottom had the least influence.

watching.

Similarly, it was reasonable that midstory removal was the second most desirable decision alternative across probability combinations and value scenarios (Table 5) because midstory removal has a positive influence on four of the first-order fundamental objectives. Midstory removal positively influenced the *Maximize RCW Group Number, Maximize Forest Health, and Maximize Aesthetics* first-order objectives because it is positively associated with RCW nest success (Conner et al., 1995; Franzreb, 1997), native species diversity increases with midstory removal (Harrington & Edwards, 1999; Harrington, 2011), and midstory removal creates more open stands (Outcalt & Brockway, 2010). Midstory removal also has a positive influence on the *Maximize Local Economic Health* objective because it requires workers to conduct midstory removal.

It was also logical that bird brochure creation was most often considered the least desirable decision alternative (Table 5) because it was intended to target an objective that received relatively little weight ($0.056 = 0.17 \times 0.33$) from stakeholders, the *Maximize Bird Watching* second-order objective under the *Maximize Recreational Enjoyment* first-order objective (Table 1).

Next, we will discuss the most desirable and least desirable decision alternatives for increasing RCW group number. It was logical that cavity insert installation was the decision alternative that was most likely to increase RCW group number. RCWs require cavities to breed, and it can take 10 months to years to excavate a cavity (Baker, 1971; Jackson, Lennartz, & Hooper, 1979). Several studies have also found that artificial cavity insert installation significantly ($p < 0.05$) increased RCW group size (Carrie, Moore, Stephens, & Keith, 1998; Kappes, 2008) and group number (Conner et al., 1995; Copeyon et al., 1991; Franzreb, 1997). It was also logical that planting longleaf pine seedlings was the least desirable decision alternative for maximizing RCW group number because our Bayesian belief network modeled a ten year time scale and RCWs prefer to forage on pine that are > 60 years old (Zwicker & Walters, 1999).

It is important to recognize that our Bayesian belief network assessed the extent to which individual decision alternatives fulfill stakeholder objectives. While applied management often uses more than one management method at a time, our Bayesian belief network is useful because it highlights the relative contribution of individual management methods given different stakeholder values and conditional probabilities. Our Bayesian belief network can serve as a valuable tool to prioritize management methods given stakeholder objectives and time constraints. To better understand how multiple decision alternatives work in tandem to meet stakeholder objectives, suites of decision alternatives that include prescribed burning and other decision alternatives, such as midstory removal, can be evaluated in the future.

4.3. Uncertainties and model robustness

We used conditional probabilities from the scientific literature and experts to account for uncertainty, such as environmental and demographic stochasticity, in our model (Appendix 8, Supplementary material; Conroy et al., 2008; Irwin et al., 2011). Many of the experts who provided probabilities did not work in the Oakmulgee, and none of the studies we used to determine probabilities took place in the Oakmulgee. Since we obtained more general probabilities, our Bayesian belief network is applicable to other parts of the RCW range. However, not having probabilities related to our study site in particular adds another degree of uncertainty because the specific management history of longleaf pine impacts structure and species richness (Brudvig & Damschen, 2010).

We conducted a one-way sensitivity analysis to evaluate whether our Bayesian belief network was sensitive to particular inputs and determine whether data collection was necessary to refine probabilities, thereby reducing parameter uncertainty. However, the sensitivity analysis determined that the Bayesian belief network was insensitive to changes in probabilities. We conclude that the robust nature of our Bayesian belief network also suggests that including more or different stakeholders in our analysis is unlikely to change our results.

4.4. Using Bayesian belief network results to understand RCW population dynamics

While the sensitivity analysis indicated the most desirable decision alternative was insensitive to changes in probabilities, it did allow us to identify which nodes had the greatest influence on each fundamental objective. RCW group number was most affected by RCW population size, cavity availability, helper survival, breeder survival, and the number of fledglings produced (Fig. 5). It was reasonable that cavity availability had the highest impact on group number after population size because RCWs require cavities to reproduce and cavity availability can be a limiting resource. It was also logical that breeder survival influenced group number since it is directly related to reproduction, as is helper survival because helper presence is positively associated with reproductive output (Beyer, Costa, Hooper, & Hess, 1996; Conner et al., 2004; Garabedian, Moorman, Peterson, & Kilgo, 2017; Heppell, Walters, & Crowder, 1994; Lennartz, Hooper, & Harlow, 1987; Neal, James, Montague, & Johnson, 1993). In addition, it was reasonable that fledgling number had some of the highest impact on RCW group number since it is directly related to RCW recruitment, which influences whether more groups form.

Some other factors that had a noticeable influence on the probability of RCW group number increasing included food availability and herbaceous understory. It is logical that food availability could influence RCW reproduction and hence RCW group number. However, while some studies have examined how vegetation age and structure impact arthropod availability (Hanula & Engstrom, 2000; Hooper, 1996; Horn & Hanula, 2008) and some have assessed RCW breeder and nestling diet composition (Hanula & Engstrom, 2000; Hess & James, 1998), none have explored how arthropod availability influences RCW survival or reproduction rates. It was also logical that herbaceous understory impacted RCW group number because it has been associated with RCW nest success (James et al., 1997; James, Hess, Kicklighter, & Thum, 2001).

To better understand why the RCW population in the Oakmulgee has not exceeded 123 groups despite cavity installation and other management by the USFS, field data could be collected to investigate how RCWs select cavity tree location. This information could be used to improve the chance that RCWs use artificial cavities to form new groups. It would also be beneficial to explore the relationship food availability and vegetation composition have with RCW adult survival and nest success. It also could be helpful to study how prescribed burning regimes affect RCW population growth. Analysis of these data would give greater insight into current limits to RCW population growth and management needs in the Oakmulgee.

We also note that the fundamental objective of *Maximize RCW Group Number* can actually be considered a means objective for the fundamental objective of *RCW Population Persistence*, but managers treat *Maximize RCW Group Number* as a fundamental objective because of directives in the RCW Recovery Plan.

The Bayesian belief network we built for compartments 45, 48, and 49 could also be used to inform management decisions in other areas in the Oakmulgee and similar forests. Although, some tailoring of the Bayesian belief network, such as including other objectives or decision alternatives, may be required to address specifics of other management areas.

5. Conclusion

Our study showed that cavity insert installation was associated with the greatest chance of the RCW group number increasing and the number of RCW groups was most influenced by RCW population size, cavity availability, helper survival, breeder survival, and the number of fledglings produced. These findings give the USFS in the Oakmulgee ideas of ways to reduce previous limits to RCW population growth and approach the RCW Recovery Plan Goal. Additionally, our study found that prescribed burning was always the most desirable decision alternative, followed by midstory removal, frequent herbicide treatment, and planting longleaf pine seedlings. These findings give the USFS in the Oakmulgee information about the relative contribution single management alternatives are expected to make to fulfilling the suite of stakeholder objectives. When making future decisions about which management methods to apply, the USFS can consider using multiple methods but with the knowledge that some methods individually are expected to have a lower probability of fulfilling objectives than others, for example, APHIS hog removal compared to midstory removal. Our collaboration with the USFS is ongoing, and future work could include analyzing portfolios with multiple management methods as decision alternatives. Public lands are managed for multiple uses, and SDM aids management because it helps identify objectives considering stakeholders with different values, create an explicit model of system dynamics as understood by managers and stakeholders, and evaluate management alternatives in a way that is transparent, incorporates uncertainty, and is easily updated in the future.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jnc.2019.01.010.

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