Recognizing trade-offs in multi-objective land management

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As natural resource management and conservation goals expand and evolve, practitioners and policy makers are increasingly seeking options that optimize benefits among multiple, often contradictory objectives. Here, we describe a simple approach for quantifying the consequences of alternative management options in terms of benefits and trade-offs among multiple objectives. We examine two long-term forest management experiments that span several decades of stand (forest tree community) development and identify substantial trade-offs among carbon cycling and ecological complexity objectives. In addition to providing improved understanding of the long-term consequences of various management options, the results of these experiments show that positive benefits resulting from some management options are often associated with large trade-offs among individual objectives. The approach to understanding benefits and trade-offs presented here provides a simple yet flexible framework for quantitatively assessing the consequences of different management options.

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Although natural resource management has always involved a struggle in terms of meeting multiple objectives (Dale *et al.* 2000), this has become particularly acute as changing climatic conditions, biological invasions, and land-use patterns have created a novel and diverse set of societal demands for ecosystem services and a challenging array of stressors (Kirilenko and Sedjo 2007; Meehl *et al.* 2007; Bonan 2008). In particular, as the reality of these global change processes becomes increasingly apparent, natural resource managers are seeking site-level management options that can be applied over space and time to promote adaptation to new climatic conditions, and that will help to mitigate the effects of increasing atmospheric carbon dioxide (CO_2) concentrations (Millar *et al.* 2007; Canadell and Raupach 2008). At the same time, these management options should continue to maintain native species abundance, ensure wildlife habitat quality, and in many cases continue to provide traditional, economically valuable goods and services (Lant *et al.* 2008; Hunter *et al.* 2010).

However, there is growing evidence that management options that are beneficial for one of the abovementioned objectives may result in trade-offs in which benefits for other objectives are reduced (D'Amato *et al.* 2011; Dickie *et al.* 2011). For example, managers might seek to promote adaptation by creating ecosystems with high ecological complexity because ecological theory and limited evidence suggest that more complex systems may exhibit greater stability in terms of ecosystem function, as a result of niche partitioning (ie exploiting differences in resource acquisition strategies among individuals or species) or differences in responses to stressors (McNaughton 1977; Naeem 2002; Elmqvist *et al.* 2003; Hooper *et al.* 2005; Loreau 2010). In addition, because rising atmospheric CO_2 is a major driver of climate change, natural resource managers might also seek to contribute to climate-change mitigation by maintaining or maximizing both carbon (C) stores or sequestration (Canadell and Raupach 2008; Malmsheimer *et al.* 2008). However, important trade-offs may exist if the conditions that maximize C stores or sequestration do not support high levels of ecological complexity. The potential for trade-offs between objectives increases as the number and variety of management objectives grows.

As a consequence, scientists, natural resource managers, and policy makers need straightforward, user-friendly methods for characterizing and quantifying the individual and combined benefits and trade-offs of multiple, potentially conflicting objectives. Techniques for assessing multi-objective land-management outcomes have been developed but often rely on complicated mod-

In a nutshell:

- Long-term forest management experiments have demonstrated the existence of important trade-offs among different objectives, complicating efforts to understand the overall consequences of various management options
- Benefits for individual objectives in response to individual management options can be combined to quantify overall benefit and overall trade-off
- This approach is simple enough to be widely used by scientists, managers, and policy makers; is applicable to a vast array of ecosystems; and is flexible enough to capture site-specific management objectives

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eling frameworks and decision support structures that are difficult to apply in many situations, may not always address the potential for trade-offs among objectives, and are often not computationally simple enough to be routinely used by land managers and/or policy makers (Lamy *et al.* 2002; Bettinger and Chung 2004; Cai *et al.* 2004; Matthews *et al.* 2006; Mendoza and Martins 2006; Spies *et al.* 2007; Alvarez and Field 2009). Despite the clear need for a strategy to understand the impacts of alternative management options, few approachable methods for quantifying trade-offs have emerged. Yet without such approaches, there is a risk that focusing attention on a given objective related to global change may compromise the overall long-term sustainability of benefits. Our objectives here are (1) to describe a simple approach to quantifying the consequences of alternative management options in terms of benefits and trade-offs between multiple, potentially conflicting objectives and (2) to provide an example of this approach when applied to long-term forest management experiments to assess benefits and trade-offs in C cycling and ecological complexity.

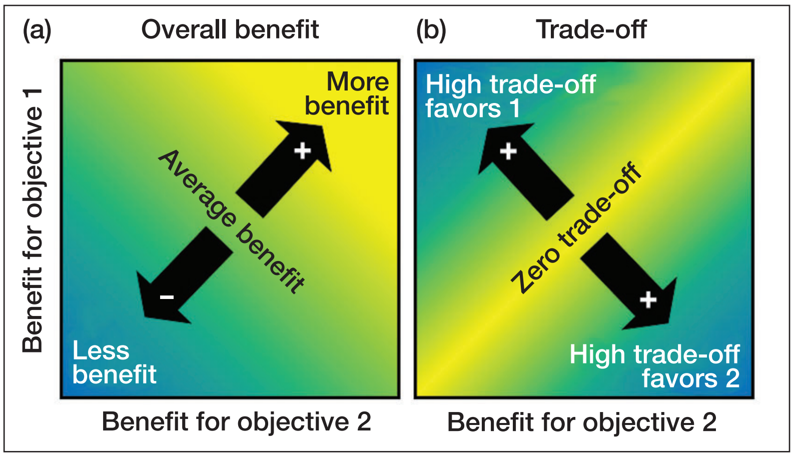

Figure 1. *Illustration and example of overall benefit and trade-off between two land-management objectives. (a) Overall benefit is calculated as the mean of individual benefits and increases from low benefit in the lower left to greater benefit in the upper right. (b) Trade-off is calculated as the root mean squared error of the individual benefits and increases with distance from the 1:1 line, where benefit in 1 equals benefit in 2.*

Benefits and trade-offs

Understanding how management options can impact overall benefits (ie degree to which objectives are achieved) and trade-offs (ie disparity in level of achievement among objectives) for multiple objectives requires an understanding of the responses of individual objectives to those management options. This understanding should be based on scientific data, but in many cases, it may need to be derived from expert knowledge or other non-quantitative sources. Overall benefit and trade-off among individual benefits are calculated as follows:

Benefit for a single management objective is defined as the relative deviation from the mean for a given observation and can apply to any response variable of interest within a managed system. In the context of global change and terrestrial ecosystems, the focus may be on response variables related to C cycling and ecological complexity (although the specific objectives will depend on the ecosystem being managed and the desired overall outcomes). Given observations of the relationship between a management option and an individual objective A, the magnitude of benefit for objective $A(B_A)$ is calculated as:

$$B_A = \frac{A_{OBS} - A_{Min}}{A_{Max} - A_{Min}} \quad \text{(Eq 1)},$$

where A_{OBS} is the observed value of variable A and A_{Max} and A_{Min} are calculated from the entire population of potential outcomes for that objective. Individual benefit ranges from 0 to 1 and can be conceptualized as the proportion of possible benefit in objective A realized in response to a given management option. In cases where some objectives are considered more valuable or important than others, individual objectives can be weighted to incorporate these differences into calculations of overall benefit and trade-off.

The overall benefit for multiple objectives can be estimated by simply taking the mean of individual benefits, which can be weighted based on objective importance (Figure 1a). The trade-off between two benefits is a measure of the extent to which the individual benefits of a management option are very different between individual objectives (Figure 1b). Obviously, the ideal outcome of a management option is a high degree of benefit for all individual objectives, which results in high overall benefit and low trade-off, and the least desirable outcome is one that results in low benefit for all objectives – an outcome that also yields low trade-off. However, in some cases, management options can result in high benefit in some objectives and very low benefit in others. This situation represents a large trade-off, and characterizing that trade-off can be useful for informed decision making. One simple means for quantifying the magnitude of the trade-off between two or more objectives is to calculate the root mean squared error (RMSE) of the individual benefits. RMSE approximates the average deviation from the mean benefit and, in two dimensions, is simply the distance from the "1:1 line" of equal benefit (Figure 1b). Because it relies on straightforward, relatively simple quantitative measures, this method for assessing trade-offs and benefits represents an approachable strategy for characterizing the overall merit of alternative management options with respect to multiple objectives. Scientists, land managers, or policy makers can use the following simple steps to inform decisions about benefits and trade-offs from whatever data sources or expert opinions are available.

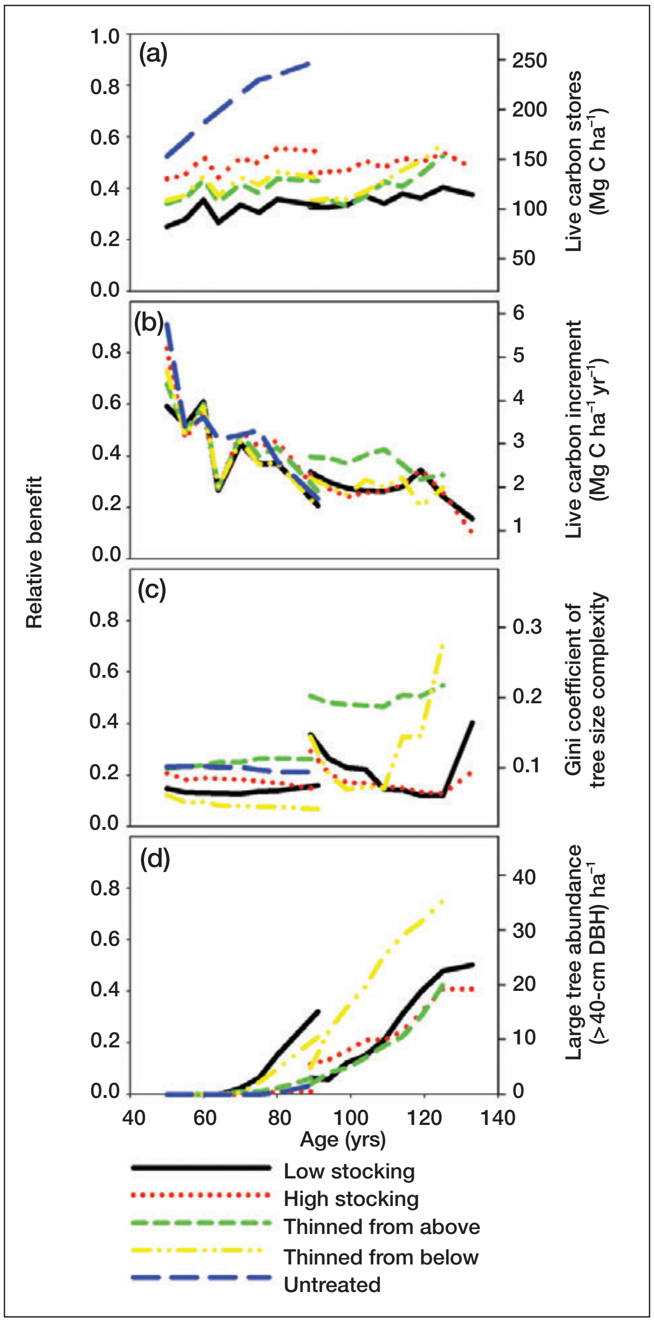

Figure 2. *Impact of forest management options on individual objectives over several decades of forest management in two long-term red pine (*Pinus resinosa*) management experiments. Benefits are expressed in absolute units (right vertical axis) and relative benefit scaled from 0–1 (left vertical axis). Lines from age 50–90 are the Birch Lake Plantation and lines from age 90–130 are the Cutfoot Experimental Forest. Line colors indicate different management options and how individual objectives responded to management options through time.*

Identify management options

These options are the different actions that managers can make to influence the delivery of ecosystem services. In the forest example presented here, the management options are stocking level, thinning method, and tree age or rotation length, whereas the spatial scale of assessment is the individual site, or stand (forest tree community), because that scale matches the relevant long-term data. In other ecosystems, management options may include livestock grazing regimes, recreation management, prescribed burning, fishing regulations, and invasive species eradication options, and the scales of assessment could range from patches of prairie vegetation to large managed landscapes, including rangelands, urban ecosystems, forested landscapes, and marine systems.

Define the individual objectives

These objectives are the services provided by the ecosystem. In this example, the objectives are C stores, annual aboveground live C increment, a general indicator of C sequestration patterns, tree size complexity, and large tree abundance, a commonly used measure of old-growth characteristics. In other ecosystems, the objectives may be forage or agricultural production, biodiversity conservation, fishery sustainability, and so on.

Quantify how objectives depend on options

This characterizes the relationship between management options and individual objectives. In this example, data from two long-term forest management experiments are used to illustrate how stocking level, thinning method, and tree age influence four individual objectives (Figure 2). Here, relationships between management options and objectives are described by quantitative data. Other approaches – including expert knowledge or surrogate data from similar ecosystems – could be used, provided that the relationship between benefits and options is quantified. To facilitate comparison between very different objectives, we suggest that the response of each objective should be scaled between 0 and 1, with 0 representing the minimum possible benefit for that objective and 1 being the maximum possible benefit for that objective. Although this example focuses on assessing benefits and trade-offs at the stand level, this method may be applied to different spatial scales, including landscapes and/or regions, if appropriate knowledge about the relationship between objectives and options exists.

Calculate total benefit

The overall total benefit can be estimated as the mean of individual benefits. If some objectives are more important than others, a weighted mean can be used to favor those objectives. Here, we weighted all objectives equally and the results illustrate outcomes.

Calculate trade-offs

We quantified trade-offs between benefits using the RMSE of the individual benefits. RMSE calculates the average difference between each individual benefit and the mean benefit, and thus describes the magnitude of spread away from the mean (Figure 1).

Forest management for multiple objectives

We examined benefits and trade-offs in two long-term forest management experiments in northern Minnesota: the Cutfoot Experimental Forest and the Birch Lake Plantation. Cutfoot is located in the Chippewa National Forest and contains natural forests that resulted from fire events in the early 1870s. Birch Lake is located in the Superior National Forest, with forests of plantation origin (seeded) that were established between 1912 and 1913. Species composition at both sites is dominated by red pine (*Pinus resinosa*), which comprises over 95% of basal area throughout the experiments. White and jack pines (*Pinus strobus* and *Pinus banksiana*, respectively) constitute the bulk of the remaining trees, with other species making up less than 1% of basal area (more detail on these studies is available in Bradford and Palik 2009; Bradford *et al.* 2010; D'Amato *et al.* 2010, 2011; and Powers *et al.* 2010).

Although originally designed to examine the effects of different management options on forest growth and yield, each of these long-term experiments includes management options that impact C dynamics and ecological complexity, such as manipulating the stocking level, influencing tree age or rotation periods, and forest thinning. Because many of these management options represent the same options available for addressing global change, examination of these long-term data provides valuable insights into trends and trade-offs related to C cycling and ecological complexity. At Cutfoot, management options examined included three levels of residual basal area (23.0, 27.5, and 32.1 m^2 ha^{-1}) and, in separate stands, two types of thinning method (thinned from above or from below). In short, thinning from above involves the removal of trees primarily in co-dominant crown classes, but also occasional dominant and intermediate individuals to favor the best trees in the co-dominant and dominant crown classes; likewise, thinning from below removes trees from the lower crown classes (overtopped and intermediate) to favor trees in the upper crown classes. All options at Cutfoot are replicated in three randomly selected stands. At Birch Lake, management options included three levels of residual basal area (21, 28, and 35 m^2 ha^{-1}) crossed with two types of thinning methods (thinned from above and from below), for a total of six different options, each represented by a single ~1 ha stand. In addition, the Birch Lake experiment included three unmanipulated control stands.

Both experiments were thinned at 5–10-year intervals from the experiment origination cut (stand ages 50 and 85 years at Birch Lake and Cutfoot, respectively) until the trees were 95 (Birch Lake) and 142 (Cutfoot) years old. Forest tree communities were assessed by repeatedly measuring diameter at breast height (DBH: 1.37 m above ground surface) of all trees with DBH > 8.9 cm immediately before each thinning on a single (Birch Lake) or 10 (Cutfoot) permanent 0.08-ha plots per experimental manipulation. In combination, the Cutfoot and Birch Lake experiments represent tree ages ranging from 50 to 142 years old, providing the opportunity to assess how forest tree communities respond to common management options over very long time periods.

Forest management objectives

Stand-level responses have been explored in detail by D'Amato *et al.* (2011). Here, we focus on patterns in the results from the various management options and across tree ages corresponding to the following four objectives:

(1) *Tree size complexity* – increasing and maintaining ecological complexity is a commonly recognized objective related to climate-change adaptation potential (Millar *et al.* 2007; Puettmann *et al.* 2009). We chose to focus on the degree of tree size complexity within a given stand based on the diversity of tree diameters within a given plot. The Gini coefficient (G) was used for quantifying tree size diversity and was calculated from the tree list ordered by ascending diameter as:

$$G = \frac{\sum_{1}^{n} (2i - n - 1)x}{n^2 \mu} \quad \text{(Eq 2)},$$

where n is the number of trees in the plot, x is the diameter of tree i, and μ is the mean tree diameter. The Gini coefficient was chosen because of its strong performance relative to other measures of tree size diversity (Lexerod and Eid 2006). Values for G range from 0 to 1, with 0 values corresponding to stands with perfect size equality and values of 1 representing stands in which all trees but one have a value of 0.

(2) *Large tree abundance* – restoring late-successional forest structure has become an increasingly common objective for forests managed for wood production, due in large part to the benefits of these systems to the conservation of biodiversity. As a general measure of old-growth characteristics, we quantified the density of trees ≥ 40-cm DBH as a surrogate for achieving late-successional conditions given the association of this structural characteristic with late-successional temperate forests in North America (Whitman and Hagan 2007; Zenner and Peck 2009).

(3) *Carbon stores* – there is considerable interest in managing forests to mitigate atmospheric CO_2 through maintaining and maximizing ecosystem C stores. We used the total aboveground C stored in trees as an indicator of C stores. Specifically, aboveground biomass estimates were derived from existing allometric equations based on species-group and tree diameter (Jenkins *et al.* 2003). Total aboveground biomass was converted to aboveground C stores under the assumption that 50% of a given tree's dry mass was C. Aboveground tree C – although certainly not the only C pool – is typically both the largest and most dynamic C pool in forest ecosystems, and the pool most directly influenced by forest management.

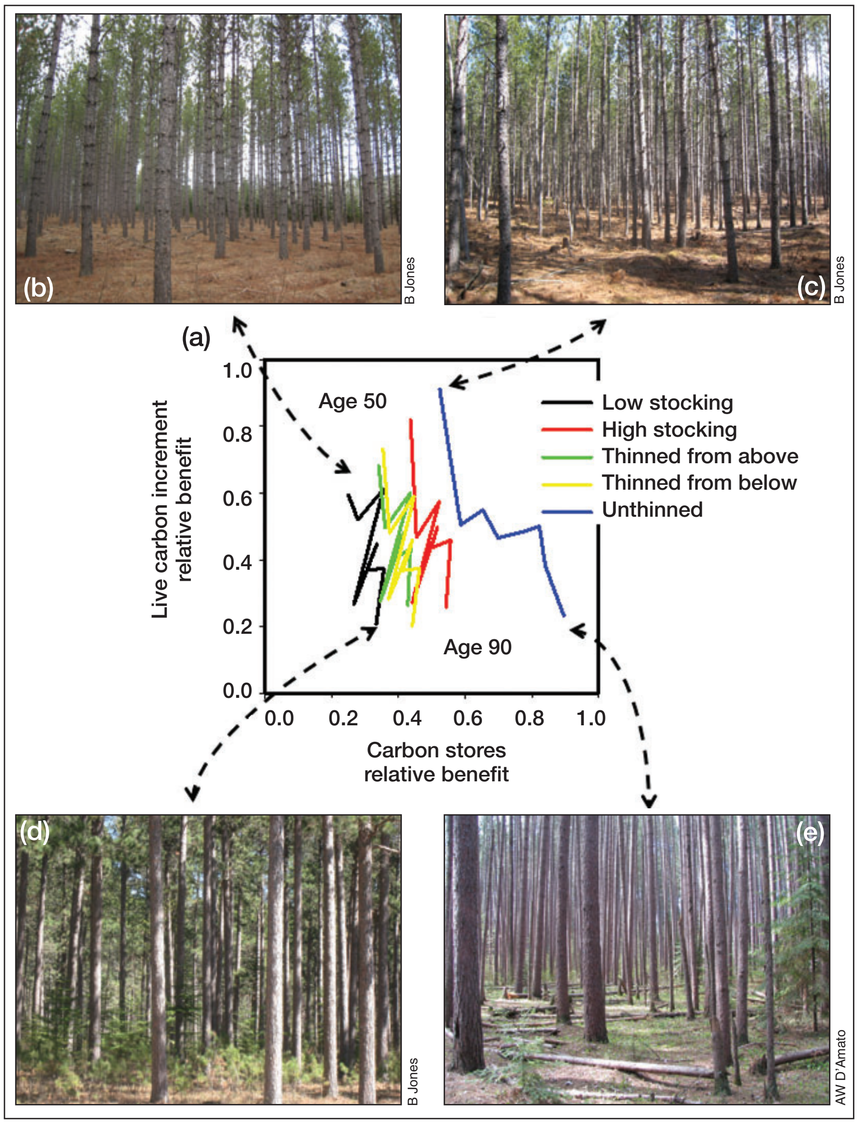

Figure 3. *A framework for assessing overall benefit and trade-offs in multi-objective land management. Example scatterplot (a) depicts the relationship between carbon (C) stores and aboveground live C increment (ΔAGC) for a long-term forest management experiment. Relative benefit for C stores (x axis) is plotted against relative benefit of ΔAGC (y axis), and line colors relate to specific management options (see text for details). As forest tree communities age, they progress from high ΔAGC and low stores (upper left of [a]) to lower ΔAGC and higher stores (lower right of [a]), although the specific path is influenced by management options. This approach allows comparison of two management objectives; although visualization of more than two objectives is difficult, these calculations can easily be extended to assess benefits and trade-offs for many objectives. Photos illustrate these outcomes in red pine forest tree communities that range from young thinned and unthinned ([b] and [c], respectively) to older thinned and unthinned ([d] and [e], respectively).*

(4) *Aboveground live C increment* – as with C stores, an additional objective related to mitigating rising atmospheric CO_2 levels is related to maximizing the rate at which C is sequestered and integrated into ecosystem C pools. We quantified the annual increment in C stored in aboveground live biomass (ΔAGC) between measurements as an indicator of C sequestration. Although not inclusive of all forest C pools, ΔAGC represents changes in the largest and most dynamic C pool in forest ecosystems, and the pool that is most directly impacted by forest management activities (Fahey *et al.* 2010).

Benefits and trade-offs in forest management

Although the outcomes of management options for individual objectives are discussed more completely elsewhere (eg D'Amato *et al.* 2011), they are worth briefly examining here to illustrate the challenge of assessing the integrated benefits and trade-offs when considering multiple objectives. Benefit for C stores was considerably higher in unmanaged forest tree communities than in thinned communities and clearly higher in heavily stocked communities than in lightly stocked communities (Figure 2a). However, tree age and thinning method had only modest impacts on C stores. ΔAGC benefit, by comparison, consistently declined with tree age in all forest tree communities and was somewhat higher in communities that were thinned from above (Figure 2b). Tree size complexity benefit was also impacted by thinning method, with greater levels of complexity in forest tree communities thinned from above (Figure 2c). The benefit for large tree abundance was positively related to age and was lowest in unmanaged forest tree communities and highest in communities thinned from below (Figure 2d).

The relationship between management options and individual objectives is often contradictory, complicating efforts to quantitatively assess the overall desirability of specific management options. A useful example is the dichotomy between benefit for C stores and benefit for ΔAGC; the effects on the conflicting objectives can be easily visualized through the method presented here (Figure 3). A similar trade-off exists between maintaining forest tree communities with older tree ages, which has advantages for the abundance of large trees but disadvantages for ΔAGC. Likewise, thinning from above appears to enhance tree size complexity, yet clearly restricts the abundance of large trees. Even the costs and benefits of leaving forest tree communities unmanaged versus active management can be difficult to assess when considering multiple objectives; management decreases C stores, yet increases the abundance of large trees.

Although benefits and trade-offs between two objectives can be relatively easily described and visualized (eg Figure 3), adding further objectives complicates interpretation. Integrating these complicated results into a quantitative measure of benefits and trade-offs, as described above, provides a more coherent picture of overall outcomes. At young ages, unmanaged communities have the highest mean benefit, yet also encompass the highest trade-off among individual benefits (Figure 4). High stocking levels and thinning from above also appear to have higher mean benefit than lower stocking levels or thinning from below, respectively, and the magnitude of the trade-offs between stocking levels and thinning methods is relatively modest.

Conclusions

These results indicate complicated outcomes in response to forest management and suggest that the overall consequences of specific management options can and should be viewed in the context of trade-offs among multiple objectives. The specific benefit and trade-off results presented in this example are dependent on the range of objectives selected in this case study and are not intended to necessarily identify the "best" management strategy for red pine forests. Rather, these results show that important trade-offs can exist among land-management objectives, underscoring the need for an accessible yet flexible tool for assessing benefits and trade-offs. Calculating benefit and trade-off as outlined here provides scientists, resource managers, and policy makers with a framework for quantitatively assessing the outcomes of specific management actions with respect to multiple objectives. The calculations rely on simple, well-known statistical measures that do not require an advanced mathematical or statistical background. In addition, the differential weighting of individual objectives provides an opportunity to favor some objectives over others without completely discarding any given objective. This assessment method is user-friendly, quantitative, and flexible enough to be applicable to a variety of management options and objectives, and has the potential to be integrated into other modeling frameworks and decision support systems.

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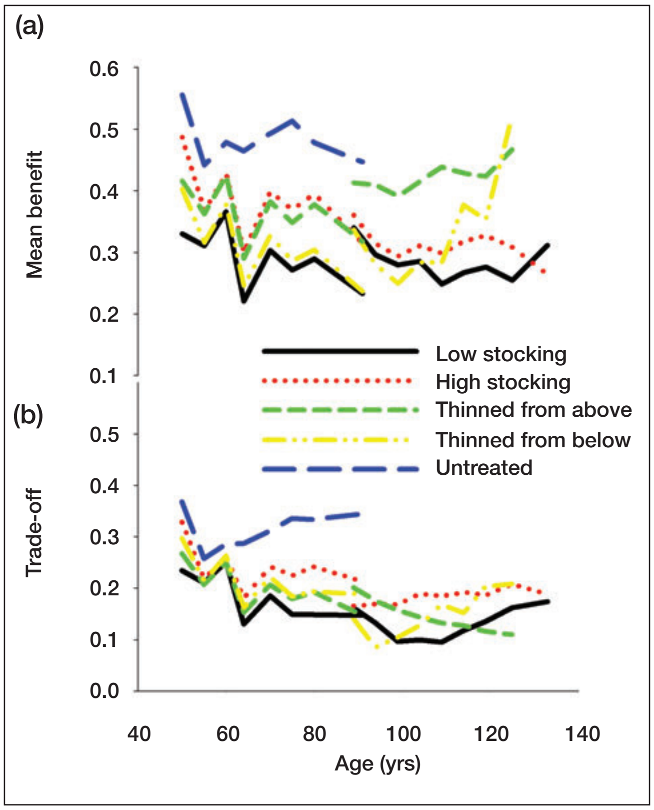

Figure 4. *Impact of forest management options on (a) overall benefit and (b) trade-off over several decades of forest development in two long-term red pine management experiments. Benefit is calculated as the mean of individual benefits and can be weighted based on the importance of each benefit. Trade-off is calculated as the root mean squared error of individual benefits. Lines from age 50–90 are the Birch Lake Plantation and lines from age 90–130 are the Cutfoot Experimental Forest. Line colors indicate different management options and illustrate the relatively high benefit–trade-off in unmanaged stands, as well as the importance of tree age for mean benefit and the magnitude of trade-off.*

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