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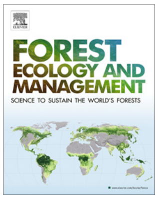

Recovery trends for multiple ecosystem services reveal non-linear responses and long-term tradeoffs from temperate forest harvesting

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ABSTRACT

A major challenge for forest management is to reduce unintended tradeoffs resulting from timber harvesting. However, few empirical studies provide quantitative evidence for how ecosystem service trade-offs in forests persist over longer timeframes. Here, we examine the long-term recovery of multiple ecosystem services following harvest of old-growth forest stands on Vancouver Island, BC, Canada. We used a novel 212-year forest chronosequence approach to estimate recovery of a coastal temperate forest's capacity to provide eight ecosystem services. We examined: wood volume, carbon storage for climate regulation, potential nesting habitat for an old-growth associate bird species the marbled murrelet (*Brachyramphus marmoratus*), coarse woody debris, habitat provided by standing dead trees, large heritage trees, wild edible berries, and large redcedar (*Thuja plicata*) trees used traditionally by First Nations for carving canoes and totem poles. Ecosystem service recovery trajectories followed u-shaped or s-shaped trajectories with varying times to reach old-growth conditions. Some services remained high post-harvest (e.g., habitat services of coarse woody debris) or recovered quickly in the first 100 years (e.g., carbon storage). However, cultural ecosystem services such as the large cedar trees used in traditional First Nations carving, had 200+ year delays in recovery. Our empirically-derived ecosystem services recovery trajectories demonstrate the complexity of long-term dynamics of harvest tradeoffs and help identify strengths and limitations of management approaches for sustaining multiple forest ecosystem services.

1. Introduction

Understanding tradeoffs among ecosystem services (ES) is a focal challenge in ecosystem management. Yet our understanding of how tradeoffs develop and persist over time remains limited because most ES studies are mere snapshots at a single point in time (Tallis et al., 2008; Renard et al., 2015), and omit the temporal dynamics of ES recovery. However, understanding the long-term responses of ecosystems to management may be critical to mitigating tradeoffs (Rodriguez et al., 2006; Higgs et al., 2014; Cavender-Bares et al., 2015). While forest management has a history of computer-based modeling of forest tradeoffs through time (Gibbons et al., 2010; Lutz et al., 2016), empirical information on the dynamics of recovery for multiple forest ES remains limited. Furthermore, ecosystem recovery following disturbance can be a non-linear process with differing timing and rates of recovery (Chazdon, 2008; Robson et al., 2011; Bullock et al., 2011; Messier et al., 2013), an idea which has been under-explored in ES research. As such, empirical tracking of ES bundles (the set of ES provided by an area) along the trajectories of a recovering ecosystem is a critical next step for informing management of multiple ES.

Harvesting of old-growth forests and converting them to managed timber production areas has often caused declines (and thus tradeoffs) in a variety of non-timber ES, such as carbon storage, wild edible foods, and large trees with ecological and cultural value (Franklin and Johnson, 2011; Lindenmayer et al., 2012). Because many forest ES are mechanistically linked to specific forest structural attributes (Bauhus et al., 2010; Sutherland et al., submitted for publication), their recovery is likely to track the structural regeneration of the forest. For instance, carbon storage increases rapidly in young forests, and maturation of large trees creates cultural heritage values in old forests (Franklin et al., 2002; Blicharska and Mikusinski, 2014; Poorter et al., 2016). Understory plants that provide wild edible berries often regenerate in recently disturbed and late successional forests (Clason et al., 2008; Swanson et al.,

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2010). Thus, accurate unraveling of long-term dimensions of tradeoffs requires understanding the role of forest stand dynamics and complex recovery trajectories of forests. Despite this, the recovery of forest ES beyond typical rotation ages of forest harvesting plans (typically, 50–100 years) is rarely examined (Bauhus et al., 2009; Gibbons et al., 2010; Gerzon et al., 2011). Tracking the long-term recovery trajectories of forest ES can clarify the extent that second-growth forests—now comprising 64% of global forests (FAO, 2010)—provide ES relative to the remaining old-growth forests (Chazdon, 2008; Poorter et al., 2016).

In few places have the consequences of tradeoffs become more apparent than in the forests of western North America (MacKinnon, 2003). Harvest of very old "old-growth" forest stands (at least 250 years old) has caused widespread declines in many non-timber ES (Bunnell et al., 2003; Franklin and Johnson, 2011), making this a model ecosystem to assess long-term harvesting tradeoffs and ES recovery. Historically, with methods such as clear-cut harvesting (i.e., the felling and removal of all trees from a site), the immediate provisioning of timber is accompanied by declines in ecosystem capacity to provide other ES such as carbon storage (climate regulation), coarse woody debris (forest floor habitat services) or large redcedar trees (a cultural resource for First Nations carving). Because forest structural features recover along non-linear and variable trajectories (Chazdon, 2008; Bauhus et al., 2009; LePage and Banner, 2014), we hypothesize that the ES derived from them recover along varying trajectories, as well.

To address this empirical gap, we investigated the long-term (212-year) recovery of multiple ES in coastal temperate rainforests on Vancouver Island, British Columbia, Canada, which have been extensively harvested for timber (Trofymow et al., 1997; MacKinnon, 2003; Gerzon et al., 2011). We examined a 212-year chronosequence of forest structural development compiled from existing databases. Eight different ES, which may have long timeframes for recovery, were tracked in order to represent diverse economic, ecological, and cultural values of the region's forests. Our objectives were to: (1) estimate baseline ES in representative unharvested old-growth forests and (2) identify the shapes and timeframes of ES recovery toward an old-growth forest baseline.

2. Methods

We compiled a dataset of change in forest structure spanning a 212-year chronosequence for Vancouver Island, BC, Canada (Fig. 1). We then used forest structural attributes to estimate the capacity of the forest to produce eight ES throughout the 212-year time series (Table 1). Finally, we fit curves to characterize the long-term recovery trajectory of each ES toward a forest baseline condition (defined as the mean ES in representative old-growth plots).

2.1. Study region and chronosequence data

Our work examined coastal temperate forests below 500 m elevation on north and western Vancouver Island (Fig. 1). These forests are dominated by the coniferous tree species western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), amabilis fir (*Abies amabilis*), Douglas-fir (*Pseudotsuga menzesii*), and Sitka spruce (*Picea sitchensis*) reflecting the region's cool, maritime climate (mean annual precipitation = 2787 mm; Meidinger and Pojar, 1991). Forests in this region roughly correspond to the *T. heterophylla* ecosystem classification of Oregon and Washington (MacKinnon, 2003). Forest fires are rare in the humid environment, and natural disturbances are typically caused by low-severity wind, fungal or insect disturbances (MacKinnon, 2003). This lack of severe disturbance results in very old stands (Parish and Antos, 2004), at which point forest-stands exhibit distinctive structural features such as large trees, large standing dead trees, large pieces of coarse woody debris, diverse understory plant communities, and a vertically complex canopy (Franklin et al., 2002). However, the areal extent of old-growth in this ecosystem has markedly declined as most productive forests have been logged and supplanted by second-growth forests less than 100 years old (Meidinger and Pojar, 1991).

Our chronosequence dataset included 49 forest field plots distributed throughout the CWH vm1. Forest field plot data were combined from two previous forest chronosequence studies, which tracked recovery of forest structure attributes across different forest ages (Table 1). All forest stands aged 4–76 years old ($n = 12$) were derived from the Canadian Forest Services Coastal Chronosequence Study (Trofymow et al., 1997), which contrasted the structure of young forest stands ($n = 12$) with that of old-growth forest stands (1 site is 176 years, 3 are >250 years). Data on older forest stands, aged 70–212 years ($n = 24$), were derived from a 'BC Ministry of Forests Ecological Research Plot' study (Gerzon et al., 2011) which analyzed the structural transition from second-growth ($n = 28$) to old-growth forests (>250 years, $n = 9$). Stand age was determined by tree ring counts of several dominant, non-residual trees. Both studies used nested vegetation sampling to measure and record the following forest attributes: trees by species size class and abundance, understory plants by percent cover, and coarse woody debris by species, decay state, and abundance. To control environmental variation (an assumption for chronosequences) caused by soil moisture and topography, both studies systematically selected sites with vegetation characteristics reflecting the region's cool, maritime climate; thus, they primarily sampled mid-slope sites defined as the CWHvm1 01 site series (BC BEC classification system; Meidinger and Pojar, 1991). Stands originated following various stand-replacing disturbances (wind, fire, insects, and harvesting), as detailed in Table 1. Old-growth sites ranged in age from 255 and 470 years (Table 1); thus they represent variable disturbance, climate, and site histories, permitting us to assume that the old-growth sites represent a reasonable proxy of the recovering sites' historical conditions. Thus our dataset is broadly representative of average old-growth and recovering stands in the CWHvm1 01, which is one of Vancouver Island's most widespread and economically important site series (Gerzon et al., 2011). We defined old-growth forests as those exceeding 250 years, based on the standard definition used on coastal BC (MacKinnon, 2003).

2.2. Estimating ecosystem services

Through literature review, we identified key forest structural attributes that determine the forests capacity to provide ES and used these attributes (which were recorded in the chronosequence datasets) as biophysical indicators to estimate provision of the eight ES at each plot (Table 2). These ES included: wood volume, carbon storage, potential nesting platforms used by an emblematic bird species the marbled murrelet (*Brachyramphus marmoratus*), forest floor habitat services provided by coarse woody debris, canopy habitat services provided by standing dead trees, wild edible berries, large heritage trees, and large western redcedar trees used traditionally by First Nations for carving canoes and totem poles.

Large cedar as an ES were indicated by western redcedar (*T. plicata*) trees >1 m diameter at breast height (DBH; diameter measured at 1.34 m above ground). The indicator calculated is the presence or absence of large redcedar. We based this size threshold on the size criteria specified by the Haida First Nation (HN and BC, 2007). Large redcedar are a keystone traditional resource used for traditional housing or totem poles and canoe