NOTE / NOTE

Does coring contribute to tree mortality?

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Abstract: We assess the potential of increment coring, a common method for measuring tree ages and growth, to contribute to mortality. We used up to 21 years of annual censuses from two cored and two uncored permanent plots in the Sierra Nevada of California, to detect changes in mortality rates 12 years following coring for individuals >5 cm DBH from two coniferous species, *Abies concolor* (Gordon & Glend.) Lindl. (white fir) and *Abies magnifica* A. Murr. (red fir). Using a randomized before–after control impact (BACI) design, we found no differences in mortality rates following coring for 825 cored and 525 uncored *A. concolor* and 104 cored and 66 uncored *A. magnifica*. These results support the view that collecting tree cores can be considered nondestructive sampling, but we emphasize that our 12-year postcoring records are short compared with the maximum life-span of these trees and that other species in different environments may prove to be more sensitive to coring.

Résumé : Les auteurs ont évalué la possibilité que la méthode de sondage qui consiste à prélever une carotte de bois dans le tronc, une méthode courante pour mesurer l'âge et la croissance des arbres, contribue à la mortalité. Ils ont utilisé jusqu'à 21 années de relevés annuels provenant de deux places-échantillons permanentes où les arbres avaient été sondés et deux autres où les arbres n'avaient pas été sondés dans la Sierra Nevada en Californie. L'objectif consistait à détecter les variations dans le taux de mortalité 12 ans après le sondage de tiges de plus de 5 cm au DHP appartenant à deux espèces de conifères : *Abies concolor* (Gordon & Glend.) Lindl. (sapin concolore) et *Abies magnifica* A. Murr. (sapin rouge). À l'aide d'un dispositif aléatoire de contrôle d'impact avant-après (BACI), nous n'avons observé aucune différence dans le taux de mortalité de 825 tiges sondées et 525 tiges non sondées d'*A. concolor*, et de 104 tiges sondées et 66 tiges non sondées d'*A. magnifica*. Ces résultats supportent le point de vue que le prélèvement de carottes chez les arbres peut être considéré comme un échantillonnage non destructif. Cependant, nous insistons sur le fait que nos relevés, qui vont jusqu'à 12 ans après qu'il y ait eu un sondage, couvrent une courte période comparativement à la durée de vie maximum de ces arbres et que d'autres espèces dans différentes conditions environnementales pourraient s'avérer plus sensibles au prélèvement de carottes.

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Introduction

Collecting increment cores is a standard method for measuring tree ages and growth in seasonal environments where annual rings are formed. These data are fundamental for our understanding of historic and contemporary forests and their environments (Graumlich 1993; Harper 1977; Kobe et al. 1995; Weiner 1984). However, sampling can have unintended side effects and may influence the ecological systems being studied (Cahill et al. 2001). There is a possibility that the damage caused by coring creates a pathway for disease agents that contributes to tree mortality.

The physiology of wound responses to coring has been relatively well studied (Grissino-Mayer 2003). Living trees

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are thought to compartmentalize coring injuries by developing a boundary limiting the spread of pathogenic microorganisms (Shigo 1984). Although there is wide variation in the immediate response to coring among species, conifers are believed to be generally more resistant to coring damage than hardwoods (Campbell 1939; Grissino-Mayer 2003; Hepting et al. 1949). The pathogenic response to coring is also mediated by environmental factors, with warm, humid environments encouraging fungal growth, and by season of coring, with compartmentalization being most efficient during the growing season (Dujesiefken et al. 1999; Eckstein and Dujesiefken 1999). Plugging wounds, usually in conjunction with a fungicide treatment, has been proposed to ameliorate coring damage, but has not been effective in reducing infections (Campbell 1939; Dujesiefken et al. 1999).

While other forms of sampling have not been found to have strong effects on tree death (Heyerdahl and McKay 2001; Phillips et al. 1998), there is a lack of evidence to determine whether coring damage ultimately influences tree mortality. If coring has a measurable effect on tree mortality, it may be important to consider how it shapes subsequent forest dynamics and limit its use to situations where destructive sampling is considered acceptable. We use up to

21 years of annual-resolution data from two cored and two uncored permanent plots in the Sierra Nevada of California to detect changes in mortality rates 12 years following coring for two coniferous species, *Abies concolor* (Gordon & Glend.) Lindl. (white fir) and *Abies magnifica* A. Murr. (red fir). Fungal pathogens commonly attack these species following mechanical damage (Aho et al. 1989), and *A. concolor* wood decays rapidly (Harmon et al. 1987), so responses to coring should be easy to detect for *A. concolor* and *A. magnifica*.

Materials and methods

Permanent study plots were established in old-growth white fir mixed-conifer forests of Sequoia National Park in the Sierra Nevada of California (Table 1). The sites have never been logged. The climate is mediterranean, with hot, dry summers and cool, wet winters, with about half of the annual precipitation falling as snow (Stephenson 1988). Average January and July air temperatures are roughly 2 and 19 °C, respectively (Major 1977). Frequent fires characterized Sierran forests prior to European settlement, but the areas containing the study plots have not burned since the late 1800s (Swetnam et al. 1992).

In each plot, all trees ≥1.37 m in height were tagged, mapped, measured for diameter, and identified to species. We assessed mortality annually starting at the time the plots were established. Trees were recorded as dead only if they showed complete needle browning or loss. We continued to track dead trees for as long as we were able to relocate the stems to insure a correct judgment of tree death. Following the mortality checks in 1991 and prior to the mortality checks in 1992 trees >5 cm diameter at breast height (DBH, 1.37 m) in the LogSEGI and LogABCO permanent plots were cored once with a standard increment borer to determine stand age structure. We compared mortality rates for trees >5 cm DBH in the cored plots against uncored paired plots chosen for their geographical proximity and elevational similarity. We limit our analysis to the species where we had sufficient data to detect temporal trends in mortality rates, which included *A. concolor* and *A. magnifica*. Occasionally, individuals >5 cm DBH in the cored plots were not cored for undocumented reasons, representing 3% of *A. concolor* and 6% of *A. magnifica* individuals in the LogSEGI plot and 8% of *A. concolor* in the LogABCO plot. These trees were dropped from the analysis, leaving us with a total of 620 cored *A. concolor* and 104 cored *A. magnifica* in the LogSEGI plot, compared against 228 uncored *A. concolor* and 66 uncored *A. magnifica* in the LMCC plot. We refer to this plot pair as the Crescent Creek plots. We also compared 245 cored *A. concolor* in the LogABCO plot against 297 uncored *A. concolor* in the LogPILA plot. We refer to this plot pair as the Log Creek plots.

Standard statistical analyses of these data would be unreliable because the trees selected for coring were not a random sample of individuals. We therefore compared mortality rates between the paired plots using a before–after control impact (BACI) design. These procedures are used to measure the effects of poorly replicated large-scale disturbances such as oil spills, lake eutrophication, or wildfires (Carpenter et al. 1989; Manly 2001; van Mantgem et al. 2001; Wiens and Parker 1995). Time-series data are collected at an im-

pacted and an unimpacted reference site, both before and after the disturbance. Differences between paired impact and reference sites are measured, and if the average difference between the sites diverges from the predisturbance interval following disturbance, this change may be attributed to the disturbance.

The rationale of this approach is that paired sites should respond similarly to environmental variation (e.g., interannual differences in rainfall), allowing the serial observations of differences between the sites to be considered statistically independent, as long as strong temporal correlations in the data are not found (Stewart-Oaten et al. 1986). These data can be analyzed using standard parametric statistics (Manly 2001). However, temporal trends or lagged responses can cause non-normal error distributions, and the count data typical for BACI designs may show heterogeneous variances, which complicates the use of parametric statistics. We used randomization tests to help overcome these problems (randomized intervention analysis or RIA, Carpenter et al. 1989). Our randomization tests consisted of 10 000 random permutations of the observed annual differences in mortality rates between the cored and uncored plots, using the test statistic

$$\theta = \left| \overline{D}_{pre} - \overline{D}_{post} \right|$$

where $\overline{D}_{pre}$ and $\overline{D}_{post}$ are the average differences between the paired cored and uncored plots during the pre- and post-coring intervals. Randomization was achieved by assigning differences to before or after the coring, regardless of their actual position in the observed time series. The frequency of randomized values of $\theta \geq \theta_{obs}$ (the observed value of θ) provides a P value (Manly 1997). Low P values indicate a high probability of a nonrandom change having occurred. Serial correlations in the observations may lead to high rates of false positives (type I errors) (Carpenter et al. 1989; Murtaugh 2002), so the interpretation of significance should be restricted to $P < 0.01$ (Manly 2001). Although nonrandom changes can be detected, these designs are unreplicated, so the change cannot unequivocally be assigned to a particular cause (i.e., changes may be due to causes other than the disturbance). We strengthened our inferences by considering whether any of the paired observations responded differently to coring, using data starting in 1987 when observations were collected in all of the plots (Table 1). We used 10 000 randomized permutations of the test statistic SD(θ), where SD(θ) is the standard deviation of θ, and the frequency of SD(θ) $\geq$ SD(θ_{obs}) provides a P value. Tree size may mediate the response to coring. As a rough check of this possibility, we defined small and large trees as those 5.1–20.0 and >20.0 cm DBH and reanalyzed these size classes separately. We also considered the effects of coring on very small trees (5.1–10.0 cm DBH).

Tree death may result from a variety of causes, some of which may not be logically linked to disease agents associated with coring. For example, mortalities related to suppression, the preemptive use of resources by neighbors, would unlikely be directly associated with coring. We distinguished mortalities where the proximate cause of death was a pathogen that might reasonably be associated with coring, specifically fungal and bark beetle attacks. We used proximate mortality causes, because the process of tree death is com-

Table 1. Characteristics of permanent forest plots.

Plot pair	Plot name	Establishment year	Core status	Elevation (m)	Plot size (ha)	Stem count*	Species composition†
Crescent Creek	LogSEGI	1983	Cored	2170	2.5	1055	**ABCO** 76%; **ABMA** 15%; PILA 5%; SEGI 3%
	LMCC	1983	Not cored	2128	2.0	672	**ABCO** 71%; **ABMA** 20%; SEGI 7%; PILA 2%
Log Creek	LogABCO	1987	Cored	2207	1.1	458	**ABCO** 75%; ABMA 22%; PILA 2%; SEGI 1%
	LogPILA	1987	Not cored	2210	1.0	434	**ABCO** 90%; ABMA 6%; CADE 2%; PIJE 1%; QUKE 1%

Note: Species names presented in bold had sufficient data for analysis.

*Stems defined as individuals ≥1.37 m tall at time of plot establishment.

†Species composition of all stems at time of plot establishment. Percentages may not add to ≥100 because of rounding. ABCO, *Abies concolor*; ABMA, *Abies magnifica*; CADE, *Calocedrus decurrens*; PIJE, *Pinus jeffreyi*; PILA, *Pinus lambertiana*; QUKE, *Quercus kelloggii*; SEGI, *Sequoiadendron giganteum*.

monly a result of numerous contributing causes acting in concert (Manion 1991), obscuring more exact determinations of death causes. We analyzed these data using a randomized BACI design, as described previously.

Results

Annual mortality rates in the cored and uncored paired plots are presented in Fig. 1. The BACI approach appears to be appropriate for these data, as there did not appear to be strong serial correlations in the annual mortality rates. The difference in mortality rates between the cored and uncored plots did not change systematically after coring for any plot pair, as shown by randomization tests using 10 000 permutations of the data (Crescent Creek *A. concolor*, frequency of $\theta \geq \theta_{obs} = 3731$, $P = 0.37$; Crescent Creek *A. magnifica*, frequency of $\theta \geq \theta_{obs} = 732$, $P = 0.07$; Log Creek *A. concolor*, frequency of $\theta \geq \theta_{obs} = 8426$, $P = 0.84$). While the difference for the Crescent Creek *A. magnifica* pair approached significance, this trend was due to a coincidental reduction in mortality rates for the uncored LMCC plot following 1991. We were unable to detect any differences in the response to coring among the paired observations ($SD(\theta) \geq SD(\theta_{obs}) = 1443$, 10 000 random permutations, $P = 0.14$).

Tree size did not appear to affect these results. For all plot pairs we found nonsignificant differences in the mortality rates following coring for small trees (5.1–20.0 cm DBH, frequency of $[\theta \geq \theta_{obs}] \geq 1181$, 10 000 random permutations, $P = 0.12$) and large trees (>20.0 cm DBH, frequency of $[\theta \geq \theta_{obs}] \geq 1906$, 10 000 random permutations, $P = 0.19$). We did not find significant differences among the paired observations for small and large trees (5.1–20.0 cm DBH, $SD(\theta) \geq SD(\theta_{obs}) = 2609$, 10 000 random permutations, $P = 0.26$; >20 cm DBH, $SD(\theta) \geq SD(\theta_{obs}) = 6241$, 10 000 random permutations, $P = 0.62$). We obtained similar nonsignificant results when testing the effects of coring on stems 5.1–10.0 cm DBH.

There were no changes in the frequency of deaths associated with fungal and bark beetle attacks following coring, as shown by randomization tests with 10 000 permutations of the data (Crescent Creek *A. concolor*, frequency of $\theta \geq \theta_{obs} = 1781$, $P = 0.18$; Crescent Creek *A. magnifica*, frequency of $\theta \geq \theta_{obs} = 8030$, $P = 0.80$; Log Creek *A. concolor*, frequency of $\theta \geq \theta_{obs} = 5838$, $P = 0.58$). No paired observation responded differently to coring with respect to mortality associated with these disease agents ($SD(\theta) \geq SD(\theta_{obs}) = 8703$, 10 000 random permutations, $P = 0.87$).

Discussion

Coring did not appear to affect mortality over a 12-year period for either *A. concolor* or *A. magnifica* at our sites. These findings support the idea that coniferous trees sustain little serious damage from tree coring. There are, however, several caveats that apply to these results. Most critically, our 12-year postcoring interval is short compared with the >300-year potential maximum life-span of these species (Laake 1990; Pitcher 1987). We cannot rule out the possibility that cored trees may have damage, such as internal and unobservable fungal infections, which could result in future elevated mortality rates. Also, under more challenging conditions (e.g., drought, windstorms, pathogen outbreaks) coring damage could

Fig. 1. Annual mortality rates for *Abies concolor* and *Abies magnifica* in the cored and uncored plots for the Crescent Creek and Log Creek plot pairs. The vertical line between the years 1991 and 1992 represents the timing of coring.
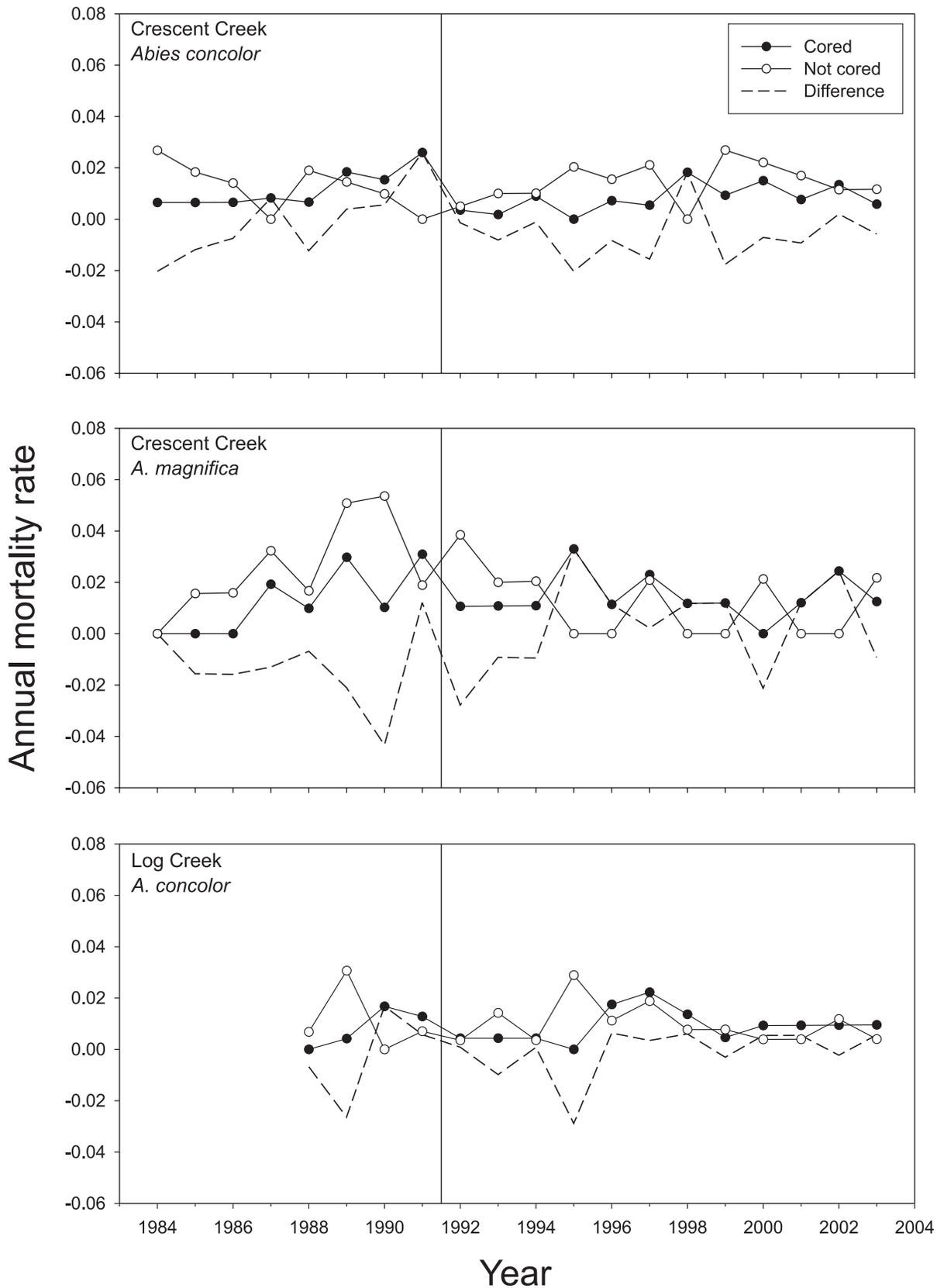
become a more important contributing factor of tree death. Finally, given the wide variation of species responses to coring (Grissino-Mayer 2003), other species, particularly hardwoods, are likely to show greater susceptibility to fungal attacks following coring, possibly leading to mortality. More research is needed to conclude categorically that coring causes no significant harm.

Stronger inferences could, of course, be drawn from better replicated studies using a random application of coring treatments, where the data would more closely follow the assumptions of classical statistical analysis. The full response to coring may occur over decades for many species, so broad-scale multispecies studies would require substantial funding. A more promising avenue for future research would be to exploit information from historic or ongoing projects. While statistical challenges will arise in the analyses of these data, numerous approaches exist for extracting at least some useful information from these sources (Manly 2001; Wiens and Parker 1995). The use of tree cores will remain an invaluable tool for ecological studies, but until further research is done, investigators should continue to use caution when collecting these samples.

Acknowledgements

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