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Ecohydrological energy inputs in semiarid coniferous gradients: Responses to management- and drought-induced tree reductions

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ABSTRACT

Large-scale, rapid reductions in forest and woodland tree cover caused by fire, drought-induced die-off, or wildfire-mitigating thinning prescriptions, all three of which differentially affect canopy structure, are increasingly altering coniferous-dominated landscapes across extensive regions such as western USA. These types of reductions in canopy cover can result in substantial increases in near-ground solar radiation, which in turn drive numerous ecological processes. However, existing relationships for how reductions in canopy cover translate into changes in incoming near-ground solar radiation do not account for the ways in which fire, die-off, and thinning differentially alter either or both the foliar and woody components of canopy architecture and the degree to which such alterations depend on foliar density. We systematically quantified trends in near-ground solar radiation for a broad range of canopy cover for two of the most extensive semiarid coniferous forest and woodland vegetation types in the western USA: those dominated by a combination of piñon and juniper (using *Pinus edulis* and *Juniperus monosperma* as representative species) or by ponderosa pine (*Pinus ponderosa*). We used hemispherical photography to account for how canopy architecture affected mean and variance in near-ground solar radiation over a broad range of canopy cover (from as low as ~5% to as high as ~85%). For both vegetation types, we evaluated four disturbance types: undisturbed, controlled burns, drought- and beetle-induced die-off, and prescriptive thinning treatments. We also assessed near-ground solar radiation for undisturbed vegetation spanning an elevation continuum that included both piñon-juniper and ponderosa pine vegetation types. Our results quantify how near-ground solar radiation varies substantially and systematically among forest gradient types and as a function of forest disturbance type. Trends in near-ground solar radiation differed among gradients associated with fire, die-off, or thinning, dependent on how each affects the foliar and/or woody components of canopy architecture. Deviations from undisturbed conditions for remaining disturbed tree cover were greatest for burned, intermediate for die-off and least for thinned. The differences in microclimate quantified here and how they vary with type of tree reduction are relevant for assessing vegetation responses following reductions in tree cover. In addition, the differences are large enough to require consideration in evaluating land surface interactions of forests and woodlands with the atmosphere (e.g., increases of >40 W m^{-2} relative to undisturbed conditions). Our results provide a means to enable managers to rapidly relate readily-obtainable field estimates of canopy cover to approximate estimates of near-ground solar radiation.

1. Introduction

A key characteristic of much of the terrestrial biosphere and its forested landscapes is the proportion of woody plant cover. Landscape gradients of woody cover fundamentally differentiate ecosystems ranging from sparse savannas and parklands to dense woodlands and forests with closed canopies, particularly for semiarid gradients (Belsky and Canham, 1994; Breshears, 2006). The amount of cover and spatial heterogeneity of woody vegetation influences processes at ecosystem and landscape scales (Breshears, 2006), perhaps most directly via canopy cover effects on the amount and variation of radiation that penetrates the overstory and arrives near the land surface. Below-canopy solar radiation has broad ecohydrological relevance that includes effects on soil evap-

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oration and other aspects of the water budget; light limitations and phenological responses for understory herbaceous species and forest and woodland seedlings; and heat loads that can drive nurse plant effects on other plants or behavioral ecology and habitat utilization for animals (Kittredge, 1948; Forseth et al., 2001; Guthery et al., 2005; Huxman et al., 2005; Suarez and Kitzberger, 2008).

Near-ground solar radiation depends on the overall amount of canopy cover at a site. Although near-ground solar radiation generally increases with reductions in forest or woodland canopy cover, specific characteristics of such trends that may be potentially important in an ecohydrological context have not been directly assessed, including the rate of attenuation with increases in canopy cover, the nature the relationship (e.g., linear, curvilinear, or polynomial), and the spatial variation in near-ground solar radiation. Collectively these characteristics could result in substantial differences in landscape-scale estimates of near-ground solar radiation that are important for forest and woodland dynamics, as well as atmospheric and land surface interactions (Gash and Nobre, 1997; Kurc and Small, 2004; Notaro et al., 2006; Chapin et al., 2008). Initial estimates of such relationships have been modeled previously by assuming homogenous canopy architecture (Martens et al., 2000), but these relationships do not account for the role of canopy heterogeneity associated with variation in the foliar and woody components of the canopy. Consequently, more direct assessments of how near-ground solar radiation changes systematically with forest and woodland canopy cover and canopy architecture are needed.

The importance of assessing landscape-scale trends in near-ground solar radiation is particularly relevant given a suite of ways in which forest and woodland tree cover can be reduced by both management and drought. Large-scale, rapid reductions in tree cover caused by fire, drought- and beetle-induced die-off, or wildfire-mitigating thinning prescriptions are increasingly altering coniferous vegetation across extensive regions such as western USA. Piñon-juniper (*Pinus* and *Juniperus* species) woodlands and ponderosa pine (*Pinus ponderosa* P. & C. Lawson) forests are the predominant semiarid coniferous vegetation types in the western USA (McPherson, 1997). In some cases, such reductions could return forest structure to less dense, pre-fire suppression conditions, which is indeed the target of some management activities. Other types of disturbances such as windfall can also reduce tree canopy cover, and the dynamics of semiarid coniferous vegetation can be driven by many factors that can be interrelated. Nonetheless thinning, fire, and die-off are three particularly prevalent, extensive and rapid ways in which tree cover is reduced and warrant particular focus. Forest management in these semiarid coniferous systems is undertaking substantial thinning with specified prescriptions that might change trends in the mean amount of near-ground solar radiation along gradients of tree cover and/or the associated spatial variance (Naumburg and DeWald, 1999). Even more dramatic are extensive reductions in tree cover that can result from fire (Allen et al., 2002; Romme et al., 2009; Hurteau and North, 2009), or from drought- and beetle-induced tree die-off, as recently observed across much of the western USA (Breshears et al., 2005; Gitlin et al., 2006; Floyd et al., 2009; Negron et al., 2009) and across the globe (Allen et al., 2010). Due to climate change, more such large-scale disturbances are likely (Nicholls, 1995; Allen et al., 2002; Westerling et al., 2006; Adams et al., 2009, 2010). Notably, thinning, fire, and drought-induced die-off differ with respect to their effects on the foliar and woody components of the tree: thinning removes both the foliar and woody components systematically, whereas die-off only initially removes the foliar components, and the effects of fire can be complex, affecting either only the foliar component or both the foliar and woody components. Importantly, the way in which each of these three types of tree reduction could alter near-ground solar radiation depends not only on the effect of each on the foliar and woody components but are also expected to do so in a density-dependent manner. These three major types of tree reductions driven by management or drought are occurring across expansive landscapes, but effects of such reductions on near-ground radiation are complicated and less well understood than might be initially thought because they have not been systematically evaluated both across types of reduction and across a gradient of tree density. Such estimates could help managers relate readily-obtainable field estimates of canopy cover to approximate estimates of near-ground solar radiation, thereby allowing more direct consideration of how changes in tree cover on near-ground solar radiation may influence properties of interest such as soil water content and understory vegetation.

In short, although solar radiation penetration through canopy overstory should increase as canopy cover decreases, surprisingly how such response functions change with vegetation type, canopy cover, and type of canopy reduction remains unclear. We addressed this knowledge gap by systematically assessing near-ground solar regimes along gradients of canopy cover associated with piñon-juniper woodland and ponderosa pine forest, using example study sites from northern Arizona. We assess how site-specific tree cover and type of canopy reduction relate to mean conditions of solar radiation and corresponding spatial variance in direct radiation penetration through overstory canopy. Our first objective was to quantify near-ground radiation as related to canopy cover (from as low as ~5% to as much as ~85%) for three undisturbed (reference) coniferous canopy cover gradients. These reference gradients included one for piñon-juniper woodlands, one for ponderosa pine forests, and one for an elevation continuum that spanned both vegetation types. Our second objective was then to quantify near-ground radiation as related to canopy cover for locations impacted by fire, die-off, and thinning for both piñon-juniper woodlands and for ponderosa pine forests. We also conducted supplemental analyses to assess the robustness of the results. We discuss our results in the context of their relevance for ecosystem management, including assessing land surface–atmosphere interactions in climate change projection.

2. Materials and methods

2.1. Study sites and associated gradients of tree canopy cover

Our research sites were distributed within 150 km of Flagstaff, AZ, USA (Appendix A). Regional climate in the area is characterized by warm dry springs and cold winters with annual precipitation in the form of rain and snow (610 mm, 30-year average, Western Regional Climatic Center, http://www.wrcc.dri.edu/index.html) nearly equally divided between frontal precipitation in winter and monsoonal precipitation in summer. We systematically quantified trends in near-ground solar radiation for a broad range of canopy cover for two of the most extensive coniferous vegetation types in the western USA: those dominated by a combination of piñon and juniper (using *Pinus edulis* Engelm. and *Juniperus monosperma* [Engelm.] Sarg. as representative species) or by ponderosa pine (*P. ponderosa*). For both vegetation types, we evaluated four disturbance types: undisturbed, controlled burns, drought- and beetle-induced die-off, and prescriptive thinning treatments (Table 1). We also assessed near-ground solar radiation for undisturbed vegetation spanning an elevation continuum from 1707 m to 2426 m that included both piñon-juniper and ponderosa pine vegetation types and encompassed 7 dominant ecosystem types: grassland, juniper savanna, juniper woodland, piñon-juniper woodland, piñon woodland-ponderosa pine ecotone, ponderosa pine forest, and mixed conifer/aspen forest. Characteristics of the selected disturbed sites are as follows (additional details pro-

Table 1
Gradients evaluated for near-ground solar radiation for piñon-juniper and ponderosa pine ecosystems for different disturbance types – undisturbed (for reference), burned, die-off, and thinned – and the number of transects associated with each gradient. Each gradient included several transects spanning a range of canopy cover from as low as 5% to as much as 85%. A function for estimating Direct Site Factor (DSF) from canopy cover (x) is reported for each transect. In addition, to highlight where each gradient is most sensitive to disturbance, for each disturbance type the cover value at which the deviation is greatest from the corresponding undisturbed gradient is listed, as is the magnitude of that deviation ($W\,m^{-2}$).

	Transects	DSF function	Cover for maximum Δ	Maximum Δ ($W\,m^{-2}$)
Piñon-juniper				
Undisturbed (reference)	7	$0.98–0.01x + 4.48 \times 10^{-5}x^2$		
Burned	6	$0.93–0.0036x$	65%	+58.5
Die-off	7	$0.97–0.0064x$	35%	+41.9
Thinned	5	$0.97–0.0076x$	25%	+16.9
Ponderosa pine				
Undsiturbed (reference)	7	$0.81–0.0091x + 4.41 \times 10^{-5}x^2$		
Burned	4	$0.81–0.0022x$	65%	+82.9
Die-off	3	$0.83–0.0046x$	65%	+42.5
Thinned	6	$0.80–0.0086x + 4.17 \times 10^{-5}x$	65%	+7.3

vided in Appendix A). Undisturbed ponderosa sites with higher amounts of cover (≥75%) were ungrazed and generally dense relative to historic conditions, as is characteristic in many western forests (Swetnam et al., 1999; Allen et al., 2002), whereas lower cover (≤35%) sites were more analogous to forest cover that characterizes much of the "healthy" ponderosa ecosystem prior pre-Euro-American land use regimes (*sensu* Allen et al., 2002). Reference piñon-juniper woodlands were grazed and ranged in cover from minimum to maximum that is generally observed for piñon-juniper throughout its range (Romme et al., 2009; relative composition of piñon and juniper is variable across the region, as well). Drought-induced piñon mortality gradients reflected that of the area, which is high, averaging 52% at the stand scale and approximately 30% of total tree cover (Floyd et al., 2009). The sites selected for our fire-induced cover gradients in both piñon-juniper woodlands and ponderosa forests experienced only low to medium intensity burn with moderate canopy scorching, bole chare and fine fuel consumption, with <10% fallen trees and standing tree architecture still intact. It is common that wildfires in ponderosa escalate to high intensity stand-replacing fires in overly dense ponderosa forests (Allen et al., 2002); therefore our estimates for increases in near-ground radiation associated with fire in high cover sites are conservatively low in such cases.

Each gradient (Table 1) was selected with a stratified design relative to canopy cover such that the transects within the gradient represented a range of canopy cover values from as low as ∼5% to as much as ∼ 65% in piñon-juniper and up to ∼85% in ponderosa pine. The piñon-juniper undisturbed gradient included transects with approximate canopy cover of 5%, 15%, 25%, 35%, 45%, 55%, and 65%; the ponderosa pine undisturbed gradient included transects with approximate canopy cover of 15%, 25%, 35%, 45%, 55%, 65, and 85%%. The actual canopy cover of each individual transect was within 3% of the above targeted cover. We established gradients with the same range of cover for the three disturbance types where feasible. In all cases transects were selectively targeted for their potential match to a needed vegetation type, disturbance type, and cover level, and then initially evaluated to determine if the cover level was within 3% of the target cover level. Transects within the same gradient were 0.5–3.0 km away from one another and assumed to be independent; transects between reference and disturbed gradients were an average of 30 km apart (specific locations in Appendix A). The undisturbed gradients for ponderosa pine and for piñon-juniper have been compared to those for other vegetation types elsewhere (Villegas et al., 2010b).

All transects along each gradient were oriented east–west with low slope (<3%) to minimize topographic influence on below-canopy light attenuation (Zou et al., 2007). Along each transect, we measured percent canopy cover using line-intercept method (Booth et al., 2008), in which we estimated cover using visual estimates of foliar drip-lines of trees intersecting the transect. If foliage from trees was reduced or absent, as a result of disturbance, we included the outermost peripheral remaining branches (dead or alive) of individual tree crowns. Transects established in piñon-juniper ecosystems were 50 m in length, which was sufficient to assess spatial variation based on previous studies (Breshears et al., 1997); the average tree height and crown diameter were 6.87 ± 0.60 m and 4.58 ± 0.83 m, respectively. We extended transect length to 100 m in ponderosa pine forest to accommodate the taller tree stature (average height of 21.20 ± 2.88 m; average crown diameter of 8.07 ± 0.67 m). Supplemental analyses were conducted to assess potential spatial autocorrelation related to distribution of study plots and observed trends, and the efficacy of using line-intercept for estimating cover while accounting for disturbance-specific defoliation. First, additional estimates were obtained from randomly selected undisturbed plots (five 50 m transects in piñon-juniper and five 100 m transects in ponderosa pine; ranging from 12% to 78% canopy cover) and trends were compared with those obtained from the systematically identified plots that our study is based on. These supplemental transects were dispersed across a broader area than the original transects and provided insight into whether larger scale spatial patterns might have a pronounced effect on results. Second, we used supplemental photos underneath and around individual trees of similar crown diameter and height in reference and disturbed areas (burned and drought killed only) to assess the affect of canopy loss on near-ground radiation on a tree-by-tree basis. We calculated near-ground solar radiation as a function of canopy cover from individual trees and plotted values against trends derived at the 50 m gradient scale and determined if near-ground radiation before and after disturbance on a tree-by-tree basis fell within the 95% confidence interval of the mean for trends derived at the gradient scale. For example, at undisturbed and burned piñon-juniper sites, both with similar overall pre-disturbance canopy cover and woodland architecture, we isolated a single piñon and juniper tree from each site and calculated near-ground radiation in relationship to canopy cover. If canopy cover underneath a single tree was 65% cover before disturbance and 15% cover after fire, we plotted values accordingly along the regression trend we derived from the undisturbed plot scale gradient at 65% cover, and from the burned gradient at 15% cover. This allowed us to evaluate how our line-intercept approach of using drip-line-to-drip-line intervals for canopy cover affected results for which woody components of canopy architecture persisted but foliage was reduced for the cases of fire and die-off (we limited the scope of this supplemental analysis to piñon-juniper transects).

2.2. Hemispherical photographs and statistical analyses

We used hemispherical photos to obtain estimates of the proportion of direct solar radiation reaching a given location over a year, relative to that in the same location with no sky obstructions under clear sky conditions (Rich et al., 1999; see also Anderson, 1964). Assuming clear sky conditions, this approach accounts for obstructions imposed by plant canopies and surrounding topographic features over an entire course of a year, and can also be adjusted to estimate corresponding near-ground solar radiation flux in W m^{-2}. For each transect within each gradient, hemispherical photographs were taken between July 2007 and August 2008. Photographs were taken 1 m above ground at 1 m intervals in piñon-juniper transects and every 2 m in ponderosa transects with a digital camera (Nikon Coolpix 5400, Nikon, USA). The camera was fitted with a 10.5 mm Nikkor fisheye lens (Nikkor FC-E9, Japan) and leveled using a self-leveling mount. Photographs were generally taken after sunset or under uniform cloud cover to ensure homogenous light conditions; a subset of photos obtained under other conditions was used only if visual assessment indicated unambiguous discrimination between overstory components and sky. We used Hemiview canopy analysis software (Delta-T Devices Ltd., Cambridge, UK) to calculate the annual mean proportion of direct near-ground radiation (Direct Site Factor or DSF – a proprietary dimensionless value from 0 to 1 corresponding to 0–100% direct light penetration below the canopy) and the equivalent energy (W m^{-2}). Hemiview Canopy Analysis provides a detailed map of sky visibility and obstruction and predicts solar radiation regimes for time unit of interest (i.e. annual, monthly, hourly) based on sky geometry and annual solar mapping trajectory. Radiation outputs are based on user defined inputs (latitude and longitude) and angle of incidence between surface and incoming radiation. The amount of solar radiation reaching the surface is directly proportional to the amount of attenuating canopy, if canopy is present; and the angle of incidence. Hemiview calculates extraterrestrial incoming radiation values based on geometrical relationships similar to other solar models that are universally applicable and do not necessarily require observed solar input (Hargreaves and Samani, 1982). Previous studies have shown excellent agreement between hemispherical modeled values and direct solar radiation measurements taken with conventional meteorological equipment (i.e. pyranometers, quantum PPFD solar sensors; Becker, 1987; Rich et al., 1993). Our analyses assumed zero cloud interference and can be adjusted by actual cloud cover for site-specific applications.

We evaluated trends in near-ground solar radiation as a function of canopy cover for our undisturbed gradients using simple linear regression. We evaluated the change in near-ground solar radiation in each of our three disturbed gradients for both vegetation types relative to the corresponding undisturbed (reference) gradients using multiple regressions. In this approach we had two factors for assessing trends (canopy cover and disturbance type), allowing us to determine if there was a significant change in solar radiation after accounting for the affect of canopy cover. To meet normality and homogeneity of variance assumptions of regression analysis, we transformed percent cover using a logit function. The results are not impacted by within-transect spatial autocorrelation because our analysis for each gradient used the single mean value from the 50 individual photo locations for each transect. As noted, transects within a gradient were at least 0.5 km away from one another and assumed to be independent. We determined the best fits for each regression model by testing each model with and without a quadratic term using the extra sum of squares analysis. All Statistics were done with JMP 5.1 (SAS Institute, Carry, NC, USA). Results were considered significant at an alpha level of 0.01.

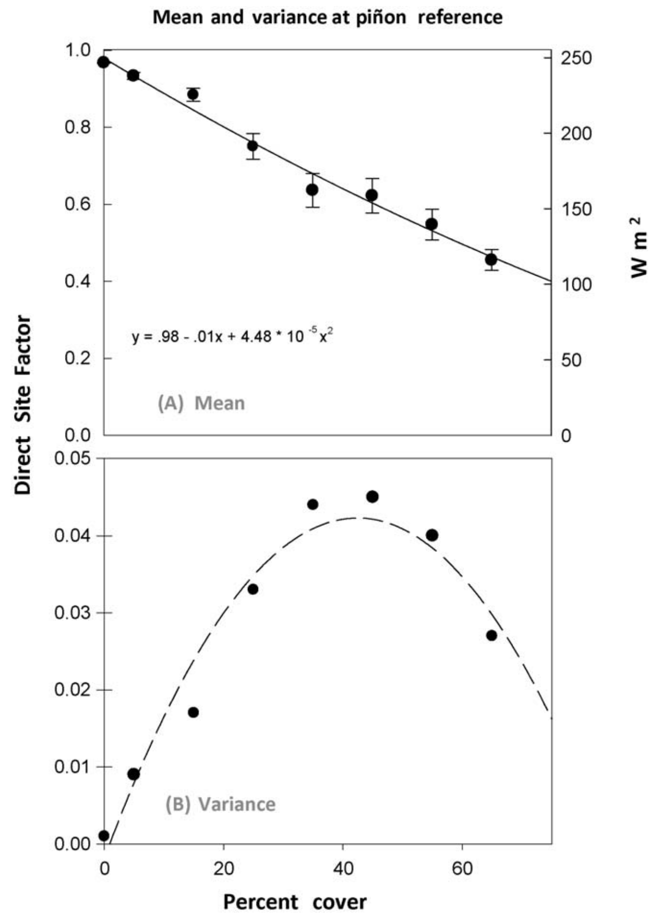

Fig. 1. Mean annual direct site factor (DSF) values (left axis) and corresponding energy in W m^{-2} (right axis) for the piñon-juniper undisturbed (reference) gradient as a function of canopy cover (A) and associated change in spatial variance (B). Each data point is the mean (±Std) of 50 DSF measurements for that transect (measurement at every 1 m for 50 m). The average values were fitted with second-degree polynomial equations. Trend line from A is from composite figure in Villegas et al. (2010b).

3. Results

3.1. Undisturbed gradients for piñon-juniper, ponderosa pine and an elevation continuum

For the undisturbed gradients for piñon-juniper woodland and for ponderosa pine forest, DSF values varied among and within transects, as highlighted in a subset of three of the transects (Appendix B and C). Values of DSF across the entire cover gradient were significantly associated with percent cover ($p < 0.01$; Figs. 1 and 2; trend lines but not energy units or error estimates are also reported in Villegas et al., 2010b). The spatial variation in DSF peaked at the intermediate canopy cover level of ∼45% in piñon-juniper woodland and of ∼25% canopy cover in ponderosa pine forest. DSF values for the elevational continuum were significantly affected by percent cover ($p < 0.01$) and elevation ($p < 0.01$). The variance peaked at intermediate levels of elevation (between ∼1800 m and 2100 m) and canopy cover (28%; Fig. 3).

3.2. Disturbed gradients from fire, die-off and thinning for piñon-juniper and ponderosa pine

Relative to corresponding undisturbed gradients, mean values of DSF increased significantly after fire and die-off for piñon-juniper

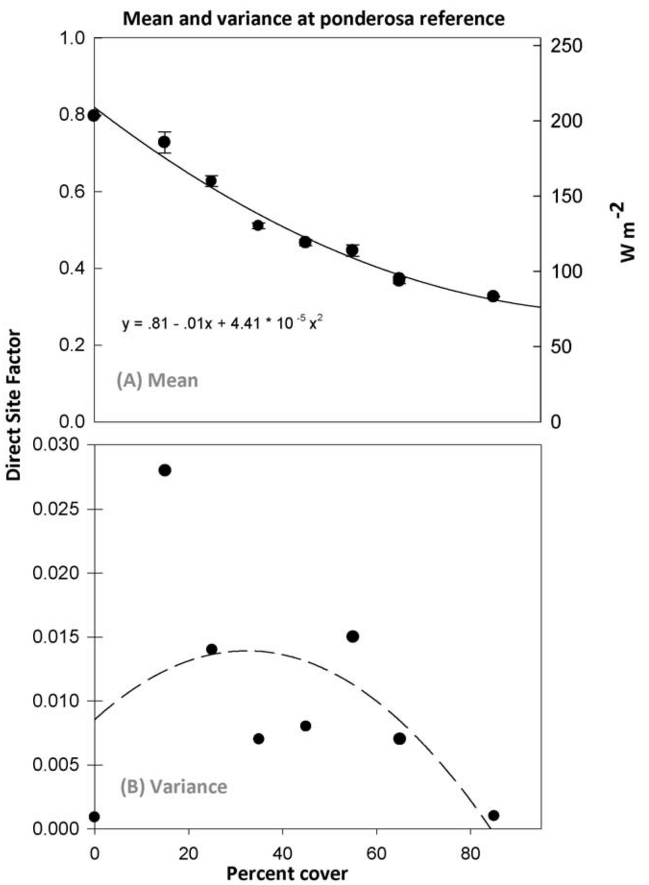

Fig. 2. Mean annual direct site factor (DSF) values (left axis) and corresponding energy in W m^{-2} (right axis) in ponderosa pine undisturbed (reference) gradient as a function of canopy cover (A) and associated change in spatial variance (B). Each data point is the mean (±Std) of 50 DSF measurements for that transect (measurement at every 1 m for 50 m). The average values were fitted with second-degree polynomial equations. Trend line from A is from composite figure in Villegas et al. (2010b).

woodland (Fig. 4A and B) and for ponderosa pine forest (Fig. 5A and B) (all $p < 0.01$). In contrast, for both piñon-juniper woodland and ponderosa pine forest, mean values of DSF were not significantly different between thinned and undisturbed gradients ($p = 0.09$ and 0.61, respectively; Figs. 4C and 5C), although overall variances showed a declining trend for thinned gradients. For piñon-juniper woodland, the difference in DSF values between burned and undisturbed gradients was positively correlated with increasing canopy cover values ($p < 0.01$, test for non-zero slope/interaction; Fig. 4A). For ponderosa pine forest, differences relative to gradients in mean DSF were greatest and significant ($p < 0.01$) for the burned gradient, followed by the die-off gradient ($p < 0.01$), and not significant for thinned gradient (Fig. 5A–C). Similar to piñon-juniper disturbed gradients, the spatial variation of DSF for ponderosa pine varied with disturbance gradient (Fig. 5D–F).

3.3. Supplemental analyses related to robustness of results

Two supplemental analyses indicated that the trends we have quantified are relatively robust. First, additional estimates that we obtained from supplemental randomly selected plots were consistent with those obtained from the systematically identified plots that our study is based on (based on comparison of mean DSF and slopes between random and non-random transects: $p = 0.94$ and $p = 0.87$, respectively for piñon-juniper ecosystems; and $p = 0.84$ and $p = 0.23$, respectively for ponderosa pine ecosystems). Second, supplemental analyses correctly accounted for differences between continuous and discontinuous foliar cover produced similar results for both burned and drought-killed piñon trees. When we applied these corrections the corresponding estimates of DSF fell within the 95% predicted confidence intervals for the undisturbed plot means. This supplemental analysis simply verifies that when the reductions in foliage are accounted for in greater detail, consistent results for mean near-ground solar radiation are obtained, indicating that the results are robust.

4. Discussion

4.1. Trends in near-ground solar radiation within coniferous vegetation gradients

Our results quantify clear trends in near-ground solar radiation with changes in amount and type of canopy cover, in both mean values and spatial variance. The general relationships we quantified for the piñon-juniper undisturbed (reference) gradient exhibited trends in both the mean and spatial variance that were consistent with a previous modeling assessment that used a ray tracing model, depicting tree crowns as three dimensional ellipsoids (Martens et al., 2000). That modeling study showed how mean near-ground solar radiation decreased as a function of increasing cover and increasing tree height (parallel to the undisturbed slope in this study), and the peak variance shifted towards lower cover values as tree height increased. This similarity indicates that foliar architecture does not necessarily need to be accounted for when evaluating simple increases or decreases in tree cover within a single vegetation type, such as the conifers with relatively high foliar density. This is not the case for tall trees with sparser foliage that have the lower extent of their foliage many meters above the ground;

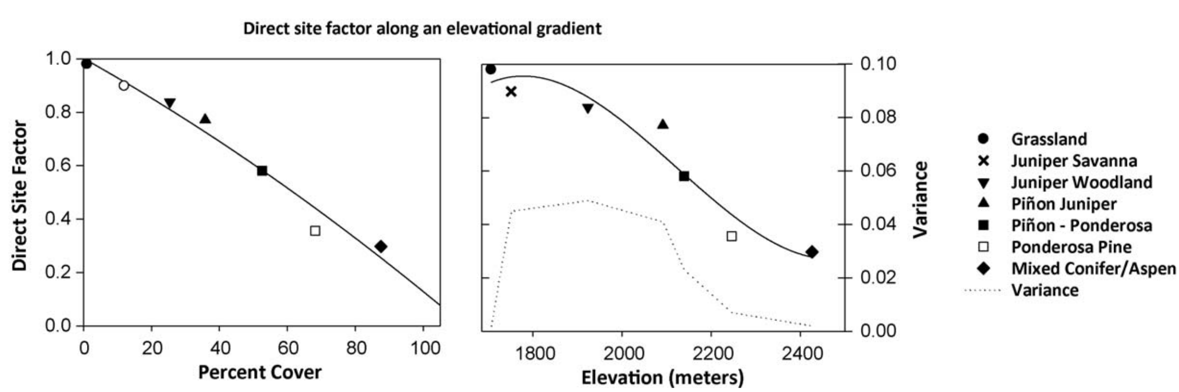

Fig. 3. Mean direct site factor (DSF) the reference elevational gradient (ranging from 1707 m to 2426 m) as a function of cover (left) and elevation (right). Spatial variance (dashed lines) corresponds to right axes; symbols indicate corresponding vegetation.

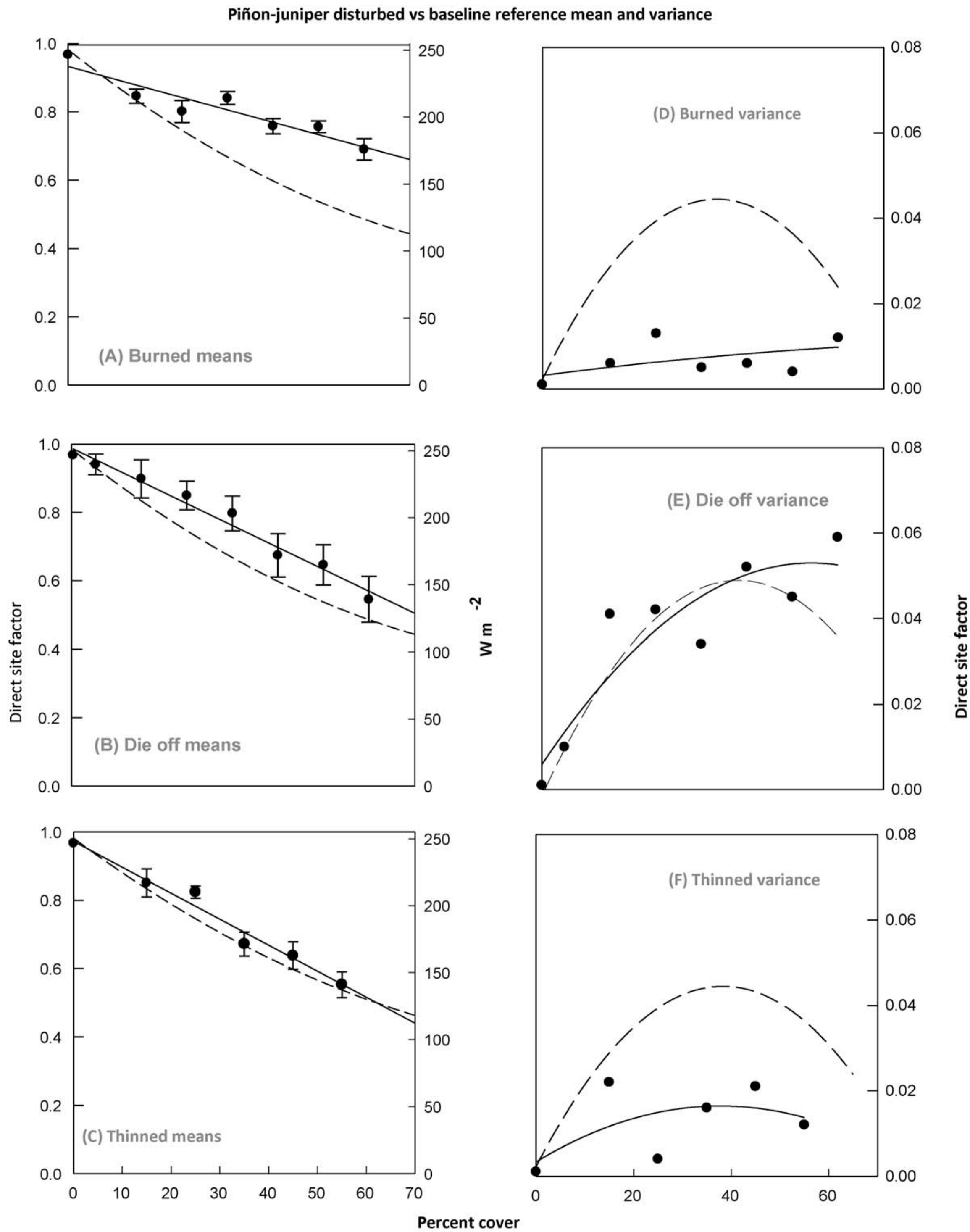

Fig. 4. Mean annual direct site factor (DSF) values (left axis) and corresponding energy in W m^{-2} (right axis) in piñon-juniper gradients impacted by fire (A), die-off (B), or thinning (C) and associated changes in spatial variance (D, E, and F, respectively); results are contrasted with results for the corresponding reference gradient (dashed line).

e.g. (eucalypt systems; Breshears and Ludwig, 2010; Villegas et al., 2010b).

Notably, our results quantify substantial differences in how fire, die-off, and thinning differentially alter the relationship between near-ground solar radiation and amount of canopy cover. Deviations from undisturbed conditions for remaining tree cover were greatest for burned, intermediate for die-off and least for thinned. Trends related to fire and drought-induced die-off was consistent with expectations based on types of canopy reduction. Dependent on fire intensity, fire can potentially affect both the foliar and woody components in both piñon-juniper (Romme et al., 2009) and ponderosa (Allen et al., 2002) ecosystems, with effects likely to be greatest at higher amounts of canopy cover (recall that woody components remained in the burned sites, so cover was the same but most of the foliage was removed). In contrast, change in near-ground radiation at die-off sites was primarily affected only by loss of foliage from piñon trees because co-dominant junipers largely survived (Breshears et al., 2005). In addition, the reduction in

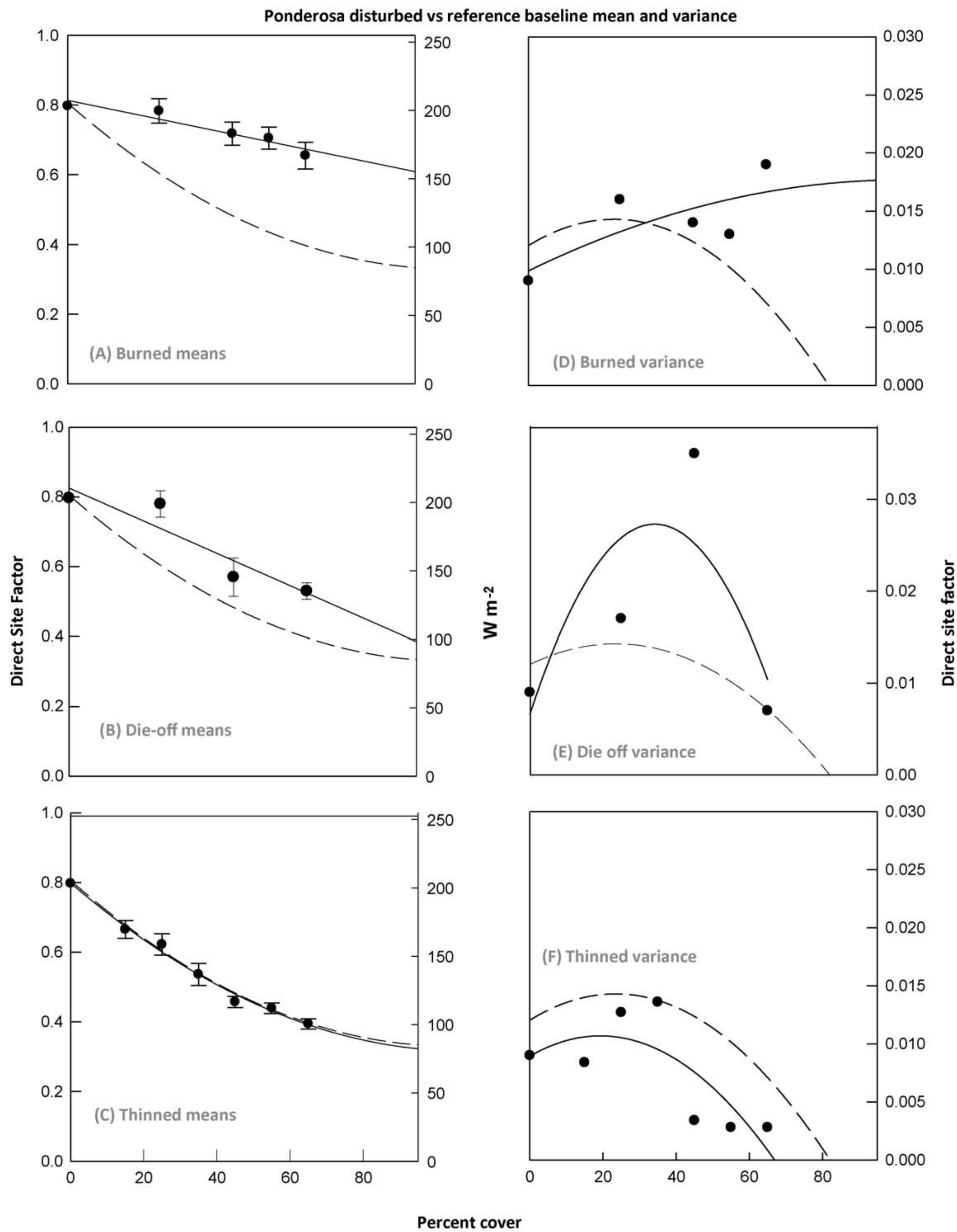

Fig. 5. Mean annual direct site factor (DSF) values (left axis) and corresponding annual total energy in W m^{-2} (right axis) in ponderosa pine gradients impacted by fire (A), die-off (B), or thinning (C) and associated changes in spatial variance (D, E, and F, respectively); results are contrasted with results for the corresponding reference gradient (dashed line).

canopy cover due to die-off of piñon does not necessarily increase with canopy cover (and density; Clifford et al., 2008), in contrast to the case for fire-related reductions. The difference between these two disturbance types suggests that both will increase near-ground solar radiation, but fire should produce larger increases in near-ground solar radiation and that this effect should increase with canopy coverage. We assessed the effects of controlled burns but expect that wildfire would have similar effects if fire intensity is similar; of course, for more intense fires a greater increase in near-ground solar radiation due to greater loss of foliar and woody components would be expected. The trends in the mean for the thinned plots do not differ from the undisturbed plots; this is because thinning, in contrast to fire or die-off, is removing the entire tree, and could be viewed as support for correctly altering an ecosystem property through restoration (note though that thinning might alter the trend in spatial variance).

Overall, our systematic evaluation of the impacts of different types of tree cover reduction for both major vegetation types –

piñon-juniper and ponderosa pine ecosystems – provides an initial basis for moving toward assessment of how near-ground solar radiation varies along such extensive western USA landscape gradients of forest and woodland in response to different combinations of tree reduction. Our analyses with the supplemental randomly located transects suggests our study is not confounded by spatial autocorrelation across transects: the randomly located transects were dispersed over greater distances and yet still fell within the relationships predicted from the original transects. Our results are limited in geographic extent, and do not assess the degree to which stand physiognomy may vary regionally, but provide the basis for an initial set of relationships which might also be applicable to other areas with similar stand structures. We focused on relatively flat locations, but in extending across more diverse landscapes the effects of canopy cover relative to those of slope and aspect can also be accounted for (Zou et al., 2007). Our approach accounted for variation associated with (i) major vegetation type individually and in combination, (ii) amount of tree canopy cover, and (iii) type of disturbance and how it affects canopy architecture. Our results provide a foundation for a more general approach that could be developed and applied to much of the forest and woodland landscapes of western USA, as well as perhaps other regions dominated by coniferous gradients.

4.2. Implications of near-ground solar radiation trends within coniferous gradients

Our results have important implications for improving both understanding of land–surface interactions and for managing forests and woodlands. Given projected increases in abrupt reductions in tree cover due to tree mortality (Breshears et al., 2005; Gitlin et al., 2006; Adams et al., 2009) and wildfire (Westerling et al., 2006) in association with climate change, and increases in forest thinning and control burns as management tools for mitigating the risk of stand-replacing fires (Bonan, 2008; Hurteau and North, 2009), the microclimate across broad landscapes will likely be changing rapidly in the near future. The changes in near-ground energy that we document associated with predominant types of reduction in tree cover are important because they affect available energy that drives other processes (i.e. energy available to be partitioned into sensible and latent heat). The major changes in vegetation cover such as those we consider here alter near-ground energy inputs largely through changes in albedo (Field et al., 2007). The magnitude of these changes in energy is comparable to those associated with other important land surface changes globally (Gash and Nobre, 1997). For example, increases in woodland cover in the southwestern United States can produce a similar reduction in midday available energy loss near the ground surface of about 70 W m^{-2}, representing a 20% loss of total energy input, as was reported at one site in central New Mexico (Kurc and Small, 2004). Such energy changes are of similar in magnitude to those elsewhere that have substantial impacts on both the regional and global climate (Da Silva et al., 2008; Lawton et al., 2001) and could also be important in the semiarid regions studied here. Our results can provide approximate estimates of available energy at the near-ground surface associated with fire, die-off and thinning (Table 1, which include the specific value of canopy cover that produced the greatest change in energy for each type of tree reduction). For both the piñon-juniper and ponderosa pine ecosystems, fire driven land cover changes result in the largest increases in available energy of 60 W m^{-2} and 80 W m^{-2}, respectively (Table 1). Our estimates of available energy are limited in that that they do not take into account factors such as albedo for the ground surface itself or long wave radiation, but nonetheless the general functions developed in this study (Table 1) could potentially be valuable for predicting modifications in surface energy associated with changes in land cover at sub-regional scales, in conjunction with spatially explicit topography-based approach such as the Solar Analyst tool (Fu and Rich, 2000) within the Spatial Analyst extension of ArcGIS to model the direct and diffuse insolation (Veatch et al., 2009). The relationships that we quantified may even need to be evaluated at larger spatial scales to determine if such changes might need to be considered in Global Climate Models (GCMs; Adams et al., 2010).

Our results are also directly applicable to site-specific forest and woodland management. Managers may need to explicitly consider near-ground solar radiation in at least two contexts. First, in an ecohydrological context, near-ground solar radiation is a key driver of snowmelt and soil evaporation rates, which determine soil moisture and associated plant available water. The amount of water available on a per tree, per leaf area, or per unit biomass is related to interactions between tree cover and microclimate (Zou et al., 2008). Snow water equivalent relates to amount of canopy cover in large part because of the density-dependent effects of trees on microclimate solar radiation (Veatch et al., 2009; see also Kittredge, 1948). Similarly, shading associated with tree cover affects the partitioning between evaporation and transpiration (Raz-Yaseef et al., 2010). Therefore, the relationships we have developed could aide managers in more directly considering how changes in cover related to thinning, fire, and die-off affect such water balance relationships via their impacts on incoming energy. Second, in the context of managing forest understory species (e.g., herbaceous species for grazing, and tree seedlings for forestry or associated with encroachment) light and temperature requirements are important factors that need to be considered explicitly (Kolb and Robberecht, 1996; Chambers, 2001; York et al., 2003; Law and Kolb, 2007). Our results enable managers to more directly consider how reductions in tree cover of a specified amount and type will affect the understory light conditions. In the context of both ecohydrology and understory response differences in ground cover also need to be accounted for; for example, litter and logging residue can have pronounced effects on soil evaporation or seedling establishment (Villegas et al., 2010a; Law and Kolb, 2007). Nonetheless, incoming near-ground solar radiation will in many cases be a fundamental driver of relevant processes. Although the relationship between tree cover and understory light regimes can be complex and may include non-linear aspects, our results provide a means to enable managers to rapidly relate readily-obtainable field estimates of canopy cover to approximate estimates of near-ground solar radiation, provided that canopy architecture is similar to those studied here and that surrounding topography does not have a pronounced effect (Zou et al., 2007).

5. Conclusion

We have quantified the systematic variation in near-ground solar radiation across vegetation types, canopy cover, and type of canopy reduction for semiarid coniferous gradients. Our approach is notable in that rather than providing only a few site-specific estimates, it provides a general basis for estimating near-ground solar radiation for a broad range of forest and woodland ecosystems extending to sub-regional scales, conditional on the degree to which the canopy spatial patterns and architecture are similar to the one that we studied. The trends that we identified are consistent with previous model predictions, but also highlight the importance of considering how type of tree reduction differentially alters the relationships in a manner consistent with how foliar and woody components of canopy architecture are altered. The trends we document may be of broader relevance to other semiarid woodland and forest gradients, and in improving both assessments of atmospheric and land–surface interactions and to site-specific forest and woodland management. For managers, our results provides a means that can relate field estimates of canopy cover to approximate estimates of near-ground solar radiation that can be considered in a variety of forestry related contexts.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2010.07.036.

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