SUPPLEMENTAL INFORMATION
No. 5
For Planning Commission Agenda of:
November 21, 2019

Item No. F-1

Re:  Applicant: Humboldt Wind
Case Numbers: CUP-18-002

Attached for the Planning Commission’s consideration are the following comments:

**Comments provided since Supplemental #4**

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To the Planning Commissioners:

Please heed the objections of the Wiyot Tribe to the Humboldt Energy Wind Project, which will desecrate their sacred worship sites.

Many more appropriate wind energy development sites are available; as a white person, I would be ashamed to profit from yet another gratuitous ethnocidal cruelty to Native Americans.

Thank you,

Jessica Crosson
Hello Beth, Suzanne, Director Ford, and Planning Commissioners,

Attached are some comments, questions, photographs of Tsakiyuwit which are within the project and WTG footprint, and related citations in opposition to the Terra Gen project and noting inadequacies within the FEIR, for the Commissioners. I had printed out the 14 copies for the PC last night, but somehow in the fluster of dealing with the disrespecting words of Commissioner Robert Morris toward Wiyot elder Cheryl Seidner and coordinating with other elders who wanted to speak, I completely forgot to submit them. I hope that they can still be incorporated into the record as the public comment period is still in continuance until the 11/21 meeting. These comments only address a dearth of the issues within the FEIR that concern the Tribe, or seem inadequately addressed without substantial evidence. It has been difficult to wade through a document of this nature in the time allowed since availability. The Tribe started a petition on change.org encouraging the PC to deny the project permits, which at this writing had 1285 signatures. See https://www.change.org/p/humboldt-county-planning-commission-help-protect-the-coastal-prairies-of-bear-river-ridge-tsakiyuwit. Please feel free to reach out to with any questions or clarifications and thank you for your time and consideration.

Rra’dutwas (with kindness), Adam

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November 14, 2019

Humboldt County Planning Commission
Planning and Building Department
3015 H St. Eureka, CA 95501

RE: Opposition to proposed Humboldt Wind/Terra-Gen development CUP on Bear River and Monument Ridges

He’bla’lo (Greetings) Commissioners

This letter is to express the Wiyot Tribe’s vehement opposition to the proposed Terra Gen Wind Project on Tsakiyuwit (Bear River Ridge) and encourage the Commission not to certify the Final EIR and refuse to approve the conditional use permit for the project. The Wiyot have experienced mass cultural genocide, which the approval of this ill-planned project would only re-enforce, as everyday, Tribal citizens on Table Bluff (and throughout the region) would be forced to look up at Tsakiyuwit and see the destruction of their high prayer grounds as an ever-present reminder of colonialism, the murder of their ancestors, and the theft of their lands.

A Statement of Overriding Considerations (SOC) cannot be the basis for approving the Project because the Tribe’s cultural values outweigh the other applicable considerations, all feasible mitigations measures have not been exhausted or addressed, and thus the California Environmental Quality Act (CEQA) requirements are not being upheld, which would be a violation of State law. Due to the multitude of negative impacts to the environment and Wiyot tribal cultural resources (TCRs) that would occur, the project should NOT be approved.

One major concern about the FEIR and project is the absence of a financial viability statement and a Decommissioning Bond and Plan. There is also no mention to the duration of the Power Purchase Agreement (PPA) for the project. According to Kassandra McQuillen, J.D. at the National Wind Institute at Texas Tech University, very few wind development projects occur on steep, geologically unstable, seismically active, and difficult to access ridge tops like Bear River and Monument Ridge. The heavy winds at such sites, which here can be coastal, as well as updrafts and thermals from multiple directions will accelerate wind turbine generator (WTG) fatigue, thereby increasing the cost of the maintenance, while potentially shortening the lifespan of the project. Since Terra Gen will be transferring ownership to Humboldt Wind LLC, there is no guarantee without a Decommissioning Bond and viable PPA that the tax payers, property owners, or Humboldt County wouldn’t be stuck with the cleanup from this massive project should the lifespan be less than the 30 years predicted (or less than the PPA contract period). This is significant due to the 200K cost/WTG for decommissioning and the fact that the fiberglass blades cannot be recycled. Will Humboldt County landfills be responsible for accepting this waste, or will we have to transport them out of the area? Within the FEIR, it notes that “Decommissioning activities are anticipated to be similar to construction-related activities. The project
applicant would be financially responsible for restoring the land to its preconstruction condition after project operations and would be conditioned to prepare a decommissioning and restoration plan at the time of decommissioning. These responsibilities are tied to the project through the conditions of project approval and would be transferred to any future owners of the project. The approval of a decommissioning plan would be subject to further environmental review, to be conducted when such a plan is submitted for consideration by County decision makers.” Due to the magnitude of the predicted impacts from construction, it does not seem financially and ecologically wise for the County to approve the project without having a solid plan for decommissioning as well as a bond to go with it.

This utility scale, land-based project is not appropriate for our County, whose primary contribution to carbon footprint reduction is our world-renowned forests and prairies. The potential increased fire risk posed by the project could threaten the mammoth carbon sinks of our old-growth redwood forests in Humboldt Redwoods State Park and the Van Duzen River groves (i.e. Grizzly Creek Redwoods, Pamplin, Cheatham). We know that “California’s ancient redwood trees store more carbon dioxide per acre than any other forest in the world, including tropical rain forests like the Amazon”. The findings were the result of a seven-year study by scientists at Humboldt University and the University of Washington. Redwoods store 2,600 metric tons of carbon per hectare (2.4 acres), more than double the absorption rate of the Pacific Northwest’s conifer trees or Australia’s eucalyptus forests, the study found.” (see Van Pelt & Sillett et al. 2016 attached) (https://e360.yale.edu/digest/california_redwoods_co2_storage)

If we want to contribute to combating global climate change, the best thing that Humboldt County can do is protect and care for our world-renowned forests and prairies. A recent study from the University of California, Davis, found that grasslands and rangelands are more resilient carbon sinks than forests in 21st century California. As such, the study indicates they should be given opportunities in the state’s cap-and-trade market, which is designed to reduce California’s greenhouse gas emissions to 40 percent below 1990 levels by 2030.” https://climatechange.ucdavis.edu/news/grasslands-more-reliable-carbon-sink-than-trees/. Being that Bear River Ridge is such an extensive grassland prairie with intact native perennial bunchgrasses, like Deschampsia cespitosa, it would be an ideal grassland site for use in the cap and trade market.

In addition to these potential impacts to carbon stored in our forests and grasslands, wind turbine generators (WTG’s) are known to effect local micro-climate (see attached Miller & Keith 2018). This has not been evaluated within the redwood fog belt, as no other wind projects occur within this zone. These dynamics are complex and are still trying to be understood by scientists (see Torregrosa, A., C. Combs, and J. Peters 2016-attached). The giant size of these WTG’s (650 feet tall, with a rotor diameter of 450 feet) could easily affect downwind humidity and soil moisture, thereby interrupting advection fog and the associated transpiration cascade up the Eel River and into Humboldt Redwoods State Park and the Bull Creek drainage. Summer fog is critical to the habitat suitability for redwoods. While this relationship is complex, it still needs to be addressed within the EIR due to the significance of redwoods role in global climate stability. https://baynature.org/article/fog-and-redwoods-demystifying-the-mist/. Without this analysis there is not full a disclosure of potential physical environmental impacts, which is a violation of CEQA.

The Tribe has made clear its vested concerns over negative significant and unmitigable impacts to TCR’s and biological resources of this ecologically diverse project footprint (an ecological transect from Cape Mendocino grasslands through redwood, grand fir, Doug fir, tanoak, mixed evergreen, riparian, and oak woodland habitats in Bridgeville). However, these impacts and concerns are not adequately addressed
and are dismissed within the FEIR without "substantial evidence or reasonable analysis" and are thus
cursory, conclusive, and incomplete and do not provide sufficient enough information to allow for an
informed decision by the County (i.e. see responses to Tribal comments T2-T4).

The coastal prairies and grasslands within the project footprint on Bear River and Monument Ridges
host a handful of sensitive types in the state that will be impacted by the project, which without
evidence and comparable reference sites are noted within the FEIR as being "not pristine and have been
subject to grazing and other agricultural activities for decades and include common weed species. Very
few coastal grasslands in California remain weed free, which highlights the fact that the native grassland
elements which still occur at Tsakiyuwit illustrate exceptional examples of pre-contract California
herbaceous types. For example, within the FEIR, one response to questions is that “the DEIR for the
proposed project provides an adequate, complete, and good faith effort at full disclosure of the physical
environmental impacts and the conclusions are based upon substantial evidence in light of the whole
record”, however in the FEIR response to sensitive natural community impacts they note, “it is the
County's and the applicant's opinion that grasslands of the same quality as those currently existing can
be established onsite, once construction is complete.” This not backed up by evidence, comparisons,
pier reviewed literature, or pre-identified reference sites. It has been widely acknowledged that “native
perennial grasslands in California are among the most endangered ecosystems in the United States”
(Peters and Noss 1995), while also being biodiversity hotspots, with documented species richness
“nearly twice that of relatively diverse serpentine California grasslands, and other North American
grazlands” (Stromberg et al 2001). The proposed development of the coastal prairie complex on Bear
River and Monument Ridges would severely impact these premier and fleeting examples of this critically
endangered habitat, whose origins most likely lie with the cultural burning practices of Wiyot ancestors.
This has been well supported in California tribal ethnobotany, where “village and shell mound sites are
frequently found adjacent to remaining coastal prairie areas and, interestingly appear correlated with
the most intact remaining examples of this habitat type” (Ford & Hayes 2007, Terrestrial Vegetation of
California). As noted, California indigenous peoples were most likely “responsible for maintaining most
large areas of grassland along the coast up to the time of contact with Old World Peoples” (Gordon
1985). In speaking with CDFW and the State's Senior Vegetation Ecologist, Todd Keeler-Wolf, about this
project and the relevance of coastal prairie, he expressed grave concerns about the potential impacts,
noting that “the highest nativity sites are pretty rare and exceptional”. The soil disturbance, concrete
pad installation, and road expansion for the WTG development would certainly negatively impact the
environment and the coastal prairie plant community populations found on Tsakiyuwit, and the quality
and availability of their habitats.

One very telling error within the cultural resource survey reporting for both the DEIR and FEIR includes a
significant site on Tsakiyuwit, P-12-003314 (Roscoe 2010), which the Tribe knew existed, that was not
able to be re-located by Stantec archaeologists in 2018. The Tribe requested that the site be re-
re-inventoried and in 2019 Stantec was able to re-locate the site. However, the EIR does not include this
significant new information nor, was it provided independently to the Tribe with other supplemental
"confidential" reports, which was a surprise to the Tribe when upon seeing the response to our
comments within the FEIR. It is also unclear if and how the site will be avoided during project
implementation, which is suggested by capping. This should not be considered avoidance. Additionally,
the expansion of the site (and presence of obsidian) could illustrate a continuance with adjacent site
HUM_TG_02, where a Tuluwat-barbed projectile point was located, artifacts of past Wiyot people. The
additional survey that resulted in the relocation of site P-12-003314 shows a new, substantial
environmental impact resulting from the project and thus recirculation of the EIR is required. The fact that this significant site was not initially identified and then later identified shows incompetence on part of the applicant.

There has never been a utility scale project within the habitat for the marble murrelet, nor has there ever been one built within such an ecologically diverse mosaic along a coast to inland transect. You must see this project for what it really is; the greenwashing of a mega-corporation that’s trying to take advantage of a rural population and our quality of life, for the profits of few wealthy elite. Even at 2 million dollars a year in tax revenue, this only comes out to $15.00 per County citizen a year, which is not worth it.

This Project is not the only way or project to meet our local and State mandated divestment from fossil fuels. We have off-shore wind, solar, tidal, wave, geo-thermal, micro-hydro, and micro-grid applications that are all viable alternatives which were not fairly considered giving the rapidly changing energy developments. This projects is non-innovative for a community that prides itself on ingenuity, sustainability and environmental and cultural ethics.

The Tribe recommends that the project be denied on the grounds of un-mitigatable impacts to Tsakiyuwit, its culturally important sites, flora, fauna, and the remainder of Wiyot territory that is within its viewshed. The Wiyot Tribe have experienced mass genocide and been robbed of most of their sacred lands around Humboldt Bay and the lower Eel River. Much of their ancestral land has been developed, or the native vegetation types they helped to shape and tend, converted to alien pasture grasses and weeds. In the spectrum of impacted landscapes, Tsakiyuwit has persisted to the present as an iconic gem of native coastal prairie, that still holds the signs of the Wiyot’s caretaking and stewardship. We have the opportunity to protect this iconic cultural landscape, and this gateway to Humboldt Bay, for future generations to be able to look up and see the checkerblooms blowing in the free wind, with the birds gliding aimlessly, absent of the stamp of human greed and destruction, the way that Wiyot ancestors would have seen this amazing place, unencumbered, all the way to outer-space. Thank you for your time, consideration, and concern regarding our concerns over the magnitude of this development project. It would be culturally devastating for this area to be developed.

Kra’dutwas (with kindness)

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Climatic Impacts of Wind Power

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HIGHLIGHTS
Wind power reduces emissions while causing climatic impacts such as warmer temperatures

- Warming effect strongest at night when temperatures increase with height
- Nighttime warming effect observed at 28 operational US wind farms
- Wind’s warming can exceed avoided warming from reduced emissions for a century

Wind beats fossil, but wind power does cause non-negligible climatic impacts. This study advances work on wind power’s climate impacts by: (1) providing a mechanistic explanation for wind turbines’ climate impacts by comparing numerical simulations with observations, (2) filling a current gap between small- and very-large-scale wind power simulation studies, (3) making the first quantitative comparison between wind power’s climatic impacts and benefits, and (4) using the same framework to make a quantitative comparison with solar power.
SUMMARY

We find that generating today’s US electricity demand (0.5 TWe) with wind power would warm Continental US surface temperatures by 0.24°C. Warming arises, in part, from turbines redistributing heat by mixing the boundary layer. Modeled diurnal and seasonal temperature differences are roughly consistent with recent observations of warming at wind farms, reflecting a coherent mechanistic understanding for how wind turbines alter climate. The warming effect is: small compared with projections of 21st century warming, approximately equivalent to the reduced warming achieved by decarbonizing global electricity generation, and large compared with the reduced warming achieved by decarbonizing US electricity with wind. For the same generation rate, the climatic impacts from solar photovoltaic systems are about ten times smaller than wind systems. Wind’s overall environmental impacts are surely less than fossil energy. Yet, as the energy system is decarbonized, decisions between wind and solar should be informed by estimates of their climate impacts.

INTRODUCTION

To extract energy, all renewables must alter natural energy fluxes, so climate impacts are unavoidable, but the magnitude and character of climate impact varies widely. Wind turbines generate electricity by extracting kinetic energy, which slows winds and modifies the exchange of heat, moisture, and momentum between the surface and the atmosphere. Observations show that wind turbines alter local climate,1–10 and models show local- to global-scale climate changes from the large-scale extraction of wind power.11–15 Previous studies have assessed climate impacts of hydropower,16 biofuels,17 and solar photovoltaic systems (PVs).18 Rapid expansion of renewable energy generation is a cornerstone of efforts to limit climate change by decarbonizing the world’s energy system. In addition to climate benefits, wind and solar power also reduce emissions of criteria pollutants (NOx, SOx, and PM2.5) and toxic pollutants such as mercury that cause significant public health impacts.19,20 The climate impacts of wind and solar are small compared with the impacts of the fossil fuels they displace, but they are not necessarily negligible. Improved understanding of the environmental trade-offs between renewables would inform choices between low-carbon energy sources. With growth of wind and solar PVs far outstripping other renewables,21 we combine direct observations of onshore wind power’s impacts with a continental-scale model, and compare it to prior estimates of PVs’ impacts to assess the relative climate impacts of wind and solar energy per unit energy generation.

Climatic impacts due to wind power extraction were first studied using general circulation models (GCMs). These studies found statistically significant climatic impacts within the wind farm, as well as long-distance teleconnections, with impacts outside the wind farm sometimes as large in magnitude as impacts inside the wind farm.11–13,22 Note that such impacts are unlike greenhouse gas (GHG)-driven warming, as in some cases wind power’s climatic impacts might counteract such GHG

Context & Scale

Wind power can impact the climate by altering the atmospheric boundary layer, with at least 40 papers and 10 observational studies now linking wind power to climatic impacts. We make the first comparison between the climatic impacts of large-scale wind power and site-scale observations, finding agreement that warming from wind turbines is largest at night. Wind power’s climatic impacts will continue to expand as more are installed.

Do these impacts matter? How do these impacts compare to the climate benefits of reducing emissions? We offer policy-relevant comparisons: wind’s climatic impacts are about 10 times larger than solar photovoltaic systems per unit energy generated. We explore the temporal trade-off between wind’s climatic impacts and the climate benefits it brings by reducing emissions as it displaces fossil fuels. Quantitative comparisons between low-carbon energy sources should inform energy choices in the transition to a carbon-free energy system.
warming—at least four studies have found that mid-latitude wind power extraction can cool the Arctic.\textsuperscript{11,12,23,24} However, these studies often used idealized or unrealistic distributions of turbines installed at unrealistic scales. Model simulations of geometrically simple, isolated wind farms at smaller scales of 3,000–300,000 km\(^2\) (10- to 1,000 times larger than today’s wind farms) in windy locations found substantial reductions in wind speed and changes in atmospheric boundary layer (ABL) thickness, as well as differences in temperature,\textsuperscript{11,13,14,24} precipitation,\textsuperscript{14,25} and vertical atmospheric exchange.\textsuperscript{15,26}

We want to assess wind power’s climate impacts per unit of energy generation, yet wind's climatic impacts depend on local meteorology and on non-local climate teleconnections. These twin dependencies mean that wind power’s impacts are strongly dependent on the amount and location of wind power extraction, frustrating the development of a simple impact metric.

As a step toward an improved policy-relevant understanding, we explore the climatic impacts of generating 0.46 TWe of wind-derived electricity over the Continental US. This scale fills a gap between the smaller isolated wind farms and global-scale GCM. We model a uniform turbine density within the windiest one-third of the Continental US, and vary the density parametrically.

Our 0.46 TWe benchmark scenario is \(~18\) times the 2016 US wind power generation rate.\textsuperscript{21} We intend it as a plausible scale of wind power generation if wind power plays a major role in decarbonizing the energy system in the latter half of this century. For perspective, the benchmark’s electricity generation rate is only 14% of current US primary energy consumption,\textsuperscript{25} about the same as US electricity consumption,\textsuperscript{27} and about 2.4 times larger than the projected 2050 US wind power generation rate of the Central Study in the Department of Energy’s (DOE) recent Wind Vision.\textsuperscript{28} Finally, it is less than one-sixth the technical wind power potential over about the same windy areas of the US as estimated by the DOE.\textsuperscript{28,29}

Modeling Framework

We use the WRF v3.3.1 high-resolution regional model\textsuperscript{30} with a domain that encompasses the Continental US, forced by boundary conditions from the North American Regional Reanalysis.\textsuperscript{31} The wind farm region is more than 500 km from the model boundaries, and encompasses only 13% of the domain (shown in Figure 1A). The model configuration used dynamic soil moisture and 31 vertical levels with 3 levels intersecting the turbine’s rotor and 8 levels representing the lowermost kilometer. The model is run for a full year after a 1-month spin-up using horizontal resolutions of 10 and 30 km. The wind turbine parametrization was originally released with WRF v3.3,\textsuperscript{32} and represents wind turbines as both a momentum sink and turbulent kinetic energy (TKE) source. We updated the wind turbine parameterization to make use of the thrust, power, and TKE coefficients from a Vestas V112 3 MW. This treatment of wind power is very similar to previous modeling studies.\textsuperscript{14,15,24}

The advantage of the regional model is that we can use a horizontal and vertical resolution substantially higher than previous global modeling studies,\textsuperscript{11–13,22,23,26,33,34} allowing better representation of the interactions of the wind turbines with the ABL. The disadvantage of using prescribed boundary conditions is that our simulations will underestimate the global-scale climatic response to wind power extraction compared with a global model with equivalent resolution, which would allow the global atmosphere to react to the increased surface drag over the US and would reveal climate teleconnections.
We tested horizontal resolution dependence by comparing the 10- and 30-km simulations with a turbine density of 3.0 MW km\(^2\) with the respective 2012 controls. Differences in the annual average 2-m air temperature were small, as shown in Figure S1. The following results use a 30-km resolution (about one-ninth of the computational expense) and 2012, 2013, and 2014 simulation periods to reduce the influence of interannual variability. We use four turbine densities (0.5, 1.0, 1.5, and 3.0 MW km\(^2\)) within the wind farm region to explore how increased wind power extraction rates alter the climatic impacts.

**RESULTS AND DISCUSSION**

Figure 1 shows the climate impacts of the benchmark scenario (0.5 MW km\(^2\)). The wind farm region experiences warmer average temperatures (Figure 1A), with about twice the warming effect at night compared with during the day (Figures 1B and 1C). Warming was generally stronger nearer to the center of the wind farm region, but...
perhaps because teleconnections are suppressed by the forced boundary conditions. The climate response is concentrated in the wind farm region, but there are regions well outside the wind farm region also experiencing a climate response. The clearest example here is along the East Coast during the daytime, where average daytime temperatures are 0.1°C–0.5°C cooler (Figure 1B).

To separate the local direct boundary layer impacts from the mesoscale climate changes, we ran a diagnostic simulation with a 250×250-km “hole” near the center of the wind farm region, finding that the “hole” experienced about half the warming of the original “no hole” benchmark scenario during 2014 (Table S1 and Figure S2). This suggests that about half the warming effect is attributed to localized changes in atmospheric mixing, with the other half attributed to mesoscale changes, but this requires further study.

Changes in precipitation are small and show no clear spatial correlation (Figure S3). The warming is greatest in an N-S corridor near the center of the wind turbine array, perhaps because of an interaction between wind turbines and the nocturnal low-level jet (LLJ). The LLJ is a fast nocturnal low-altitude wind (>12 m s⁻¹ at 0.5 km) common in the US Midwest, which occurs when the atmosphere decouples from surface friction, resulting in a steep vertical temperature gradient—meteorological conditions that might be sensitive to perturbations by wind turbines. We quantified the presence of the LLJ in our control simulation but did not find a strong spatial correlation between the probability of LLJ occurrence and the nighttime warming (Figure S4). To explore mechanisms, we examine the vertical temperature gradient, atmospheric dissipation, and wind speed (Figure S5), and then explore the relationship between warming and these variables using scatterplots (Figure S6). We find some consistency between the dissipation rate of the control and the warming effect of wind turbines, but the correlation is weak.

Figure 2 explores the relationship between changes in vertical temperature gradient, atmospheric dissipation, and the simulated warming. Wind turbines reduce vertical gradients by mixing. During the day, vertical temperature gradients near the surface are small due to solar-driven convection and are only slightly reduced by the turbines. Gradients are larger at night, particularly during summer, and the gradient reduction caused by turbine-induced mixing is larger. The largest warming occurs when the reduction in gradient is strongest and the proportional increase in TKE is largest.

Warming and power generation saturate with increasing turbine density (Figure 3). The temperature saturation is sharper, so the ratio of temperature change per unit energy generation decreases with increasing turbine density. This suggests that wind’s climate impacts per unit energy generation may be somewhat larger for lower values of total wind power production.

Power generation appears to approach the wind power generation limit at turbine densities somewhat above the maximum (3.0 MW km⁻²) we explored. A capacity density of 1.5 MW km⁻² roughly matches that of US wind farms installed in 2016, and that simulation’s power density of 0.46 Wₑ m⁻² is very close to the 0.50 Wₑ m⁻² observed for US wind farms during 2016. The highest turbine density yields an areal (surface) power density of 0.70 Wₑ m⁻², consistent with some previous studies, but half the 1.4 Wₑ m⁻² assumed possible by 2050 from the same 3.0 MW km⁻² turbine density into windy regions by the DOE. While we did not compute a maximum wind power generation rate here, extrapolation of
Figure 3 suggests that it is about 2 TWh, significantly less than the 3.7 TWh of technical potential estimated by the DOE\textsuperscript{28,29} over less land area. Clearly, interactions of wind turbines with climate must be considered in estimates of technical wind power potential.

Interpretation

The climatic impacts of wind power may be unexpected, as wind turbines only redistribute heat within the atmosphere, and the 1.0 W m\(^{-2}\) of heating resulting from kinetic energy dissipation in the lower atmosphere is only about 0.6% of the diurnally averaged radiative flux. But wind’s climatic impacts are not caused by additional heating from the increased dissipation of kinetic energy. Impacts arise because turbine-atmosphere interactions alter surface-atmosphere fluxes, inducing climatic impacts that may be much larger than the direct impact of the dissipation alone.

As wind turbines extract kinetic energy from the atmospheric flow and slow wind speeds, the vertical gradient in wind speed steepens, and downward entrainment increases.\textsuperscript{15} These interactions increase the mixing between air from above and air near the surface. The strength of these interactions depends on the meteorology and, in particular, the diurnal cycle of the ABL.

During the daytime, solar-driven convection mixes the atmosphere to heights of 1–3 km.\textsuperscript{35}
Figure 3. Variation in Mean Response to Changes in Installed Capacity Density

(A–D) The shared x axis is the installed electrical generation capacity per unit area. All values are averages over the wind farm region. (A) Eighty-four-meter hub-height wind speed, (B) capacity factor, (C) generation rate ($T_{W_e}$), and (D) 2-meter temperature ($\Delta T_{2m}$)
Wind turbines operating during the daytime are enveloped within this already well-mixed air, so climatic impacts such as daytime temperature differences are generally quite small. At night, radiative cooling results in more stable surface conditions, with about 100–300 m of stable air separating the influence of surface friction from the winds aloft.\(^{35}\) Wind turbines operating at night, with physical extents of 100–150 m and an influence height at night reaching 500 m or more,\(^{15}\) can entrain warmer (potential temperature) air from above down into the previously stable and cooler (potential temperature) air near the surface, warming surface temperatures. In addition to the direct mixing by the turbine wakes, turbines reduce the wind speed gradient below their rotors and thus sharpen the gradient aloft. This sharp gradient may then generate additional turbulence and vertical mixing.

This explanation is broadly consistent with the strong day-night contrast of our benchmark scenario (Figures 1B and 1C). Within the wind farm region during the day, most locations experience warmer air temperatures, although \(\sim 15\%\) of locations show a daytime cooling effect in July-September. At night during July-September, less than 5\% of locations show a cooling effect, and the warming effect at night over all months is much larger than during the daytime. This daytime and nighttime warming effect is also larger with higher turbine densities (Figure S7). Finally, the temperature perturbation in the benchmark scenario shows a strong correlation to differences in TKE within the lowest model level from 0 to 56 m (Figure 2B), with these increases in TKE downwind of turbines previously observed in Iowa\(^{4}\) and offshore Germany,\(^{37}\) and supporting our explanation that the temperature response is driven by increased vertical mixing (Figure 2).

**Observational Evidence of Climatic Impacts**

While numerous observational studies have linked wind power to reduced wind speeds and increased turbulence in the turbine wakes,\(^{1,4,7,38,39}\) ten studies have quantified the climatic impacts resulting from these changes (Table 1).

Three ground-based studies have measured differences in surface temperature\(^{1,5,7}\) and evaporation.\(^{5}\) Generally, these ground-based observations show minimal climatic impacts during the day, but increased temperatures and evaporation rates at night.

Seven satellite-based studies have quantified surface (skin) temperature differences. By either comparing time periods before and after turbine deployment, or by comparing areas upwind, inside, and downwind of turbines, the spatial extent and intensity of warming for 28 operational wind farms in California,\(^{25}\) Illinois,\(^{6}\) Iowa,\(^{7}\) and Texas\(^{8-11}\) has been observed. There is substantial consistency between these satellite observations despite the diversity of local meteorology and wind farm deployment scales. Daytime temperature differences were small and slightly warmer and cooler, while nighttime temperature differences were larger and almost always warmer (Table 1). Interpretation of the satellite data is frustrated by fixed overpass times and clouds that sometimes obscure the surface.
Joule

Although our benchmark scenario is very different in scale and turbine placement compared with operational wind power, it is nevertheless instructive to compare our simulation with observations. We compare results at a single Texas location (100.2°W, 32.3°N) where one of the world’s largest clusters of operational wind turbines (~200 km², consisting of open space and patchy turbine densities of 3.8–4.7 MW km⁻²) has been linked to differences in surface temperature in 3 of the observational studies in Table 1. Weighting the observations by the number of observed-years, the Texas location is 0.01°C warmer during the day and 0.29°C warmer at night (data in Table S2). Our benchmark scenario with a uniform turbine density of 0.5 MW km⁻² at this location is 0.33°C warmer during the day and 0.66°C warmer at night. To explore the quantitative correlation between the seasonal and diurnal response, we take the 8 seasonal day and night values as independent pairs (Table S2), and find that the observations and the simulations are strongly correlated (Figure 4). This agreement provides strong evidence that the physical mechanisms being modified by the deployment of wind turbines are being captured by our model. This mechanism could be tested more directly if temperature observations upwind and downwind of a large turbine array were available at a high temporal resolution (<3 hr).

Limitations of Model Framework
Climate response is partly related to the choice and placement of wind turbine(s). We modeled a specific 3.0-MW turbine, but future deployment may shift to wind turbines with taller hub heights and larger rotor diameters. We also assumed

Table 1. Overview of Observational Studies Linking Air Temperature Differences to Wind Farms

<table>
<thead>
<tr>
<th>Reference</th>
<th>SAT or GND</th>
<th>Period</th>
<th>State</th>
<th>Notes: Climatic Impacts within or Very near to the Operational Wind Farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baidya Roy and Walsh-Thomas, 2010</td>
<td>GND</td>
<td>53 days</td>
<td>CA</td>
<td>summer; ~1°C increase in 5-m air temperature downwind at night through the early morning; slight cooling effect during the day</td>
</tr>
<tr>
<td>Zhou et al., 2012</td>
<td>SAT</td>
<td>–</td>
<td>CA</td>
<td>~2°C warmer skin temperatures extending to about 2 km downwind, with visible temperature differences to 12 km downwind</td>
</tr>
<tr>
<td>Zhou et al., 2013</td>
<td>SAT</td>
<td>9 years</td>
<td>TX</td>
<td>JJA night = +0.72°C, DJF night = +0.46°C, JJA day = -0.04°C, DJF day = +0.23°C; warming is spatially consistent with the arrangement of wind turbines</td>
</tr>
<tr>
<td>Zhou et al., 2013</td>
<td>SAT</td>
<td>6 years</td>
<td>TX</td>
<td>QA1 values: DJF night = +0.22°C, MAM night = +0.29°C, JJA night = +0.35°C, SON night = 0.40°C, DJF day = +0.11°C, MAM day = -0.11°C, JJA day = +0.17°C, SON day = -0.04°C</td>
</tr>
<tr>
<td>Xia et al., 2016</td>
<td>SAT</td>
<td>2 years</td>
<td>TX</td>
<td>QA1 values: DJF night = -0.01°C, MAM night = +0.42°C, JJA night = +0.67°C, SON night = 0.47°C, DJF day = +0.14°C, MAM day = -0.42°C, JJA day = +1.52°C, SON day = +0.12°C</td>
</tr>
<tr>
<td>Harris et al., 2014</td>
<td>SAT</td>
<td>11 years</td>
<td>IA</td>
<td>MAM night = +0.07°C, JJA night = +0.17°C, SON night = +0.15°C</td>
</tr>
<tr>
<td>Rajewski et al., 2013</td>
<td>GND</td>
<td>122 days</td>
<td>IA</td>
<td>along the edge of a large wind farm directly downwind of ~13 turbines; generally cooler temperatures (0.07°C) with daytime periods that were 0.75°C cooler and nighttime periods that were 1.0–1.5°C warmer</td>
</tr>
<tr>
<td>Rajewski et al., 2014</td>
<td>GND</td>
<td>122 days</td>
<td>IA</td>
<td>along the edge of a large wind farm downwind of ~13 turbines co-located with corn and soybeans; night-sensible heat flux and CO₂ respiration increase 1.5–2 times and wind speeds decrease by 25%–50%; daytime H₂O and CO₂ fluxes increase 5-fold 3–5 diameters downwind</td>
</tr>
<tr>
<td>Slawsky et al., 2015</td>
<td>SAT</td>
<td>11 years</td>
<td>IL</td>
<td>DJF night = +0.39°C, MAM night = +0.27°C, JJA night = +0.18°C, SON night = +0.26°C, Annual = +0.26°C</td>
</tr>
<tr>
<td>Smith et al., 2013</td>
<td>GND</td>
<td>47 days</td>
<td>confidential</td>
<td>Spring; nighttime warming of 1.9°C downwind of a ~300 turbine wind farm</td>
</tr>
</tbody>
</table>

SAT, satellite-based observations; GND, ground-based observations. Note that measurements identified as the same state were completed over the same wind farms.
that turbines were evenly spaced over the wind farm region, but real turbine deployment is patchier, potentially also altering turbine-atmosphere-surface interactions.

The model’s boundary conditions are prescribed and do not respond to changes caused by wind turbines. Yet prior work has established that non-local climate responses to wind power may be significant, suggesting that simulating our benchmark scenario with a global model (no boundary conditions restoring results to climatology) would allow possible climatic impacts outside the US to be assessed. Removal of the boundary conditions might also increase the warming in the wind farm region. The 3-year simulation period was also completed in 1-year blocks, so we do not simulate the response of longer-term climate dynamics influenced by variables such as soil moisture. Finally, model resolution influenced the estimated climatic impacts. Simulations with a 10-km horizontal resolution and the highest turbine density of 3.0 MW km\(^{-2}\) caused 18% less warming than the 30-km simulation (+0.80°C and +0.98°C). Simulations using a global model with an unequally spaced grid with high-resolution over the US could resolve some of these uncertainties.

**Comparing Climatic Impacts to Climatic Benefits**

Environmental impacts of energy technologies are often compared per unit energy production. Because a central benefit of low-carbon energies like wind and solar is reduced climate change, dimensionless climate-to-climatic comparisons between the climate impacts and climate benefits of reduced emissions are relevant for public policy.

Climate impacts will, of course, depend on a range of climate variables that would need to be examined in a comprehensive impact assessment. In this analysis we nevertheless use 2-m air temperature as a single metric of climate change given (1) that there are important direct impacts of temperature, (2) that temperature...
change is strongly correlated with other important climate variables, and (3) that use of temperature as a proxy for other impacts is commonplace in climate impacts assessments. Limitations and caveats of our analysis are addressed in the following sub-section.

When wind (or solar) power replace fossil energy, they cut CO₂ emissions, reducing GHG-driven global climate change, while at the same time causing climatic impacts as described above and elsewhere.1–15,22–26,34,40,43–45 The climatic impacts differ in (at least) two important dimensions. First, the direct climatic impact of wind power is immediate but would disappear if the turbines were removed, while the climatic benefits of reducing emissions grows with the cumulative reduction in emissions and persists for millennia. Second, the direct climatic impacts of wind power are predominantly local to the wind farm region, while the benefits of reduced emissions are global. We revisit and elaborate these differences in a systematic list of caveats at the end of this subsection.

As a step toward a climate-impact to climate-benefit comparison for wind, we compare warming over the US. We begin by assuming that US wind power generation increases linearly from the current level to 0.46 TWₜ in 2080 and is constant thereafter. We estimate the associated warming by scaling our benchmark scenario’s temperature differences linearly with wind power generation. The amount of avoided emissions—and thus the climate benefit—depends on the emissions intensity of the electricity that wind displaces. We bracket uncertainties in the time evolution of the carbon-intensity of US electric power generation in the absence of wind power by using two pathways. One pathway assumes a static emissions intensity at the 2016 value (0.44 kgCO₂ kWh⁻¹), while the second pathway’s emissions intensity decreases linearly to zero at 2100, which is roughly consistent with the GCAM model46 that meets the IPCC RCP4.5 scenario. The two emissions pathways are then reduced by the (zero emission) wind power generation rate at that time (Figure 5C). The first pathway likely exaggerates wind power’s emission reductions, while the second reflects reduced climate-benefit for wind in a transition to a zero-carbon grid that might be powered by solar or nuclear.

It is implausible that the US would make deep emissions cuts while the rest of the world continues with business-as-usual, so we include a third pathway, which functions just like the first pathway, except that the global (rather than just US) electricity emissions intensity declines to zero (Figure S8).

We estimate wind’s reduction in global warming by applying the two US and one global emission pathways to an emissions-to-climate impulse response function.47 We convert these global results to a US warming estimate using the 1.34:1 ratio of US-to-global warming from IPCC RCP4.5 and RCP8.5 ensemble means (Figure S9,48).

The benchmark scenario’s warming of 0.24°C over the Continental US and 0.54°C over the wind farm region are small-to-large depending on the baseline. Climatic impacts are small if compared with US temperature projections— historical and ongoing global emissions are projected to cause the Continental US to be 0.24°C warmer than today by the year 2030 (Figure S8). Assuming emissions cuts are implemented globally, then the climatic impacts of wind power affecting the US in 2100 are approximately equivalent to the avoided warming from reduced global emissions (green region of Figure 5D). Climatic impacts are large if the US is the only country reducing emissions over this century (blue and gray shaded regions of...
Timescale matters because climatic impacts are immediate, while climate benefits grow slowly with accumulated emission reductions. The longer the time horizon, the less important wind power’s impacts are compared with its benefits (Box 1).

Figure 5. Climate Warming Impacts Compared to Climate Benefits of Reduced Emissions
(A) Two US scenarios, static (black) and declining (blue) emissions intensity, $I$, from US electric power.
(B) A scenario in which power output, $P$, from wind or solar power increases to our benchmark scenario’s 0.46 TWe by 2080.
(C and D) Avoided emissions computed as $\Delta E = I \times P$ (C) and the resulting 2-m temperature differences within the wind farm region (dotted lines) and the Continental US (solid lines) (D). Values for wind power linearly scaled from our benchmark scenario, while values for solar power are derived from Nemet. For comparison, the avoided warming of the Continental US from reduced emissions is shown for the static US scenario (gray) and the declining US scenario (blue). The green area shows the avoided warming of the Continental US if global electricity emissions were zero by 2080. The range of avoided warming for each pathway is estimated from the min and max values within the emissions-to-climate impulse response function.
Joule

Box 1. Limitations of Using these Results to Compare the Climatic Impacts of Wind Power to Climate Change from Long-Lived Greenhouse Gases

The comparison above suggests that if US electricity demand was met with US-based wind power, the wind farm array would need to operate for more than a century before the warming effect over the Continental US caused by turbine-atmosphere interactions would be smaller than the reduced warming effect from lowering emissions. This conclusion is subject to a number of caveats including:

- Fundamentally different mechanisms cause warmer temperatures from climate change compared with wind power. Increased GHG concentrations reduce radiative heat losses to space, trapping more heat in the atmosphere and causing warmer surface temperatures. Wind power does not add more heat to the atmosphere—wind turbines redistribute heat by mixing and alter large-scale flows both of which can change climate.
- Our comparison was based solely on surface air temperature differences. Wind turbines and GHGs both alter a host of interrelated climate variables. The use of surface temperature as the sole proxy for climate impacts may bias the resulting ratio of impacts-to-benefits in either direction.
- Climate impacts of the benchmark scenario will likely be larger and more widespread if we did not use forced boundary conditions, which prevents any feedbacks from the large-scale circulation.
- Results depend on the wind electricity generation rate, consistent with previous work. Our results (Figure 3) suggest the temperature response is roughly linear to the generation rate and power density. To the extent that we see deviations from linearity (Figure S7), climate impacts per unit generation are larger for lower turbine densities.
- Results depend on the spatial distribution and density of wind turbines. We assumed that the windiest areas would be exploited and that developers would use low turbine densities to maximize per-turbine generation. Based on simulated results with higher turbine densities (Figure 3), doubling the turbine density over an area half as large as the benchmark scenario might generate almost the same power as the benchmark scenario, while increasing warming over this smaller region by only about a third.
- Our comparison metric ignores many possible benefits and drawbacks of the climate impacts caused by wind power deployment, including:
  - Arctic cooling shown in most large-scale wind power modeling studies.\(^{11,23,24,45}\)
  - Warmer minimum daily temperatures reduce the incidence and severity of frost, and lengthen the growing season. Compared to the control, the growing season of the wind farm region was 8 days longer in our benchmark scenario, and 13 days longer with 3.0 MW km\(^{-2}\).\(^{1,4}\)
  - Some locations experience cooler average temperatures during the summer (Figure 2B), consistent with observations, and could reduce heat stress.
  - Warmer minimum daily temperatures have been observed to reduce crop yield.\(^{49}\)
  - Warmer minimum temperatures could influence insect life history in unknown ways.\(^{50}\)
- The comparison depends on area-weighting. We used equal weighting but one could consider weighting by, for example, population or agricultural production.
- The comparison depends very strongly on the time horizon. We examined the century timescale consistent with Global Warming Potentials, but there is no single right answer for time discounting.\(^{51,52}\)
- Finally, results depend on the comparison of US and global-scale impacts and benefits: our model framework prevents global-scale analyses, but, assuming a substantial fraction of the warming effect occurred where US wind turbines were operating, global area-weighted benefits would offset the climatic impacts sooner than if impacts and benefits were quantified over just the US (as done here).

Implications for Energy System Decarbonization

Wind beats fossil fuels under any reasonable measure of long-term environmental impacts per unit of energy generated. Assessing the environmental impacts of wind power is relevant because, like all energy sources, wind power causes climatic impacts. As society decarbonizes energy systems to limit climate change, policy makers will confront trade-offs between various low-carbon energy technologies such as wind, solar, biofuels, nuclear, and fossil fuels with carbon capture. Each technology benefits the global climate by reducing carbon emissions, but each also causes local environmental impacts.

Our analysis allows a simple comparison of wind power’s climate benefits and impacts at the continental scale. As wind and solar are rapidly growing sources of low-carbon electricity, we compare the climate benefit-to-impact ratio of wind and solar power.

The climate impacts of solar PVs arise from changes in solar absorption (albedo). A prior study estimated that radiative forcing per unit generation increased at 0.9 mWm\(^{-2}\)TW\(_{eq}\), in a scenario in which module efficiency reaches 28% in 2100 with installations over 20% rooftops, 40% grasslands, and 40% deserts.\(^{18}\) Assuming that the climatic impact is localized to the deployment area and using a climate
sensitivity of 0.8 K W m\(^{-2}\), generating 0.46 TW\(_e\) of solar PVs would warm the Continental US by 0.024°C. This warming effect is 10-times smaller than wind’s (0.24°C, Figure 5D) for the same energy generation rate. This contrast is linked to differences in power density and thus to the areal footprint per unit energy—US solar farms presently generate about 5.4 W m\(^{-2}\), while US wind farms generate about 0.5 W m\(^{-2}\).\(^{36}\) We speculate that solar PVs’ climatic impacts might be reduced by choosing low albedo sites to reduce impacts or by altering the spectral reflectivity of panels. Reducing wind’s climatic impacts may be more difficult, but might be altered by increasing the height of the turbine rotor above the surface distance to reduce interactions between the turbulent wake and the ground, or switching the turbines on or off depending on meteorological conditions.

In agreement with observations and prior model-based analyses, US wind power will likely cause non-negligible climate impacts. While these impacts differ from the climate impacts of GHGs in many important respects, they should not be neglected. Wind’s climate impacts are large compared with solar PVs. Similar studies are needed for offshore wind power, for other countries, and for other renewable technologies. There is no simple answer regarding the best renewable technology, but choices between renewable energy sources should be informed by systematic analysis of their generation potential and their environmental impacts.

SUPPLEMENTAL INFORMATION

Supplemental Information includes nine figures and two tables and can be found with this article online at https://doi.org/10.1016/j.joule.2018.09.009.

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AUTHOR CONTRIBUTIONS


DECLARATION OF INTERESTS

D.W.K. is an employee, shareholder, and executive board member at Carbon Engineering (Squamish, BC). Carbon Engineering is developing renewable electricity to fuels projects and is developing procurement contracts for wind and solar power.

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Emergent crowns and light-use complementarity lead to global maximum biomass and leaf area in *Sequoia sempervirens* forests

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Heartwood
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**A B S T R A C T**

Forests >80 m tall have the highest biomass, and individual trees in these forests are Earth’s largest with deep crowns emerging above neighboring vegetation, but it is unclear to what degree these maxima depend on the emergent trees themselves or a broader-scale forest structure. Here we advance the concept of emergent facilitation, whereby emergent trees benefit co-occurring species. Trees reorganize foliage within crowns to optimize available light and, if long-lived, can reiterate after crown damage to become emergent. The height, depth, and spacing of emergent trees in turn allows for abundant light to pass through the canopy, leading to light-use complementarity as well as elevated biomass, leaf area, and species diversity of the forest as a whole. We chose *Sequoia sempervirens* to develop this concept and installed eleven 1-ha plots in old-growth forests spanning nearly six degrees of latitude in California. Each plot was based off a 316-m-long centerline where biomass and leaf area of all vegetation were quantified. We employed hierarchical measurements and stratified random sampling spanning the full size range of individuals to generate 180 equations for determining biomass and leaf area of all dominant plant species in these forests. Biomass (5190 Mg ha⁻¹), leaf area (LAI = 19.4), and aboveground carbon (2600 Mg ha⁻¹) are global maxima, occurring in plots with the highest proportion of emergent trees. Decay-resistant *Sequoia* heartwood contributes the bulk of this mass, ranging from 61.5 to 76.7% of plot totals. Heartwood is a key contributor to the development of trees with emergent crowns, since its durability enables trees to recover leaf area and to re-grow crowns after damage so that they can continue expanding for millennia. By distributing leaf area among fewer trees with deeper crowns, *Sequoia* maintains very high leaf area itself (LAI up to 14.5) while simultaneously allowing other species to flourish underneath (non-*Sequoia* LAI up to 8.0). Because *Sequoia* is not replaced by other species, aboveground biomass, leaf area, and carbon content of these forests are essentially asymptotic over time.

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**1. Introduction**

Globally, the tallest forests also have the highest biomass (Waring and Franklin, 1979; Keith et al., 2009). Forests with trees >80 m tall all have abundant precipitation and most occur at low elevations, but the same holds true for many other forests that do not produce tall trees (Tng et al., 2012). Beyond elevation and precipitation, an optimal temperature regime – specifically low seasonal variation in temperature – is a global determinant of maximum tree height (Larjavaara and Muller-Landau, 2011). Wet, low elevation forests with mild and stable temperature regimes only occur in coastal environments, and accordingly nearly all trees >80 m tall grow within 100 km of an ocean with most being much closer (Larjavaara, 2013).

Biomass and leaf area of the tallest forests are often more than an order of magnitude higher than shorter forests, including those in tropical Central and South America as well as those in temperate Europe and eastern North America (Franklin and Waring, 1980; Keith et al., 2009). The largest trees consistently occur in forests with near-maximum biomass and leaf area (Sillett and Van Pelt, 2007; Sillett et al., 2015b). Linkages between large trees and forest structure are so strong that aboveground biomass in Central African forests is predictable with information from only the largest 5% of their trees (Bastin et al., 2015). Large trees are a critical element of forest structure, but it is unclear to what degree maximum biomass and leaf area are attributable to the presence of large trees or a broader-scale forest structure. Even in
high-biomass forests dominated by a single species, other species often substantially contribute to plot-level leaf area (Grier and Logan, 1977; Van Pelt et al., 2004). Massive accumulation of biomass in living trees is also associated with large logs and snags that can represent as much as one-third of total forest carbon (Smithwick et al., 2002; Burasciano et al., 2013), especially in cool temperate rainforests (sensu Alaback, 1991) where saturated logs have slow rates of decay (Harmon et al., 1986; Daniels et al., 1997).

1.1. Crown development of tall trees

The six species in the world verified >90 m tall represent the two largest members of three families and two phyla (Table 1). Achieving these dimensions not only requires an immense leaf area, but also an optimal scaffolding on which to array leaves. Trees with the highest leaf areas are those that can maintain foliage in shade and develop deep crowns (Horn, 1971; Leverenz and Hinckley, 1990). The tallest Cupressaceae (Sequoia sempervirens and Sequoiadendron giganteum) are the only known trees to support leaf dry masses >900 kg (Sillett et al., 2015a), and among 30 crown-mapped trees with this much foliage, mean crown depths are >60 m with crown-depth-to-diameter ratios >3.0 (Table 1). Despite profound differences in crown structure and physiology, the largest individuals of the other four tallest species also develop deep crowns (Table 1). Each of these species can produce emergent trees – large trees in dominant canopy positions above neighboring vegetation with crowns exposed to extremes of sun and wind. Interacting processes at leaf, branch, and whole-crown scales contribute to emergent crown development.

Trees make many leaf-level adjustments to maximize carbon gain. Since leaves reach photosynthetic saturation at a fraction of full sunlight, trees adjust leaf angles to minimize excessive heat loading and water loss (Duncan, 1971; Hikosaka and Hirose, 1997). Long-lived trees have constantly changing crowns and reiterate (resprout) following disturbance to restore leaf area (Smith and Brewer, 1994; Ishii and Ford, 2001). Within-crown growth produces leaves in newly illuminated regions, effectively maximizing productivity of the individual tree (Monsi and Saeki, 1953; Falster and Westoby, 2003). Leaves of many species are also phenotypically plastic, allowing them to vary widely in size, shape, and tissue density (Poopter et al., 2009; Oldham et al., 2010), expressed as leaf mass per unit area (LMA).

In tall crowns, leaves aggregate at the shoot level, shoots aggregate at the branch level, and branches are dispersed vertically at the tree level in response to penumbral effects (Anderson, 1964; Miller and Norman, 1971). Penumbral effects occur as the sun and wind. Interacting processes at leaf, branch, and whole-crown scales contribute to emergent crown development. Penumbral effects occur as the sun tapers into a region of diffuse shadow (Miller and Norman, 1971). Penumbral effects occur as the sun tapers into a region of diffuse shadow (Miller and Norman, 1971). The umbrella, which is too dark for positive net photosynthesis, is minimized behind small objects such as leaves and shoots, because refracted light quickly illuminates behind them. On cloudy days, when diffuse light comes from all sides, the umbrella is nearly eliminated. Aggregation of leaves at multiple scales effectively minimizes the umbrella to relatively small regions directly underneath branches (Van Pelt and Sillett, 2008).

We refer to the combined influences of phenotypic plasticity, aggregation at multiple scales, and crown reorganization as crown optimization (sensu Coomes et al., 2012), a phenomenon occurring to some extent in all trees. All long-lived species that also grow tall have the potential to develop an emergent crown.

1.2. Plot-level implications of emergent trees

During the lengthy process of crown optimization, abundant opportunities are created for other species to add leaf area in various canopy positions along the vertical gradient (Canham, 1988; Ishii et al., 2004). Diverse architectures and strategies of leaf display allow many trees, shrubs, and other plants that can grow in deep shade to exploit diffuse light (penumbra) in forest understories (Pickett and Kempf, 1980; King, 1994; Van Pelt and Franklin, 2000). Higher total leaf area due to shared canopy space by multiple species is termed light-use complementarity (hereafter LUC), which is a potential contributor to forest diversity and productivity (Ishii et al., 2013). Emergent trees maintain a high plot-level leaf area by growing deep crowns with larger, but fewer individuals. Vertical reorganization of foliage in large trees releases horizontal space and through LUC may increase total leaf area along the way – a process we call emergent facilitation (Fig. 1). Demonstrating emergent facilitation requires detailed, spatially explicit leaf area data from all species present. In tall, old-growth forests, these data must cover long distances (at least 3 times dominant tree height – Kuiper, 1988; Van Pelt and Nadkarni, 2004) to capture the full range of horizontal variability present in the forest.

Detecting LUC resulting from emergent facilitation might require considering forests as a collection of discrete, developmental units. Horizontal diversity in old-growth forests includes canopy gaps, regeneration patches, zones of dense trees, snags and logs, as well as sections with emergent trees (Richards, 1952; Franklin et al., 1981). In primary (old-growth) tropical rainforests, a silvatic mosaic is defined as a collection of eco-units (i.e., distinct patches with a similar internal structural and developmental trajectory following disturbances) and is the minimum landscape surface encompassing the full spectrum of horizontal diversity (Oldeman, 1983, 1990). Eco-units in the oldest forests consist of structural ensembles – cohorts of trees stratified vertically (e.g., understory, middle canopy, upper canopy). The largest trees define both the eco-unit and the

Table 1

Data from comprehensively mapped trees with the largest crowns of the six tallest species. Numbers reported are the highest leaf masses ever directly measured, come from trees with similar crown shapes, yet different in structure, genetics, and shade-tolerance.

<table>
<thead>
<tr>
<th>Family</th>
<th>Taxa</th>
<th>Largest subset of mapped trees</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Largest tree (Mg)</td>
<td>Leaf dry mass (kg)</td>
</tr>
<tr>
<td>Cupressaceae</td>
<td>Sequoia</td>
<td>425^b</td>
</tr>
<tr>
<td></td>
<td>Sequoiadendron</td>
<td>550^b</td>
</tr>
<tr>
<td>Pinaceae</td>
<td>Pseudotsuga menziesii</td>
<td>158^c,c</td>
</tr>
<tr>
<td></td>
<td>Pinus sitchensis</td>
<td>152^d</td>
</tr>
<tr>
<td>Myrtaceae</td>
<td>Eucalyptus regnans</td>
<td>215^c</td>
</tr>
<tr>
<td></td>
<td>Eucalyptus globulus</td>
<td>230^d</td>
</tr>
</tbody>
</table>

^ Sillett et al. (2015a).
^ Van Pelt and Sillett (2008).
^ Sillett et al. (2015b).
EMERGENT FACILITATION

uppermost structural ensemble and have a strong influence over the other ensembles. Whether trees can become emergent or not depends in part on the species and in part on the structural context of neighboring trees. As trees age, damage from crown breakage and subsequent decay can lead to tree death and the degeneration of structural ensembles (Oldeman, 1990). If defined by canopy height, structural ensembles might be identifiable using remote sensing technologies such as aerial LiDAR (Lefsky et al., 1999; Kane et al., 2011). Further, if ensembles are defined by tree structure, and leaf area of all species within plots is quantified spatially, contributions of emergent trees to the forest as a whole can be determined.
1.3. Study system and objectives

Unique among the tallest species, some S. sempervirens (hereafter Sequoia) forests were intact throughout the Holocene such that they are much older than the oldest individual trees (Sawyer et al., 2000). In the rainforest (i.e., northern) part of its range, individual Sequoia reach heights >115 m and ages >2500 years (Sillett et al., 2015a). Unlike many tree species, where severe damage to a dominant tree crown initiates overall decline (Oldeman, 1990), decay resistance, reiterative capacity, and shade tolerance allow Sequoia to recover leaf area and expand its crown following disturbances (Sillett et al., 2015a). Eventually such trees become emergent with deep and highly individualized crowns (Fig. 2). These tree-level attributes, in part, allow Sequoia forests to achieve biomass exceeding 3000 Mg ha\(^{-1}\) (Westman and Whittaker, 1975; Fujimori, 1977; Sillett and Van Pelt, 2007).

The geographic range of Sequoia is limited to the west coast of North America where maritime conditions interface with a Mediterranean climate of hot, dry summers and cool, wet winters (Sawyer et al., 2000). A strong north-south precipitation gradient exists across the Sequoia distribution, influencing fire regimes (Fritz, 1932; Veirs, 1982; Lorimer et al., 2009). Variability in biomass and leaf area among these forests is poorly understood, and this deficiency is especially apparent with respect to abundance of dead wood. In northern rainforests, dead wood accumulations along streams range from 100 to 1800 Mg ha\(^{-1}\) (Keller et al., 1985), and in nearby terrestrial forests range from 210 to 580 Mg ha\(^{-1}\) (Graham, 2009). These values are far higher than reported for any other forest type (Harmon et al., 1986). The range of Sequoia also extends south into a much warmer and drier part of coastal California, where chaparral is the dominant vegetation (Stephens and Fry, 2005). Fire exerts major influence on the structure of Sequoia forests in this region, reflected by both smaller trees and lower quantities of woody debris (Lorimer et al., 2009; Sillett et al., 2015a).

Our primary goal is to better understand the processes by which Sequoia forests achieve global maxima and to elucidate the effect of emergent trees on forest structure. We pose three questions: (1) Does emergent facilitation lead to LUC in Sequoia forests? (2) Are emergent trees essential to achieving maximum leaf area at the plot level, or can maxima be reached with different forest structures? (3) Given the strong precipitation gradient with latitude, how do aboveground carbon and abundance of dead wood vary across old-growth Sequoia forests in California?

2. Materials and methods

2.1. Approach

We used LiDAR data to select intact old-growth forests that included locally tall Sequoia throughout its range in California (Carroll et al., 2014; Sillett et al., 2015a). This allowed us to examine patterns in biomass, leaf area, and dead wood over a broad geographic area in the context of a strong precipitation gradient. In order to detect LUC, we needed spatially explicit plant-level biomass and leaf area over long enough distances to quantify horizontal variability within the silvatic mosaic. We installed 1-ha plots built around a centerline that was at least 315 m long, which made each centerline scaled 3 times the dominant tree height or longer. Since the centerline was so long, it was oriented to include at least two locally tall trees. Plot width was designed to ensure that any tree whose crown crossed the centerline was included in the plot, including leaning trees, making the plot at least 30 m wide. These values were increased to 316.23 × 31.62 to make each plot a full hectare that was 10 times longer than wide. While all eleven plots contained emergent trees, the 10:1 ratio of plot size was designed to capture horizontal variability of these tall forests and not emergent trees per se.

All aboveground vegetation within plots, including logs, stumps, and snags, was quantified in a spatially-explicit manner. Total dry masses of wood, bark, and leaves, as well as surface areas of cambium, bark, and leaves were computed for each plant via allometric equations for all dominant tree, shrub, fern, and herbaceous species. Historically, leaf area index (LAI), expressed as the projected area of leaves over a given area of ground, was difficult to quantify in tall forests for two reasons. First, species-level equations were inadequate to estimate the largest individuals present, or such equations did not exist. Second, optical methods for predicting LAI could not distinguish species and were plagued by issues of conversion accuracy associated with complex canopy structure (Asner et al., 2003; Olivas et al., 2013 – Bréda, 2003 has a thorough review of ground-based methods for measuring LAI). We considered the allometric approach more accurate and either made new equations for commonly encountered species or sought published equations for uncommon or minor species.

2.2. Study area

Plots were located in old-growth forests spanning a range of nearly 6 degrees of latitude across a wide precipitation gradient

![Fig. 2. Structure of an emergent tree. Few species express phenotypic plasticity of leaf form as dramatically as Sequoia (LMA changes >2-fold, right). Note that while lower crown is composed of shade foliage (center), it only represents about a quarter of leaf mass (left). Depicted tree structure is AutoCAD rendering of crown dataset for tree in RNP-low plot, which shows many branch and limb systems recovering from previous crown damage and regrowth. Silhouette generated from crown dataset, LiDAR point cloud, and photos.](image-url)
In the northernmost part of the range, *Sequoia* forests contain other tree species common in coastal sections of the Pacific Northwest – *Picea sitchensis*, *Thuja plicata*, and *Tsuga heterophylla*, which have their southernmost range limit at nearly the same location (Fig. 3). We used aerial LiDAR data from each location to quantify canopy height, crown structures, and terrain (Table 2).

Some of the most extensive old-growth *Sequoia* forests occur near the northern end of its range. Among the largest and most intact of these is the 3600 ha *Jedediah Smith Redwoods State Park* (JS) near Crescent City, California. Established in 1929 and later expanded, nearly the entire park is old-growth forest, although it does contain areas of relatively small-stature forests growing on ridges and areas recovering from fire. The 1360 ha of forest having trees >90 m tall includes some of the largest individual trees known (Van Pelt, 2001; Sillett et al., 2015a). With this location and the two that follow, *Sequoia* occupies nearly all geomorphic surfaces, so upland and lowland plots were established in each forest (shortened to ‘up’ and ‘low’ hereafter).

**Prairie Creek Redwoods State Park** (PC) is a 5300 ha reserve situated along the ocean just 34 km south of JS. Protected in the early 1920s and later expanded, the park is similar to JS in being nearly all old-growth forest. PC has 1760 ha of forest with trees >90 m (the largest single area remaining), which also contains several of the largest known individual trees (Van Pelt, 2001; Sillett et al., 2015a). Both JS and PC’s proximity to the coast makes them exposed to winter storms that damage tree crowns, but subsequent growth and recovery of *Sequoia* creates some of the largest and most complex tree crowns (Sillett and Van Pelt, 2000; Sillett et al., 2015a).

**Redwood National Park** (RNP), which currently occupies 26,700 ha of the lower Redwood Creek drainage, was an area of intense logging during the mid-20th century. The discovery of tall trees in the early 1960s led to park establishment in 1968 followed by expansion in 1977. Even though the park is large, 85% of the old-growth forest was logged and much of the remaining 880 ha of forest with trees >90 m occur in widely scattered fragments. Unlike JS or PC, the drainage is protected from ocean storms, allowing trees to grow taller – these fragments contain a dozen trees >110 m tall, including the tallest and oldest known living *Sequoia* (Sillett et al., 2015a).

Sixty km south of Arcata, CA is **Humboldt Redwood State Park** (HR) and Rockefeller Forest – named for the benefactor whose contribution to the Save the Redwoods League led to its protection in 1929. The relatively narrow swath of tall forest along Bull Creek and lower South Fork Eel River has Earth’s tallest canopy, containing ~80% of all known trees >107 m tall and >30 trees >110 m tall in 344 ha of alluvial river terraces. Even though the park is <100 km south of RNP, it is both farther inland and drier. Tree heights drop precipitously upslope of alluvial terraces, where *Sequoia* dominance quickly gives way to other genera, especially *Pseudotsuga* and *Notholithocarpus* with *Quercus* and *Arbutus* becoming common on south-facing slopes and ridges.

Old-growth *Sequoia* forests south of HR are more limited in extent primarily due to historical logging with a few exceptions. Thirty km from the ocean and at 283 m elevation, **Montgomery Woods State Natural Reserve** (MW) occupies a unique landscape position typically supporting dry forests and woodlands. The geophysical history of this location includes an ancient landslide that created a swamp along a valley bottom, providing *Sequoia* access to plentiful water, in addition to ample sunlight and protection from wind. Consequently, these conditions allow MW to achieve a higher tall tree density than even Rockefeller Forest with 15 trees >107 m tall occurring in a 9.4-ha patch of swamp forest.

**Samuel P. Taylor State Park** (SPT) is 21 km northwest of San Francisco Bay (38° latitude) and has the tallest trees in the region, which includes the nearby and heavily visited Muir Woods National Monument. The limitations of installing a plot with low human impact at the same time as locating plots throughout the latitudinal range of the species made SPT a key reference point. The area includes abundant *Notholithocarpus* and *Pseudotsuga* (some very large), and the normally scarce *Torreya californica* is fairly common.

The Santa Cruz Mountains are rugged, low-lying, and just south of San Francisco Bay, where *Sequoia* dominance extends to ridgelines in many areas. **Big Basin Redwoods State Park** (BB), established in 1902, is California’s oldest state park and located in the heart of this region. Current park boundaries contain 820 ha of old growth with large *Pseudotsuga* frequently co-occurring with *Sequoia*. Less than a dozen trees >90 m tall occur in the park.

![Fig. 3. Plot locations along the California coast. Colored areas indicate geographic range of *Sequoia sempervirens*, shaded by amount of precipitation. Red line represents southern/eastern limit of *Sequoia* associations with three Pacific Northwest tree species – *Picea sitchensis*, *Thuja plicata*, and *Tsuga heterophylla*. Top inset shows strong relationship between latitude and annual precipitation. Precipitation data from PRISM Climate Group (2012). Range map digitized from Griffin and Critchfield (1972). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image_url)
South of Monterey Bay (36.8° latitude), the steep Santa Lucia Mountain Range stretches for 170 km directly along the ocean, and Sequoia is largely restricted to deeply incised canyon bottoms. Three large state parks (Andrew Molera, Pfeiffer Big Sur, and Julia Pfeiffer Burns) and several smaller ones contain much of the old-growth Sequoia forest in the area and are heavily visited. Our southernmost plot at Landels-Hill Big Creek Reserve (LH) is even further south and occurs in the closed watershed of Big Creek at 36.1° latitude. This is the only known location south of Monterey Bay with Sequoia up to 80 m tall. Ridgelines and south-facing slopes have various mixtures of open chaparral with abrupt transitions to forest.

2.3. Plot measurements

2.3.1. Stem map creation

At each location, a centerline was established first by stretching fiberglass tapes down the plot center over its entire length (316.23 m). Within each plot, complete inventories were made of all live trees ≥5 cm in diameter at breast height (BH – measured at 1.37 m) as well as all dead trees (snags and stumps) ≥5 cm and taller than 0.5 m. Live trees were identified to species, tagged, and mapped for all live trees (316.23 m). Within each plot, complete inventories were made of slopes have various mixtures of open chaparral with abrupt transitions to forest.

2.3.2. Crown volumes

Simple shapes were used to convert measurements of crown depth and crown radii into volumes. Paraboloids were used for Alnus, Umbellularia, and most conifers. The smaller/younger Pseudotsuga trees (N = 33) were also modeled as paraboloids, but the larger/older trees (N = 19) were modeled as 2/3 ellipsoids (Van Pelt and North, 1999). Sequoia was a special case that required a more complex approach described elsewhere (Sillett et al., 2015a), which provided a smoothly varying transition from paraboloids for small trees to ellipsoids for the largest trees. All other trees and shrubs were modeled as 1/2 ellipsoids.

Measuring accurate tree heights in the world's tallest and densest forests offered several challenges. In the end, four methods were employed to measure tree height: (1) using a measuring tape lowered from the top of the tree, (2) vertical distance laser shots from a known height in a tree with a tape measure stretched from top to bottom and later corrected for base height differences, (3) sine method (sensu Jarjavara and Muller-Landau, 2013) with survey laser, and (4) extracting tree heights from LiDAR point clouds. Since plot installations and LiDAR flights were sometimes separated by a year or more, these were largely used as a check against our measurements of tree height. Methods 2 and 4 required establishing an exact link between tree locations and real Earth coordinates derived from a hybrid digital elevation model (DEM) created from LiDAR point clouds and ground surveys (see Appendix A for details on creation of the hybrid DEM).

Smaller trees, shrubs, ferns, herbaceous vegetation, and fine woody material were subsampled along plot centerlines (Table 3). Shrub plots were a 10% sample (1.58 m on either side of centerline) for the entire plot length for all shrubs ≥50 cm tall and trees <5 cm DBH yet ≥50 cm tall. We also used the centerline to establish 1-m-diameter circular plots for an inventory of understory vegetation as well as trees and shrubs <50 cm tall. Circular plots were spaced at 4-m intervals to take advantage of understory spatial independence within Pacific Northwest old-growth forests at this scale (Spies et al., 1999), yielding about 80 understory plots per centerline.

2.3.2. Crown volumes

Simple shapes were used to convert measurements of crown depth and crown radii into volumes. Paraboloids were used for Alnus, Umbellularia, and most conifers. The smaller/younger Pseudotsuga trees (N = 33) were also modeled as paraboloids, but the larger/older trees (N = 19) were modeled as 2/3 ellipsoids (Van Pelt and North, 1999). Sequoia was a special case that required a more complex approach described elsewhere (Sillett et al., 2015a), which provided a smoothly varying transition from paraboloids for small trees to ellipsoids for the largest trees. All other trees and shrubs were modeled as 1/2 ellipsoids.

Paraboloid = \[ \pi \frac{1}{2} CrD \cdot R^2 \]

Ellipsoid = \[ \frac{4\pi}{3} \frac{CrD}{2} R^2 \]

where CrD is crown depth and R is mean crown radius.

Table 2
Summary of site characteristics. Precipitation and temperature data are annual averages for period 1895–2012 (PRISM Climate Group, 2012). Sites 1–6 are rainforests.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Location</th>
<th>Latitude (°)</th>
<th>Elevation (m)</th>
<th>Slope (%)</th>
<th>Aspect</th>
<th>Establishment date</th>
<th>Proximity to ocean (km)</th>
<th>Precipitation (mm)</th>
<th>Temperature (°C)</th>
<th>LiDAR data sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 JS</td>
<td>Up</td>
<td>41.78</td>
<td>94</td>
<td>22–55</td>
<td>SW–NW</td>
<td>September 2010</td>
<td>5.2</td>
<td>2108b</td>
<td>3.5</td>
<td>20.0</td>
</tr>
<tr>
<td>2 Low</td>
<td></td>
<td>41.77</td>
<td>80</td>
<td>0–33</td>
<td>E–S</td>
<td>November 2009</td>
<td>6.0</td>
<td>2215</td>
<td>3.2</td>
<td>23.2</td>
</tr>
<tr>
<td>3 PC</td>
<td>Up</td>
<td>41.37</td>
<td>113</td>
<td>15–38</td>
<td>SW–NW</td>
<td>June 2011</td>
<td>5.2</td>
<td>1914</td>
<td>2.5</td>
<td>21.9</td>
</tr>
<tr>
<td>4 Low</td>
<td></td>
<td>41.36</td>
<td>58</td>
<td>0–13</td>
<td>W–NW</td>
<td>August 2011</td>
<td>4.7</td>
<td>1801</td>
<td>3.2</td>
<td>20.2</td>
</tr>
<tr>
<td>5 RNP</td>
<td>Up</td>
<td>41.26</td>
<td>158</td>
<td>28–80</td>
<td>N–SE</td>
<td>September 2009</td>
<td>5.0</td>
<td>1759</td>
<td>3.0</td>
<td>20.5</td>
</tr>
<tr>
<td>6 Low</td>
<td></td>
<td>41.20</td>
<td>47</td>
<td>0–18</td>
<td>W–NW</td>
<td>October 2009</td>
<td>9.2</td>
<td>1663</td>
<td>3.5</td>
<td>20.6</td>
</tr>
<tr>
<td>7 HR</td>
<td></td>
<td>40.34</td>
<td>50</td>
<td>0–8</td>
<td>SE–SW</td>
<td>August 2010</td>
<td>30.1</td>
<td>1369</td>
<td>4.1</td>
<td>24.5</td>
</tr>
<tr>
<td>8 MW</td>
<td></td>
<td>39.23</td>
<td>283</td>
<td>0–4</td>
<td>SW–NW</td>
<td>November 2010</td>
<td>30.2</td>
<td>1196</td>
<td>2.0</td>
<td>29.3</td>
</tr>
<tr>
<td>9 SPT</td>
<td></td>
<td>38.02</td>
<td>77</td>
<td>26–88</td>
<td>N–E</td>
<td>October 2011</td>
<td>7.9</td>
<td>1005</td>
<td>5.2</td>
<td>26.7</td>
</tr>
<tr>
<td>10 BB</td>
<td></td>
<td>37.19</td>
<td>327</td>
<td>6–18</td>
<td>S–SW</td>
<td>December 2009</td>
<td>12.4</td>
<td>1039</td>
<td>6.3</td>
<td>26.9</td>
</tr>
<tr>
<td>11 LH</td>
<td></td>
<td>36.09</td>
<td>167</td>
<td>23–100+</td>
<td>E–S</td>
<td>November 2011</td>
<td>2.0</td>
<td>801</td>
<td>3.9</td>
<td>23.1</td>
</tr>
</tbody>
</table>

- Does not include interception from fog and other condensation, which can add 20–30% (Ruth, 1954; Harr, 1982).
- Drainage directly exposed to open ocean.

\( T_{\text{min}} \)\( T_{\text{max}} \)
Leaf mass was not equally distributed within crowns—a cubic meter of crown volume at the top of a tree in full sun had a higher leaf dry mass than a cubic meter much lower in the crown (Fig. 2). For example, the top of a 10-m diameter crown in full sun had a higher leaf dry mass than a cubic meter much lower in the crown. This is because the top of the crown receives more light and thus higher photosynthetic rates.

Individual leaf masses were measured using a paraboloid of decay method, which is a common approach for estimating leaf mass distribution within crowns. This method involves generating cross sections of trunks at multiple heights and compiling sets of cross-sections to construct 3D models of tree stems. The area of each cross section was converted to a functional diameter (diameter of a circle with equivalent area), which was then used with conic formulae incorporating the distance between cross-sections to calculate quantities of bark and wood (Sillett et al., 2015a). We defined functional diameter at BH as fDBH, which was calculated for all Sequoia, because it was needed for use in allometric equations (Sillett et al., 2015a).

### 2.3.3. Tree base mapping and functional diameter

The buttressing influence of roots and other irregularities (e.g., fire scars) extended higher off the ground on larger trees, and with some trees >600 cm in diameter, the top of buttressing on flared lower trunks extended >10 m above the ground. In addition, due to the reiterative capacity of Sequoia, basal sprouts were common. Many of these fused into clusters of trees as they grew, and large tree clusters were highly irregular at ground level. Large trees, whether solitary or part of a cluster, usually required additional measurements due to the complexity of their bases. Buttressing, burn cavities, sprouting, and other anomalies rendered simple diameter tape measurements (tape wraps) inadequate, so we employed a number of techniques to quantify these structures. Footprint mapping involved generating cross sections of trunks at multiple heights and compiling sets of cross-sections to construct 3D models of non-round portions where trees emerged from the ground. The various methods used to generate 3D models of tree bases are described in Appendix C. The area of each cross section was converted to a functional diameter (diameter of a circle with equivalent area), which was then used with conic formulae incorporating the distance between cross-sections to calculate quantities of bark and wood (Sillett et al., 2015a). We defined functional diameter at BH as fDBH, which was calculated for all Sequoia, because it was needed for use in allometric equations (Sillett et al., 2015a).

### 2.3.4. Decay in live trees

We excluded fire cavities and broken tops from trunk volumes, but unmeasured decay associated with these injuries resulted in lower wood densities that had to be addressed before calculating final trunk masses. Non-destructive internal scanning of large-diameter trunks was impractical, so we used published mill records following old-growth Sequoia logging and their reports of decayed unmerchantable timber. In a sample of 495 Sequoia trunks from the northern 400 km of the range, 336 (68%) had at least some decay (Kimmey and Hornibrook, 1952; Kimmey and Lightle, 1955). Basal wounds, fire cavities, and broken tops were the primary regions of decay. Older wounds had greater decay, but heartwood decay usually did not extend to reiterated trunks. Northern rainforests had the highest percentage of unmerchantable timber in old trees (34% in the furthest north – 42°N), falling to 19% at the southern part of the study at 38.5°N (Kimmey, 1958). However, the definition of unmerchantable varied with timber values and costs of cutting, hauling, and milling wood, and it encompassed more than just amount or degree of decay.

To hedge against uncertainties of unseen wood decay in standing trees we doubled the measured dimensions of wounds or cavities and calculated mass based on Sequoia dead wood Decay IV (Appendix D) as a proxy for the resulting decayed volume, because this type of wood lacked structural integrity. Estimated vertical extent of decay for trees with broken tops was assigned a value five times the broken top diameter, and a paraboloid extending down from the top was assigned the lower density. The Kimmey et al. samples revealed that smaller trees without wounds rarely had decay and that decay was largely limited to the tree base, so we designated a paraboloid of decay five times...
taller than wide for all Sequoia >2 m f-DBH. We defined the volume of this paraboloid such that there was 1 m of sound wood surrounding a partially decayed core. For example, a tree with 4 m f-DBH with no external signs of decay was assigned a paraboloid of decay 2 m wide at the base and 10 m tall. In the old study, 20% of measured trunks had no decay, and decay in the other 80% was highly variable (Kimmey and Lightle, 1955), so we assigned these basal paraboloids the density of Sequoia Decay III, which retains some structural integrity.

2.3.5. Dead wood

The plot centerline was used to inventory logs <30 cm diameter with the line intercept method (Brown, 1974). Larger pieces of dead wood in forests can account for up to 90% of total mass (Sohn et al., 2013), yet their spatial extent is extremely variable (Harmon et al., 1986; Harmon and Sexton, 1996), so a 100% inventory of logs >30 cm diameter was added to each hard copied stem map initially as sketches. These were then scanned and used to update stem maps. With new maps in hand, each log was revisited and checked for location, diameter, and length. Any deviations were corrected by measuring distance and azimuth to known tree location(s) for both log ends. Dense and extensive fern glades often made log detection difficult, so during subsequent phases an additional search was conducted for large-diameter wood not previously mapped. The end diameters of each log were measured with longer logs receiving 1–3 additional diameter measurements. Heavily decayed logs as well as shards and other irregularly shaped pieces required two perpendicular diameter measurements to derive elliptical cross-sections. Tip-ups and other tree base features were mapped individually with height, width, and depth of the root plate recorded. Hollows and other features that reduced volumes of mapped pieces were also measured. We identified species and assigned a decay class to each piece of mapped woody debris.

The widely used 5-point classification system for log decay based on Pinaceae in the Pacific Northwest (Triska and Cromack, 1980) was adjusted for Sequoia to better account for its more decay-resistant heartwood. According to the original classification, Decay I and II logs were based on indicators of branch condition, sapwood decay, and bark sloughing, and Decay IV and V logs represented progressive stages degrading wood integrity. Large Sequoia logs, however, can persist in Decay III for many centuries before reaching Decay IV. During much of that time, if the log was not hollow, its heartwood was solid or at least a higher density than indicated by the outer surface. We designed a new, diameter-based decay classification to better account for this situation in Sequoia (Appendix D).

End diameters and lengths of each piece of woody debris were used for volume calculations. Straight sections of logs were modeled as conic frusta with either circular or elliptical cross-sections. Long logs often had multiple decay classes present, so these portions were separated prior to calculating mass. For logs that included the original tree base, wood density was reduced with the same paraboloid method used for standing trees to account for additional decay. Intercept data for logs <30 cm diameter were separated into groups based on species, decay class, and 5 cm diameter intervals (Harmon and Sexton, 1996). Each group’s intercept length was expressed as a proportion of total intercept length and used to compute cylinder length. The mid-point diameter of each group was then used to calculate cylinder volume.

2.3.6. Linking local and remote data sets

Once installed, each plot had a relative coordinate system with no geo-referencing. Tall, dense Sequoia canopies made precise geo-location challenging. Accuracy depended on the number of GPS satellites detected by the receiver’s antenna, but even survey-grade GPS units often recorded unacceptable location errors of several meters. Aerial LiDAR flights over each plot (Table 2) using a scanning laser mounted in an aircraft using a Global Positioning System (GPS) receiver for accurate positioning and an Internal Measurement Unit (IMU) for precise orientation aided geo-location. The resulting LiDAR data consisted of many individual laser pulse reflections from the forest, each with 3D coordinates. Data acquisition specifications constrained absolute geographic accuracy of point coordinates to <0.5 m, relative accuracy to <0.2 m, and resolution to <1 cm. The LiDAR point cloud was first used to create three primary 2.5D datasets (i.e., one Z value per X–Y pair): (1) a bare earth Digital Elevation Model (DEM), which is a model of the ground surface elevation; (2) a Canopy Surface Model (CSM), which is a model of the uppermost canopy surface elevation; and (3) a Canopy Height Model (CHM), which is the difference between the two and is a measure of canopy height. Details of how we created these are in Appendix A.

The initial LiDAR-based DEM recorded many topographic features on the forest floor only vaguely. High canopy densities created near-ground shadows (holes) in the point cloud, some of which were quite large (Fig. 4A and B). Interpolation of the remaining detectable bare ground DEM points attempted to fill the holes (Fig. 4C). A resulting artifact was that features such as rock outcrops and steep stream banks were smoothed or rounded. Ground-based laser surveys of each plot overcame these problems and captured all unusual and subtle topographic features, especially streams. Results from the ground-based laser surveys were scaled by the initial LiDAR-based DEM to create a hybrid with higher accuracy and precision than either alone (Fig. 4D, Appendix A).

2.3.7. Real Earth coordinates

Converting relative plot coordinate systems into real Earth coordinates was a multi-stage process. We used hours-long GPS track logs collected during plot installation to locate plot corners on the CHM. Once plot installation was complete and map layers were prepared, we used two additional datasets to locate plot boundaries more precisely than using the hybrid DEM alone (Fig. 4E). Because LiDAR point clouds yielded 3D models, the CHM represented a perfect orthographic view of the canopy. Ground-based measures of crown projections thus provided additional information for linking plots to real Earth coordinates (Fig. 5). Mapped logs evident in near-ground LiDAR point clouds provided another link (Fig. 4B). A minimizing algorithm was finally used to refine corner point locations calculated from all data sets to an exact rectangular 316.23 × 31.623 m plot whose border was converted to Universal Transverse Mercator coordinates. Errors in corner point locations were ±0.2–0.5 m for plots on flat ground and 0.4–0.8 m for plots on steeper terrain. Once ground-based data sets were linked to LiDAR, all stems and footprint maps were assembled on hybrid stem maps along with snags, logs, and water features (Fig. 6), and real Earth coordinates were calculated for the base and top of every tagged tree.

2.4. Plant processing for allometric equations

Our approach to quantifying aboveground attributes of standing trees via crown mapping, hierarchical sampling, and subsequent dissections for biomass was developed during studies of several tall species (Van Pelt et al., 2004; Van Pelt and Sillett, 2008; Sillett et al., 2010, 2015a,b). Here we used this approach to quantify additional species growing with Sequoia, including trees, shrubs, ferns, and other non-woody plants. We developed allometric equations that can be applied in any old-growth forest throughout the range of Sequoia and for much of the Pacific Northwest as well. Detailed tree mapping leading to whole-tree quantity estimations was done for
Sequoia (N = 97, Sillett et al., 2015a), Pseudotsuga menziesii (N = 115), T. heterophylla (N = 44), Acer macrophyllum (N = 23), Acer circinatum (N = 27), Alnus rubra (N = 58), and Notholithocarpus densiflorus (N = 118). Similarly, shrub dissections leading to whole-plant equations were done for Rubus spectabilis (N = 25), Vaccinium ovatum (N = 30), and Vaccinium parvifolium (N = 41).

Fig. 4. LiDAR point cloud links stem map to real Earth coordinates, part 1. (A) depicts portion of canopy profile at MW (LiDAR height scale in m). Pink dots in (A) and (B) are ground returns used to create DEM. (C) depicts initial DEM at 0.25-m contours. Additional field mapping used to create final DEM in (D). Logs evident in ground returns (B) also used to link final stem map (E) to real Earth coordinates, if present. Note that large holes in near-ground returns created by dense crowns (B) make interpreting streams problematic without additional survey work. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
New allometric equations for the ferns *Athyrium felix-femina* (N = 14% cover plots), *Blechnum spicant* (N = 22% cover plots), and *Polystichum munitum* (N = 45% cover plots) were also prepared, as well as the herbaceous *Oxalis oregana* (N = 30% cover plots). Details of how each of these were sampled, processed, and analyzed are found in Appendices E–K.

In summary, we produced 180 new equations – 105 of these are new whole-plant equations for predicting total wood, bark, and leaf dry mass, bark and cambium surface area, projected leaf area, and total leaf number for 11 species of trees and shrubs as well as additional equations to predict leaf mass of three fern species and *Oxalis* (Appendix L). For multi-step calculations using intermediate estimates, the standard error (SE) was carried forward at every step, so that final reported SE contains all sources of error (e.g., SE for leaf area on a single tree includes error for predicting whole-tree leaf mass, as well as error converting leaf mass to area).

All of these new allometric equations can be used throughout old-growth forests of the Pacific Northwest and the California coast. Biomass equations for minor woody plants and herbaceous plants other than *Oxalis* were obtained from published sources (Smith and Brand, 1983; Alaback, 1986; Means et al., 1994; Halpern and Lutz, 2013).

Dried and ground samples of leaves, bark, sapwood, and heart-wood of *Sequoia* were analyzed for carbon content (% dry weight) using a CHNOS elemental analyzer (Elementar, Hanau, Germany) at the Center for Stable Isotope Biogeochemistry, University of California, Berkeley, USA. Percent carbon values for most of the other dominant components of biomass were obtained from the literature (Appendix M). For shrub or herb components where species-level equations were unavailable, we used values from similar species in the Rocky (Jain et al., 2010) or Appalachian Mountains (Moore et al., 2007).

2.5. Quantifying horizontal diversity

2.5.1. Centerline analyses

Once all leaf areas were calculated, plot centerlines were analyzed, meter by meter, for all contributing leaf area in a 1 m² cylinder above each – a total of 3476 calculations for 11 plots. Shrubs and small trees were measured in a continuous transect down plot centerlines, so their leaf area contributions were scaled and shared among each centerline meter as their proportional crown diameters indicated. Similarly, trees whose crowns overlapped the centerline had leaf areas partitioned into 1-m² parcels based on crown projections, and parcels were assigned to the appropriate centerline cylinder intersecting each crown. This assumed leaf area was equally distributed throughout the crown projection, or equally in azimuth, which may not always be the case. However, an analysis from mapped tree inventories for *Sequoia*, *Pseudotsuga*, and *Tsuga* (N = 166) confirmed the curve for tree-level leaf area versus distance from main trunk was relatively flat with depressions at main trunk and crown edge. Since our crown radius measurements ignored outlier branch extensions, we modeled the curve as flat. Ferns and other non-woody plants were sampled every 4 m down plot centerlines, so values for each sampled meter were extended to neighboring 1-m² parcels.

2.5.2. Quantifying influence of emergent trees

We designed seven complementary indices based on spatially explicit information to determine if emergent trees promote LUC. At the plot level, simple metrics that isolated the influence of emergent trees were mean crown mass (i.e., whole tree dry mass – main trunk dry mass), mean crown volume, and their standard deviations. A plot with emergent trees produced a mean and standard deviation (SD) greater than those for otherwise similar plots lacking such trees. Since some plots had abundant regeneration while others did not, and we were interested in comparing the distribution and abundance of large trees, plot-level metrics that treated all trees equally overwhelmed important patterns. By examining only *Sequoia* for the seven indices and by ignoring stems smaller than 20 cm f-DBH, we eliminated most of this concern without substantially affecting plot-level basal area (0–0.7% reduction among 11 plots), leaf area (0–2.2%), or mass (0–0.3%) totals.

High mean individual crown mass or volume relative to other plots indicated many emergent trees since these forests had more smaller and fewer larger trees. The standard deviation of crown mass or volume, however, reflected the full spread from very small to very large. Since all plots had some small trees, if the plot had a few emergent trees, the SD would be relatively high compared to others. Crown mass and volume were correlated, so we created two plot-level indices out of the four possibilities that included mean and SD: (Index 1) mean crown mass, and (Index 2) SD of crown volume.

Emergent trees were also detected by skewness of plot-level leaf mass or area, as the presence of these trees skewed the median when leaf area was sorted high to low. Index 3 was the leaf mass of the median tree – the tree where the sum of leaf area for all *Sequoia* larger than it had a value no smaller than the sum of all *Sequoia* smaller than it. A related metric also derived from sorting by size was a count of how many large trees it takes to reach a sum of half
Fig. 6. Stem maps of eleven plots from north to south. First six panels are northern rainforest plots. Complex tree clusters and tree castles are visible in most of the plots. Abundance of woody debris in these plots may make it appear trees fall frequently but bulk of this material is Decay III, and thus very old wood.
the total *Sequoia* leaf area (Index 4). This was an indicator of number of emergent trees, since if the plot had trees with emergent crowns, the count to get half of the plot-level leaf mass or area was relatively small. Noteworthy, Index 4 was simply a count and so independent of tree size. Plots with emergent trees were also easily detectable using an analysis of the meter-by-meter centerline LAI with the strongest being SD of *Sequoia* LAI. Because emergent trees had high leaf areas yet were separated in space, the centerline LAI for a plot with emergent crowns had many large peaks and troughs and thus a very high SD (Index 5).

Characteristics of emergent trees were also detectable from the LiDAR CHM. At 0.75 of the CHM peak value (\(h_{\text{max}}\)), where crowns of tall trees were wide, emergent trees became large polygons, often consisting of a single crown. Lesser trees at this height either had a small polygon or none at all. Denser groups of tall trees did not have single-tree or paired polygons at this height but rather a polygon formed by multiple crowns. The first index to use the 0.75 \(h_{\text{max}}\) interval CHM was based on the fact that plots with emergent trees not only had large individual polygons (compared to those in a densely-packed plot), but they also had relatively consistent spacing. Thiessen polygons (also called Voronoi diagrams) defined regions of closeness to a set of points. Each polygon defined an area of influence around a point based on proximity to other points so that polygon boundaries were perpendicular to lines connecting pairs of adjacent points, whose lengths indicated spacing. With tree stem locations used as points, each polygon was analyzed to separate polygons at 0.75 \(h_{\text{max}}\) on the CHM into individual tree crowns and to compute tree–tree distances. The CHM beyond plot boundaries was used to extend polygons, so that all adjacent polygons had tree-to-tree distances calculated. All distinct polygons within each 1-ha plot were used for crown distance analysis and the creation of Index 6: mean tree–tree distance at 0.75 \(h_{\text{max}}\). Our final metric of emergentness, Index 7, was also derived from the LiDAR CHM in that emergent trees were the only trees that still had a large diameter crown at the 0.75 \(h_{\text{max}}\). All trees tall enough to contribute to the total 0.75 \(h_{\text{max}}\) polygon area were counted, and mean crown size was computed as 0.75 \(h_{\text{max}}\) polygon area divided by the number of contributing trees. Finally, a composite index, called the *emergent crown index* (ECI), was created by calculating the mean of the seven indices.

2.5.3. Structural ensembles

After the meter-by-meter centerline analysis of LAI and development of the ECI, our third approach for quantifying horizontal diversity used spatial information to define structural ensembles, which represented patches of differing forest structure. Just as plot width was designed to be at least 15 m from the centerline to include any tree whose crown may be directly overhead, a 15 m search radius was used to define a circular window that was moved along each centerline, meter-by-meter, to distinguish ensembles. Using the LiDAR point cloud, we constructed a *Relative Height, Canopy Height Model* (RH–CHM) scaled from 0 to 1 based on the tallest tree in each plot (see Appendix A). Within each window, all LiDAR-derived RH–CHM points were divided into 10 equal tiers with each tier representing 10% of \(h_{\text{max}}\). Since our CHM was prepared at 0.5 m horizontal spacing, each moving window contained slightly >2800 points. We wanted to quantify leaf area of all species under the moving window, so this analysis began at centerline distance 15 m (radius of the window) and moved to distance 301 m (15 m from the plot end). Once assigned to an ensemble, that meter along the centerline was removed from further classification. The first ensemble, Canopy Gap, was defined as having 50% or more of the CHM values from the bottom three tiers (i.e., <0.3 relative height).

Despite its strengths, the LiDAR point cloud alone could not distinguish conifer species in *Sequoia* forests. *Pseudotsuga* (up to 97 m tall) and *Tsuga* (up to 83 m tall) grow among *Sequoia*, while *Sequoia*, *Tsuga*, and *Notholithocarpus* can all be abundant in understory and mid-level canopy positions. We used a 30-m-diameter moving window of species-level basal area congruent with the RH–CHM to define a second ensemble, Shared Dominance, where *Sequoia* shares dominance with other tree species (i.e., at least 20% of basal area derived from non-*Sequoia*). After removing both Canopy Gap and Shared Dominance ensembles, only *Sequoia*-dominated ensembles remained.

 Former gaps, where large trees were removed through wind or fire and now refilling with young–mature trees, or where larger trees had recently fallen or been damaged in areas where smaller trees were already present, comprised the *Emerging Canopy* ensemble. This youngest and shortest of the *Sequoia*-dominated ensembles was often of limited extent and not present in all plots. Defining this ensemble was a two-step process. First, the moving window had to have <5% RH–CHM values in the top two tiers, >60% RH–CHM values in the middle four tiers, and <20% RH–CHM values in the bottom two tiers. Second, we ran a 5 m smoothing spline of standard deviation of basal area to exclude large and old trees that may have been short or broken. This curve revealed large peaks at the inclusion/exclusion boundary for large trees, which provided clear demarcation points for selection. With these three ensembles now removed from the total, most of what remained contained the tallest portions of the RH–CHM.

The *Codominant Canopy* ensemble, which was common in all plots, was characterized by a nearly continuous canopy of very tall tree crowns. It was defined as the moving window having >40% RH–CHM values in the top three tiers and <5% in the bottom two tiers. The *Emergent Crowns* ensemble was characterized by very tall trees with large crowns, yet widely spaced – leaving gaps in between that often extended to near ground level. It was defined as the moving window having >20% RH–CHM values in the top three tiers and between 10% and 30% in the bottom two tiers. Any unused portions of centerlines remained unclassified. A dichotomous key was prepared (Appendix N) to clarify the above descriptions and facilitate comparisons among ensembles.

3. Results

3.1. Plot summary

A total of 4089 live trees >5 cm \(f\)-DBH were mapped and measured in eleven 1-ha plots, including 1927 *Sequoia* and 455 standing dead trees. Tree height and \(f\)-DBH ranged up to 112.6 m and 681.2 cm, respectively, and several plot-level quantities were global maxima (Table 4). Trees >110 m tall occurred in three plots (RNP-up, HR, MW), trees >100 m tall occurred in seven plots (also JS-low, PC-up, PC-low, RNP-low), and trees >90 m tall occurred in all but the southernmost plot (LH).

Trees >1000 years old were found in all eight northern plots (Sillett et al., 2015a), and despite a limited sample for which we had age estimates, trees >1800 years old occurred in at least PC-low, RNP-up, and MW. Both SPT and BB had trees >600 years old, and the oldest trees sampled at LH were 330–390 years old. Details on individual *Sequoia* that were climbed, mapped, and aged as part of this study were published elsewhere (Sillett et al., 2015a).

All plots had trees >330 cm \(f\)-DBH, and all but three southern plots (SPT, BB, LH) had trees >450 cm \(f\)-DBH. The northernmost plot (JS-up) had 26 trees per hectare (TPH) >300 cm, and 18 TPH >400 cm, which exceed any previously reported values. Equally superlative was PC-low, which had only 14 TPH >300 cm, but 12 of these were >400 cm, seven were >500 cm, and four were >600 cm, with the latter two details exceeding JS-up. Four other
plots had at least 19 TPH > 300 cm f-DBH. The densest plot was HR with 38 TPH > 200 cm f-DBH, and four other plots had at least 30 TPH > 200 cm f-DBH. Live tree basal area ranged from 160 to 461 m² ha⁻¹ with seven plots having > 300 m² ha⁻¹ of *Sequoia* alone (Table 4). JS-up had the highest value ever recorded for a single species (449 m² ha⁻¹) as well as the record for standing dead trees in an intact forest of 115 m² ha⁻¹.

Crown volumes of all vascular plants combined ranged from nearly 200,000 to over 450,000 m³ ha⁻¹. Three plots had *Sequoia* crown volumes >350,000 m³ ha⁻¹. Two of these plots were rainforests with emergent trees, one of which (RNP-up) also had the highest non-*Sequoia* crown volume. A third plot (HR) had 370,000 m³ ha⁻¹ *Sequoia* crown volume with virtually no contributions from other species. Even though tree size varied considerably along the north-south precipitation gradient, crown diameters of the largest trees were remarkably consistent (mean radius of 10 widest trees in all plots was 9.1 ± 0.1 m), so crown depth was the primary reason for the large crown volumes reported. Mean crown depth of the 20 largest trees was >55 m in all six of the northern rainforest plots, and <55 m in all the others. Interestingly, the latter includes the two tallest forests (HR and MW), whose average crown depth was relatively low due to prevalence of the Codominant Canopy ensemble.

### 3.2. Live biomass, leaf area, and aboveground carbon

Biomass partitioning by species and tissues is described in Appendix E and resulted in the development of many new allometric equations (Appendices F–K), which allowed separate computations of leaf, bark, and wood surface areas, volumes, and dry masses by species and plot for all important tree, shrub, fern, and herbaceous species. This was achieved with complete dissection of crowns or mapping of 765 individual trees and shrubs that included subsamples to get bark thickness, wood and bark density, SLA, leaf count, and carbon content. Dissections resulted in a summary of plot-level masses, by species or life-form, including standard errors of all predicted values (Appendix 1).

Standing live biomass ranged from 1600 to 4530 Mg ha⁻¹ with the eight northern plots all having >3000 Mg ha⁻¹ (Appendix O). Most of this material was wood and bark of *Sequoia* trunks – three plots had >500 Mg ha⁻¹ of *Sequoia* bark alone. *Pseudotsuga* provided the highest two non-*Sequoia* contributions to total aboveground live biomass, which were at BB (333 Mg ha⁻¹ − 83% Pseudotsuga) and RNP-up (249 Mg ha⁻¹ − 62% Pseudotsuga).

Leaf dry masses of nine individual *Sequoia* trees exceeded 1 Mg, five of which were in one plot (PC-low, Sillett and Van Pelt, 2007). Leaf masses ranged from nearly 16 to over 31 Mg ha⁻¹ with seven plots having >20 Mg ha⁻¹ of *Sequoia* leaves (Appendix O). Vertical distribution of leaf mass showed similar distribution patterns with peaks in leaf mass generally occurring at 50–70% of hₘₐₓ (Fig. 7). Despite differences in total leaf mass, the peak 5 m height interval was similar among plots with values generally 2–2.5 Mg ha⁻¹. HR was the only plot with any *Sequoia* 5 m band exceeding 2.8 Mg ha⁻¹, and it had three – all adjacent and totaling 9.4 Mg ha⁻¹ from 70 to 85 m. HR and MW had the highest total *Sequoia* leaf mass (25.7 and 24.9 Mg ha⁻¹), while simultaneously having the lowest non-*Sequoia* leaf mass (0.3 and 0.7 Mg ha⁻¹). The highest all-species total leaf mass, however, occurred in JS-up (31.4 Mg ha⁻¹), which also had the highest non-*Sequoia* contribution to leaf mass (11.2 Mg ha⁻¹, Fig. 7, Fig. 8 top). The understory fern *Polystichum* had the highest non-*Sequoia* leaf mass of any species, especially in the six rainforest plots, where leaf mass averaged 2.9 Mg ha⁻¹ with a maximum of 5.1 Mg ha⁻¹ (JS-up). After *Polystichum*, Tsuga had the next largest contribution to non-*Sequoia* leaf mass. It was present only in the six rainforest plots (mean 1.3 Mg ha⁻¹) and reached a maximum of 2.6 Mg ha⁻¹ (JS-up). A large and old population of *V. ovatum* occurred in JS-up as well, which included 30 plants >10 cm basal diameter per hectare, and added 2.3 Mg ha⁻¹ of leaf mass. Bryophytes growing on the forest floor, logs, and tree bases were also abundant in rainforest plots, where three of the four northernmost plots had bryophyte dry masses >200 kg ha⁻¹ (Appendix O).

Overall plot-level LAI ranged from 9.9 to 19.4 with the eight northern plots all having LAI > 15.8 (Fig. 8 bottom). All eight of the northern plots had *Sequoia* LAI > 11, with the two tallest plots (HR, MW) having *Sequoia* LAI > 14 (Fig. 8 bottom). Total conifer LAI reached 15.9 in one plot (RNP-up), and >13.0 in six plots. *Polystichum* contributed substantially to leaf area in the six rainforest plots, four of which had LAI > 2.4 from this fern alone. *Oxalis*, which was abundant on the forest floor in all but one plot (SPT) and had 25–50% ground cover in five of the plots, contributed up to 1.3 LAI. Plot-level proportions of total leaf mass and area were similar (Fig. 8). The largest difference involved the herbaceous category and the presence of *Oxalis*, whose extremely thin leaves had SLA values 3–10 times higher than other species.

Dead wood mass in standing snags varied by more than an order of magnitude from 22 Mg ha⁻¹ at the southernmost plot (LH) to nearly 300 Mg ha⁻¹ at RNP-up (Table 5). While *Sequoia* comprised >95% of snag mass in eight plots, one plot (SPT) had 47.5 Mg ha⁻¹ of dead *Pseudotsuga* and only 13.1 Mg ha⁻¹ of dead *Sequoia*. PC-low also had a substantial standing dead *Pseudotsuga* component (34.7 Mg ha⁻¹), and nearly all of the 64.4 Mg ha⁻¹ of *Sequoia* snag mass in this plot was contributed by one large individual. A huge two-trunked snag in another plot (RNP-up) with both portions >70 m tall and an individual dry mass of 195.7 Mg contributed the majority of total snag mass in that plot (295 Mg). Log mass was also variable with two of the fire-prone southern plots having <100 Mg ha⁻¹. Three of the rainforest plots had log masses >500 Mg ha⁻¹ with the maximum (608.5 Mg ha⁻¹) consisting of >99% *Sequoia* heartwood (Table 5). This plot (PC-up) included bases and portions of eight fallen, non-hollow trees >250 cm f-DBH with the largest single piece (within plot boundaries) having a dry mass of 84.2 Mg. Log abundance depicted in Fig. 6 may appear that trees fall over frequently in the northern plots, but most of this material was decay-resistant heartwood from many centuries of accumulation and very little was newly fallen material in Decay 1 (Table 5). Despite idiosyncrasies of snag and log occurrence among the 11 plots, the precipitation gradient (800–2200 mm) explained 80% of variation in total dead wood mass.

Total aboveground dead mass exceeded 5000 Mg ha⁻¹ in one plot and was >4000 Mg ha⁻¹ in seven of the eight northern plots (Fig. 9). *Sequoia* heartwood contributed the bulk of this mass, ranging from 61.5% (SPT) to 76.7% (JS-low) of plot totals. Seven plots had *Sequoia* heartwood mass >3000 Mg ha⁻¹ (mean 3250 Mg ha⁻¹ in rainforest plots) with the highest (3890 Mg ha⁻¹) occurring in the wettest two plots (JS). Non-*Sequoia* contributions (two blue categories in Fig. 9) were <5% in eight of 11 plots with one plot (BB) reaching 13.3%. In terms of total aboveground carbon, all but one of the eight northern plots had >2000 Mg ha⁻¹ of carbon with the two northernmost and wettest plots (JS) having the highest (mean 2530 Mg ha⁻¹ of carbon, Table 6). *Sequoia* bark alone contained more carbon than all other species combined in every plot except BB. *Sequoia* heartwood in snags, logs, and live trees was the primary reservoir of long-term carbon storage, and seven plots had at least 1500 Mg ha⁻¹ of carbon in *Sequoia* heartwood with the two JS plots having the highest (mean 1930 Mg ha⁻¹). *Sequoia* heartwood percentages of total carbon ranged from just over 60% in dry, southern plots to nearly 80% in northern, rainforest plots.
Table 4
Tree characteristics by plot. Data are from the tagged population of trees only. Basal area and maximum diameter (Max D) were calculated from DBH (see text). Values in red are global maxima.

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<th>Basal area (m²)</th>
<th>Max D (cm)</th>
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3.3. Centerline analysis of leaf area

When viewed on a meter-by-meter basis, leaf area distribution was extremely variable with dramatic spikes caused by emergent trees (Fig. 10 – darkest red colors). The 1-m-wide sample passed through several canopy gaps >15 m wide, but small gaps between large tree crowns were common, especially in the northernmost plots. Individual trees or tree clusters could carry immense leaf area – some individual m² cells exceeded an LAI of 30 – but were often separated by gaps extending to the ground. Also apparent (especially in rainforest plots) was the abundance of *Oxalis* and *Polystichum* in the understory. Emergent crowns were evident in most plots and most obvious at JS-up. While the centerline summary statistics in Fig. 10 represented only a 1-m-wide sample,
mean centerline LAI was similar to plot-level LAI (Appendix O) with exception of BB, whose centerline passed through some large canopy gaps.

3.4. Detecting LUC with emergent crown indices

3.4.1. Plot-level metrics

The plot with 26 TPH > 300 cm f-DBH (JS-up) had the highest mean crown mass (Index 1) at 5.3 Mg, and PC-low was the only other plot to have mean crown mass >3.5 Mg (4.8 Mg - Table 7). Even though all trees <20 cm f-DBH were removed before this analysis, the mean crown mass for five of the plots was <1 Mg. Standard deviation of crown volume (Index 2) was highest in PC-low, which had 7 trees with crown volumes of 15,000 m$^3$ or more, two of which were >25,000 m$^3$. RNP-up was the only other plot with individual crown volumes >20,000 m$^3$ ($N = 2$ trees).

3.4.2. Individual tree metrics

When sorted by leaf area, the median crown mass (Index 3) was highest in two rainforest plots (JS-up, PC-low) at >10 Mg. The
skewness of this index was indicated by the next two highest plots having median crown masses of only 5–6 Mg and all remaining plots having median crown masses <3 Mg (Table 7). The same two rainforests (JS-up, PC-low) were the only plots where <15 trees were needed to reach half of plot-level LAI (Index 4).

3.4.3. Centerline variation
The SD of Sequoia LAI (Index 5), whose values were similar to means, had a maximum SD occurring at JS-up (13.9). Only JS-up and BB had SD greater than the mean. In JS-up, this was caused by regular spacing of 100 Mg trees with gaps in between. In BB this was caused by four dense clusters of trees separated by large gaps or Pseudotsuga. Another plot with SD of Sequoia LAI > 12.0 was RNP-low, which had 13 peaks with >30 LAI and two large gaps.

3.4.4. LiDAR metrics
Index 6 used tree-tree distances generated by Thiessen polygons for all crowns at 0.75 $h_{\text{max}}$. This was the only index where RNP-up scored higher than PC-low. Both plots were similar with few but very large, widely spaced polygons. This was also the only index where one of the southern plots scored high. The BB plot was more open than the others, but it also had trees with (relatively) large crowns, including contributions from nine mature Pseudotsuga. Index 7 was based on how many crowns contributed to the cross-sectional area at 0.75 $h_{\text{max}}$ and three plots (JS-up, PC-low, RNP-up) had mean emergent crown areas >70 m² with the maximum (92.8 m²) occurring at PC-low. Remarkably, at 76 m above the ground, PC-low had 26 trees within a single hectare that had a mean crown diameter of 10.9 m.

3.4.5. Emergent Crown Index (ECI)
All seven indices comprising the ECI were positively and significantly ($P < 0.017$) correlated with non-Sequoia, non-conifer, and understory LAI. Index 1 (mean crown mass) and Index 4 (# of trees to reach $\frac{1}{2}$ LAI) had the strongest relationship to non-Sequoia LAI (Table 7). However, ECI itself was the strongest correlate of all possible combinations of component indices. PC-low had the highest ECI (0.94), ranked highest on three of the seven indices, and ranked second–highest on three others. Similarly, JS-up had a very high ECI (0.90) and also ranked highest on three of the indices. Both plots had very large trees that were widely spaced – of 30 trees with the highest leaf mass among 11 plots, 16 were from PC-low and JS-up.

3.5. Demonstrating LUC using structural ensembles
The five structural ensembles occupied 85% of centerline distance (2671 m out of 3146 m total) using a 30-m-diameter moving window (Fig. 11). Based strictly on this classification, 116 different contiguous units of the five ensembles were identified,
Table 5
Summary of dead wood by log and snag categories. All values in Mg ha\(^{-1}\). Note modest values for Decay I Sequoia, which are fallen trees from recent decades. Values in red are global maxima.

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<th>JS-up</th>
<th>JS-low</th>
<th>PC-up</th>
<th>PC-low</th>
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<th>RNP-low</th>
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<th>MW</th>
<th>SPT</th>
<th>BB</th>
<th>LH</th>
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LOGS

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LOG TOTAL

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Sequoia sempervirens

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SNAG TOTAL

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Sequoia sempervirens

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</tbody>
</table>
ranging up to a single Codominant Canopy ensemble over 180 m long (HR). From the RH–CHM (which was scaled by trees >100 m tall in 7 of the 11 plots), the emergent nature of tree crowns was apparent, where spaces between trees often extended to the ground (Fig. 11). Unclassified sections were either unique or transitional between ensembles. A total of 15 Canopy Gap ensembles, occupying 285 m of centerline distance were large enough to be detected in eight plots and naturally had the lowest Sequoia LAI (1.2) and lowest total LAI (5.6) among ensembles (Table 8). The Canopy Gap ensemble had the highest deciduous LAI (0.6), containing the highest proportion of shade-intolerant species (Fig. 12).

Shared Dominance had a modest Sequoia LAI (4.7) but high contributions from other trees – Notholithocarpus, Pseudotsuga, and Tsuga (mean LAI = 6.0). Other non-Sequoia LAI was notable, including Ericaceae (0.8) and ferns (0.6). Total non-Sequoia LAI was 7.9, the highest of any ensemble (Fig. 12).

The three Sequoia-dominated ensembles were similar in that all had very high Sequoia LAI (mean 12.4), but they differed greatly in the sizes of contributing trees (Fig. 12). Apart from the size of trees contributing to the total, leaf areas between Emerging and Codominant Canopy ensembles were quite similar. In both cases, dense aggregations of Sequoia crowns kept non-Sequoia LAI to a minimum (mean 2.23), which was lower than the other ensembles. Of this, >90% consisted of the very shade-tolerant Oxalis and Polytrichum.

Emergent Crowns had the highest total, highest Sequoia, and second highest non-Sequoia LAI as well as the highest contribution from large Sequoia (Table 8, Fig. 12). Emergent Sequoia crowns held enormous leaf areas, and most of the Sequoia LAI total came from trees >100 Mg. Simultaneously, 22% of the ensemble included RH–CHM values from the bottom three 5 m vertical tiers, which included a substantial non-Sequoia leaf area (LAI = 4.1) and the second highest deciduous LAI (0.2).

4. Discussion

We identified global maximum live biomass, leaf area, and total aboveground carbon by intensively measuring tall Sequoia forests across the range of the species in California. Our approach involved detailed plot work, hierarchical measurements, and stratified random sampling to generate equations for each species spanning the full size range of individuals in these forests. Spatially explicit application of allometric equations to quantify within-plot distributions of biomass and leaf area allowed us to perform structural analyses yielding strong support for light-use-complementarity (LUC – Ishii et al., 2013) in Sequoia forests with a basis in crown optimization and emergent facilitation.

4.1. Does emergent facilitation lead to LUC in Sequoia forests?

At the plot level, LUC is detectable using the Emergent Crown Index (ECI) and even more strongly by an analysis of structural ensembles. These findings coalesce around an ecological phenomenon whereby without stand-replacing disturbance, live biomass, leaf area, and aboveground carbon increase asymptotically over time through the development of emergent trees with deep crowns. Maxima in old-growth Sequoia forests occur in the oldest and most complex forests – a concept divergent from forest development models characterized by a peak and eventual decline of these variables over time (Coomes et al., 2012; Xu et al., 2012; Foster et al., 2014).

The highest values ever recorded for biomass (5190 Mg ha−1), leaf area (LAI = 19.4), and aboveground carbon (2600 Mg ha−1) occur in the same forest. This plot (JS-up) exemplifies emergent facilitation better than any other, as the Emergent Crowns ensemble occupies over half of the centerline length. Interestingly, this plot is in the only ocean-facing drainage within the wettest location throughout the range of Sequoia. While live Sequoia biomass is only slightly higher than that found in several other plots, large contributions to leaf area from other species (LAI = 8.0) are possible because of the organization of biomass into emergent trees. The additional leaf area from other species is equivalent to or exceeds the maximum in many of the world’s forests (Asner et al., 2003), yet it occurs beneath the heaviest canopy on Earth.

Our results highlight important contributions of large trees to forest structure. Hinting at a possible universal pattern of forest structure, total biomass of Central African forests is well predicted by considering only the largest 5% of the trees (Bastin et al., 2015). Using only the largest trees is a novel approach to estimate the historically difficult metric of biomass. This method relates to emergent facilitation because the largest trees not only have the most mass, but also their spatial distribution provides the most information about how much light can penetrate the forest. Applying the Bastin et al. (2015) approach to tall Sequoia forests produces...
markedly accurate results. For example, basal area of the 20 largest trees in each plot explains 92% of the variation in total live biomass and 69% of the variation in understory leaf area.

Crown optimization allows Sequoia to undergo a developmental trajectory whereby phenotypic plasticity of leaf form, foliage aggregation at multiple scales, and regrowth of damaged crowns operate together to maximize leaf area within individual crowns (Monsi and Saeki, 1953; Ishii and Asano, 2010, and Ishii et al., 2013). Other high leaf area forests are tall, conifer-dominated, and include trees with deep crowns (Leverenz and Hinckley, 1990). Because Sequoia is the tallest species and possesses decay-resistant heartwood, there are abundant opportunities for many trees to become emergent. The emergent trees we crown-mapped are >1100 years old and have complex crowns indicating previous damage and regrowth (Fig. 2). The largest and oldest of these trees are also among the fastest growing (Sillett et al., 2015a). Provided an individual Sequoia survives the ravages of fire and storms, development of an emergent tree may be inevitable.

When Sequoia trees first reach the upper canopy, they are still relatively young – 90 m trees can be completely model-conforming and without complex structure (Sillett and Van Pelt, 2007). They can then persist for millennia, not only repairing crown damage but also growing far larger. Within the classification of the eco-unit (Oldeman, 1990), a new structural ensemble appears – one where trees of the present have grown beyond to become emergent crowns of the future. During the long and variable process of becoming emergent, Sequoia trees often differ greatly in age from neighboring emergent trees. However, collectively they form a structural cohort known as the Emergent Crowns ensemble, containing the largest trees in the forest, which may or may not retain the original eco-unit boundary.

Identifying structural ensembles in Sequoia forests improves our ability to detect LLC beyond the plot-level metric of ECI. In this investigation, moving windows scaled to include trees adjacent to an emergent Sequoia define the minimum ensemble size. Depending on forest structure and species composition, ensembles can be large and persistent in old-growth forests (Fig. 11), and in younger forests such as plantations can be quite extensive (Oldeman, 1990). We suggest that moving window analyses in other forests use a search radius scaled by tree species and structural complexity to detect ensembles. Because Sequoia forests are so tall, it was relatively easy for us to detect the uppermost structural ensembles using LiDAR and to define five structural ensembles. In other forests, fewer ensembles may be detectable remotely, depending on the complexity of forest structure and resolution of the LiDAR point cloud.

Based on our experience in other tall forests that have emergent trees (P. sitchensis, P. menziesii, S. giganteum, and Eucalyptus regnans), detecting emergent trees using 0.75 h_{max} of the LiDAR canopy height model should also work well, since these forests can all develop similar old-growth structure (Franklin and Van Pelt, 2007). In shorter old-growth forests, emergent trees may be absent or if present may be wider, but only slightly taller, than neighboring trees (e.g., Amazonian rainforests, Appalachian Mountain cove forests), and a different h_{max} value may be more useful.

Just as an emergent Sequoia represents a developmental maximum at the scale of the tree, the Emergent Crowns ensemble represents a developmental maximum at the scale of the forest. Small-scale disturbances reset structure to Canopy Gap or Emerging Canopy ensembles, but natural developmental patterns inevitably guide structure toward one dominated by emergent trees (Fig. 13). Larger disturbances such as wildfire and wind throw revert forests to an earlier developmental stage, while smaller disturbances work to maintain the structural ensembles defined here. The Sequoia silvatic mosaic is a slowly shifting assemblage of eco-units, defined by relatively small-scales disturbances and
regrowth over millennia. As these forests develop, crown optimization ensures progression toward the Emergent Crowns ensemble, which dominates six of our eleven plots. Codominant Canopy is the next most abundant ensemble and is not reflective of a disturbance (Canopy Gap) or recovery state (Emerging Canopy). Many Codominant Canopy ensembles have trees >1000 years old indicating that this ensemble not only takes centuries to form, but it also takes centuries for gap formation and subsequent crown optimization to progress toward the Emergent Crowns ensemble.

Within the old-growth Sequoia silvatic mosaic, the two most common single-tree or small group mortality events are burning in a fire or toppling from wind (Fig. 13). Even within rainforest portions of the range, fire is an important component of Sequoia forests, as large trees nearly always have charcoal on their bark, often visible well up into the crown of the tree (Brown and Swetnam, 1994; Sillett et al., 2015a). While it is unusual to see large individuals killed by fire, burn cavities at the bases of large trees are frequent in northern rainforests and nearly ubiquitous in drier southern forests. If trees are not killed, abundant sprouts (i.e., reiterated trunks) often emerge around tree bases after fire (Jameson and Robards, 2007). Multiple fires create different cohorts of sprouts, which can ultimately lead to development of tree castles – circular formations of successively larger stems leading into the central and largest trunk (Fig. 13). In such cases, charcoal is often present on the bark of all but the youngest cohort. Our southernmost plot (LH) is in a mixture of forest and chaparral, where fire is frequent. The most recent fires in this forest (1977,
<table>
<thead>
<tr>
<th>Plot</th>
<th>Site</th>
<th>Plot level metrics</th>
<th>Individual tree metrics</th>
<th>Centerline variation</th>
<th>LiDAR detection – crowns at 0.75 ( h_{\text{max}} ) CHM</th>
<th>ECI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Crown mass (kg)</td>
<td>Crown volume (m(^3))</td>
<td>Median tree at 1/2 LAI</td>
<td># trees to reach 1/2 LAI</td>
<td>Mean Index 1 SD Index 2</td>
</tr>
<tr>
<td>JS-up</td>
<td>1</td>
<td>5350 1.00 4205 0.74</td>
<td>10,191 1.00 14.0 1.17 0.86</td>
<td>13.88 1.00 21.26 0.91 2647 71.5</td>
<td>21.26 0.91 2647 71.5</td>
<td>0.90</td>
</tr>
<tr>
<td>JS-low</td>
<td>2</td>
<td>3304 0.62 3986 0.63</td>
<td>5661 0.56 16.3 1.36 0.74</td>
<td>9.59 0.69</td>
<td>9.59 0.69</td>
<td>0.68</td>
</tr>
<tr>
<td>PC-up</td>
<td>3</td>
<td>1468 0.27 3217 0.56</td>
<td>5661 0.56 16.3 1.36 0.74</td>
<td>10.38 0.75</td>
<td>10.38 0.75</td>
<td>0.55</td>
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<tr>
<td>PC-low</td>
<td>4</td>
<td>4791 0.90 5713 1.00</td>
<td>10,099 0.99 12.0 1.00 1.00</td>
<td>10.53 0.76</td>
<td>10.53 0.76</td>
<td>0.50</td>
</tr>
<tr>
<td>RNP-up</td>
<td>5</td>
<td>2369 0.44 4722 0.83</td>
<td>5067 0.50 16.7 1.39 0.72</td>
<td>8.21 0.59</td>
<td>8.21 0.59</td>
<td>0.70</td>
</tr>
<tr>
<td>RNP-low</td>
<td>6</td>
<td>891 0.17 2622 0.46</td>
<td>1496 0.15 24.0 2.00 0.50</td>
<td>12.15 0.87</td>
<td>12.15 0.87</td>
<td>0.70</td>
</tr>
<tr>
<td>HR</td>
<td>7</td>
<td>1154 0.22 3016 0.53</td>
<td>2839 0.28 24.5 2.05 0.49</td>
<td>8.10 0.58</td>
<td>8.10 0.58</td>
<td>0.50</td>
</tr>
<tr>
<td>MW</td>
<td>8</td>
<td>888 0.17 2559 0.45</td>
<td>2367 0.23 25.4 2.12 0.47</td>
<td>8.93 0.64</td>
<td>8.93 0.64</td>
<td>0.48</td>
</tr>
<tr>
<td>SPT</td>
<td>9</td>
<td>862 0.16 2318 0.41</td>
<td>1252 0.12 22.4 1.87 0.53</td>
<td>5.82 0.42</td>
<td>5.82 0.42</td>
<td>0.45</td>
</tr>
<tr>
<td>BB</td>
<td>10</td>
<td>857 0.16 2585 0.45</td>
<td>1742 0.17 18.3 1.53 0.66</td>
<td>9.39 0.68</td>
<td>9.39 0.68</td>
<td>0.39</td>
</tr>
<tr>
<td>LH</td>
<td>11</td>
<td>263 0.05 1388 0.24</td>
<td>364 0.04 37.8 3.15 0.32</td>
<td>8.41 0.61</td>
<td>8.41 0.61</td>
<td>0.33</td>
</tr>
<tr>
<td>R² with non-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sequoia LAI</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**Table 7**
Emergent Crown Index (ECI). Seven structural metrics, all derived from either plot inventory, centerline analysis, or analysis of the LiDAR canopy height model. Values in bold represent the index maximum, and those in italics the 2nd highest. All R² have \( P \)-values <0.017.
Fig. 11. RH–CHM maps for 11 plots. Analysis consisted of sampling 30-m-diameter moving window (white ring in upper left). Colored strip below each represents meter-by-meter classification of structural ensembles. The 15% unclassified ensembles (gray) were unique structurally or transitional between neighboring ensembles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
1985, 1999, 2008) all started by lightning (Rowntree, 2009). In general, the hottest portions of these burns exhibit severe fire effects on the vegetation including mortality of *Sequoia*. However, like most of the chaparral plants sympatric with *Sequoia* in this area, sprouting from lignotubers at the base usually follows death of aboveground parts (Hanes, 1971; Farjon, 2005). Genetic individuals may persist below ground, but frequent fire limits longevity, making trees >1000 years extremely rare in southern *Sequoia* forests.

The most common way large *Sequoia* die is through toppling (Fig. 13). Winter is the wettest and windiest time of year and brings normal winter storms as well as periodic atmospheric rivers. The latter originate from tropical cyclones and bring tremendous amounts of rain and high winds over a short time and are responsible for the most extreme events along the west coast of North America (Waring and Franklin, 1979; Henderson et al., 1989; Zhu and Newell, 1998; Ralph et al., 2004). With tall trees commonly carrying 100–200 Mg of biomass or more, high winds combined with saturated soils can cause tilting of trees. For trees that become as tall, large, and old as *Sequoia*, even a slight lean only gets worse. Partial crown damage as well as snapping of the upper stem occur during such events, but large *Sequoia* trees that topple from their base expose roots and mineral soil. Toppling of large trees is uncommon but is nearly always predisposed by lean (R. Van Pelt and S. C. Sillett, personal observations). Root decay is often a precursor to toppling with many Pacific Northwest tree species (Spies et al., 1990; Bible, 2001; Franklin et al., 2002; Van Pelt, 2007) but much less so with *Sequoia*, so when whole trees fall there is usually a large root-plate still intact (Boe, 1966 – Fig. 6 shows several >5 m wide).

Table 8

<table>
<thead>
<tr>
<th>Canopy gap</th>
<th>Shared dominance</th>
<th>Emerging canopy</th>
<th>Codominant canopy</th>
<th>Emergent crowns</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Sequoia</em> &gt;100 Mg</td>
<td>0.15 ± 0.09</td>
<td>2.39 ± 0.49</td>
<td>0.00 ± 0.00</td>
<td>2.52 ± 0.67</td>
</tr>
<tr>
<td>10–100 Mg</td>
<td>0.41 ± 0.21</td>
<td>1.37 ± 0.24</td>
<td>9.00 ± 1.04</td>
<td>8.15 ± 0.70</td>
</tr>
<tr>
<td>&lt;10 Mg</td>
<td>0.64 ± 0.54</td>
<td>1.81 ± 0.59</td>
<td>2.37 ± 1.20</td>
<td>0.98 ± 0.16</td>
</tr>
<tr>
<td>&lt;20 cm</td>
<td>0.54 ± 0.48</td>
<td>0.24 ± 0.06</td>
<td>0.08 ± 0.05</td>
<td>0.38 ± 0.09</td>
</tr>
<tr>
<td><em>Sequoia</em> total</td>
<td>1.74 ± 1.32 a</td>
<td>4.81 ± 1.37 a</td>
<td>11.45 ± 2.29 b</td>
<td>12.04 ± 1.62 b</td>
</tr>
<tr>
<td>Pinaceae</td>
<td>0.49 ± 0.55</td>
<td>4.98 ± 0.59</td>
<td>0.12 ± 0.20</td>
<td>0.00 ± 0.02</td>
</tr>
<tr>
<td>Deciduous</td>
<td>0.59 ± 0.12</td>
<td>0.02 ± 0.12</td>
<td>0.12 ± 0.21</td>
<td>0.03 ± 0.15</td>
</tr>
<tr>
<td>Evergreen</td>
<td>2.76 ± 0.10</td>
<td>2.94 ± 0.08</td>
<td>2.12 ± 0.92</td>
<td>2.07 ± 0.78</td>
</tr>
<tr>
<td>Non-<em>Sequoia</em> total</td>
<td>3.84 ± 0.77 c</td>
<td>7.94 ± 0.79 d</td>
<td>2.36 ± 1.33 c</td>
<td>2.10 ± 0.94 c</td>
</tr>
<tr>
<td>Total LAI</td>
<td>5.58 ± 2.09 e</td>
<td>12.75 ± 2.16 f</td>
<td>13.81 ± 3.62 fg</td>
<td>14.14 ± 2.56 fg</td>
</tr>
</tbody>
</table>

Fig. 12. Leaf area within structural ensembles. Values are means from all sites combined – black values above bars are all species LAI, and yellow values within bars are *Sequoia* only. Top panel shows Emergent Crowns had highest *Sequoia* LAI while simultaneously having relatively high LAI in all three non-*Sequoia* categories. Note that more than half of *Sequoia* LAI in Emergent Crowns came from trees >100 Mg. Bottom panel shows mean RH–CHM values for each ensemble. Note that Emergent Crowns was the only ensemble to have >3.5% represented in all ten height bands. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Dominance ensemble, the forest is in a transitional state where replacement of dead *Sequoia* by younger *Sequoia* is slow. In the southern plots, most of the Shared Dominance ensembles are associated with *Pseudotsuga* and *Notholithocarpus*. Both species do well after fire by either reseeding or basal sprouting, respectively, so are common associates of *Sequoia* in drier forests. Both can be locally dominant in small patches, but in many cases the eco-unit will eventually return to a *Sequoia*-dominated ensemble by virtue of its reiterative capacity, shade tolerance, and longevity. Despite each plot being located in a tall, old-growth forest, along the 316 m length there are naturally edaphic conditions where *Sequoia*-dominance may never be realized, including knolls and steep slopes where other species will probably always be significant contributors. These areas become much more abundant in the greater silvatic mosaic, so structural ensemble criteria would be altered to address shorter canopies of forests on upper slopes and ridges, even within *Sequoia*-dominated landscapes.

4.2. Are emergent trees essential to achieving maximum leaf area?

*Sequoia* forests eventually reach a stage of structural development where very high leaf area is maintained in perpetuity, an idea...
that has long been debated (Fritz, 1932; Roy, 1966). Our findings are contrary to widely accepted models of forest development that suggest leaf area peaks shortly after canopy closure and then slowly declines (Gower et al., 1996; Ryan et al., 1997; Binkley et al., 2002) or quickly reaches a peak and remains relatively constant thereafter (Turner and Long, 1975; Long and Smith, 1992). However, we acknowledge that leaf area is extremely difficult to quantify accurately at the plot level, no matter what techniques are used – especially in tall conifer forests (Chen and Cihlar, 1995; Bréda, 2003).

Maximum canopy occupancy occurs during the canopy closure phase of forest development, because afterwards small-scale gaps from fallen and dead trees, as well as tree-to-tree abrasion, allow light to penetrate between crowns (Putz et al., 1984; Long and Smith, 1992; Franklin et al., 2002). Consequently, maximum canopy occupancy has often been identified by a lack of understory and used to indicate that all available light is being used by overstory tree species and that a forest has attained maximum leaf area. Moving from a two-dimensional view to three dimensions, and considering penumbral effects and crown optimization, taller forests are always able to support more leaves than shorter ones (Kira and Shidei, 1967; Horn, 1971; Waring, 1983). In many instances differences in leaf area between forests with closed canopies and tall old-growth forests are small – frequently smaller than the error bars surrounding plot-level leaf area estimates. For example, a fully-stocked 21-year-old Sequoia plantation on the same floodplain as our HR plot (Sequoia LAI = 14.5) has nearly identical leaf area (LAI = 14.3 – O’Hara et al., 2007). In the plantation, canopy occupancy is at a maximum suggesting that leaf area is probably near the upper limit for Sequoia. Sequoia plantations have such dense canopies that full shade (umbra) reaches the ground and thus not enough light remains to support an understory. The HR plot, which is dominated by the Codominant Canopy ensemble, has a remarkable 37 TPH > 90 m tall, leaving only 11.2% open space at 70 m above the ground. This plot has the lowest understory leaf area among our eleven plots, but in contrast to the plantation enough penumbral light is available near ground level to support an understory LAI of 1.8, some of which is Sequoia regeneration (LAI = 0.6). Thus, both forests have extremely high Sequoia leaf area, but the taller forest has higher light availability at ground level, providing an increase in both species diversity and total leaf area. By building emergent trees, Sequoia leaf area remains high while light penetration through the canopy vastly increases.

Rainforest plots have by far the most massive understories and none more than the three plots in drainages exposed to the ocean (JS-up, PC-up, and PC-low). These plots have consistently higher understory leaf areas (mean LAI = 4.9) than the three rainforest plots sheltered behind ridges (mean LAI = 2.6). While we do not have detailed data on cloud or fog cover for our plots, ocean-facing drainages tend to have less annual sunshine than those behind ridges as a consequence of coastal fog in California facing drainages tend to have less annual sunshine than those behind ridges as a consequence of coastal fog in California (Filonczuk et al., 1995; O’Brien et al., 2013; USGS, 2015). In cloudy environments, the umbrella behind an object is diminished, allowing leaf layers to be closer than in sunny environments (Horn, 1971). Understories of Sequoia rainforests are compositionally similar with dominance switching between V. ovatum and P. menziesii (and to a lesser extent B. spicant) – Vaccinium growing on accumulated rotten wood and ferns growing elsewhere. V. ovatum has dense evergreen leaves, which are small (1–2 cm diameter), while fern fronds can be quite large (>2 m long). However, Polystichum and Blechnum fronds are divided into pinna at ~1-cm spacing, which collectively create a light environment similar to that beneath small leaves. In cloudy or foggy conditions, frond pinnae are ideally spaced to avoid creating an umbra for subtending pinnae. These three understory species efficiently capture penumbral light. A fourth species, the diminutive and shade-tolerant Oxalis is generally found under the shrubs and ferns to capture any remaining light. These four species are in large part responsible for the high non-Sequoia leaf area in rainforest plots, providing 82–95% of the understory total.

4.3. How do aboveground carbon and abundance of dead wood vary across old-growth Sequoia forests in California?

The eight northern plots have total aboveground carbon contents >2000 Mg ha−1, which is nearly twice that reported for any other forest type (Franklin and Waring, 1980; Keith et al., 2014; Sillett et al., 2015b). What makes this situation even more extreme is that 63–77% of the carbon is embedded in decay-resistant Sequoia heartwood. Within the rainforest part of the range, the wet environment, coupled with the infrequency and patchiness of fires, allows heartwood to accumulate and persist for centuries. Fine woody debris and forest floor litter were not sampled in this study, but this material was sampled in nearby forests covering the area of our 7 northernmost plots (Graham, 2009) and contributes another 30–60 Mg ha−1 dry mass (Appendix P).

Maximum carbon sequestration occurs in forests combining exceptionally productivity (Waring and Franklin, 1979; Larjavaara and Muller-Landau, 2011) and carbon storage in dead wood (Harmon, 2001; Luysaert et al., 2008). In dry or otherwise fire-prone areas where dead wood is consumed by fire, or where logs quickly decay between a combination of saturation under winter snowpack and desiccation during hot summers, nearly all aboveground carbon exists in live trees. Carbon storage in these forests depends on tree longevity, or time until the next major disturbance perturbs the tree population (Zhang et al., 2010; North and Hurteau, 2011). In wet forests, where saturated logs resist decay and infrequent fires often lack ability to combat large logs, dead wood represents a quarter to nearly half of aboveground carbon mass (Grier and Logan, 1977; Harmon et al., 2004). Like our rainforest plots with dead wood masses approaching 400 Mg ha−1 of carbon, nearly all other dead wood masses >250 Mg ha−1 of carbon come from either temperate rainforests in the Pacific Northwest (Grier et al., 1981; Agee and Huff, 1987; Keenan et al., 1993; Smithwick et al., 2002) or Tasmania (Dean et al., 2003; Keith et al., 2009; Moroni et al., 2010). Another high value is from a 2290 Mg ha−1 Agathis australis–dominated rainforest in subtropical New Zealand, where 225 Mg ha−1 of carbon is dead wood (Silverster and Orchard, 1999).

Critical considerations for residence time of forest carbon are the amount, size, and composition of dead wood inputs as well as fire regime (Spies et al., 1988; Agee, 1993; Harmon, 2001). These factors explain the increasing ability of Sequoia forests to store carbon as one moves north along coastal California’s precipitation gradient. Large-diameter logs of P. menziesii commonly persist for at least two centuries in old-growth rainforests (Sollins et al., 1987; Spies et al., 1988) and sometimes for over four (Franklin et al., 1981). Radiocarbon dating reveals that T. plicata can persist as logs for at least 1300 years due to decay-resistant heartwood (Daniels et al., 1997). Like Thuja, heartwood produced by other members of the Cupressaceae is decay-resistant (Clark and Scheffer, 1983; Farjon, 2005), and they produce persistent logs in their respective rainforests around the Pacific Rim (Andrews, 1983; Feller, 2003; Keith et al., 2009). Since Sequoia is not succeeded by other species and has the most decay-resistant wood in the region, the greatest accumulations of dead wood come from forests with the largest trees. These inputs take the form of large logs composed mostly of decay-resistant heartwood favoring long carbon residence time.

Carbon losses from forest ecosystems primarily come from decomposition and fire. Both sources of loss decrease from south to north along the California coast. Carbon gains related to productivity in temperate forests are controlled chiefly by precipitation
which share many aspects of emergent facilitation with decay more readily than In both forest types, the dominant trees are attacked by fungal time.

vant, and biomass and leaf area may continue to accumulate over greater than the age of its oldest trees, forest age becomes irrele-

turbances (Fritz, 1957; Veblen and Ashton, 1982; Kojo, 1987; et al., 2015a). Even with trees so old, the forests in which they grow can maintain dominance for centuries, and contribute to some of the highest non-Sequoia forest biomasses known (Van Pelt et al., 2004; Sillett et al., 2015b). In low-elevation rainforests of the Pacific Northwest, Pseudotsuga can maintain dominance for >500 years, by which time the few remaining individuals become emergent trees with enormous crowns (Van Pelt and Sillett, 2008) and plot-level biomass and leaf area reach a maximum (Franklin and Van Pelt, 2004). After 4–7 centuries, however, fungal decay is rampant (Franklin et al., 2002; Van Pelt, 2007) and without further disturbances to allow regeneration, emergent Pseudotsuga begin to collapse, which causes permanent reductions in canopy height, biomass, leaf area, and structural complexity as they are replaced by smaller, shade-tolerant species (Turner and Long, 1975; Franklin et al., 2002; Van Pelt and Nadkarni, 2004). A very similar scenario can be drawn for E. regnans, where without secondary disturbances, emergent trees eventually succumb to decay and are replaced by smaller shade-tolerant species with concurrent reductions in forest-level biomass and leaf area (Ashton, 2000; Wood et al., 2010; Tng et al., 2014).

In contrast, biomass of some forests may increase asymptoti-
cally toward a theoretical maximum. Primary forests in the wet tropics have continuous forest cover spanning generations of trees, such that the oldest living dominants established under forest conditions (Leigh et al., 1982; Brokaw, 1985; Oldeman, 1990; Clark and Clark, 1992). Developmentally similar temperate forests are dominated by Cupressaceae in wet coastal mountains around the Pacific Rim. Chamaecyparis, Cryptomeria, Cupressus, Fitzroya, Sequoia, Taiwania, and Thuja can all live >1500 years (Cader, 1995; Van Pelt, 2001; Farjon, 2005, 2008; Earle, 2015; Sillett et al., 2015a). Even with trees so old, the forests in which they grow may be much older because shade-tolerant individuals attain canopy dominant positions in the absence of stand-replacing dis-
turbances (Fritz, 1957; Veblen and Ashton, 1982; Kojo, 1987; Franklin et al., 1988; Enright and Hill, 1996; Farjon, 2005; Van Pelt, 2007; Lorimer et al., 2009). When the age of a forest is much greater than the age of its oldest trees, forest age becomes irrele-
vant, and biomass and leaf area may continue to accumulate over time.

Age-related declines in forest productivity are frequently reported (Bormann and Likens, 1979; Ryan et al., 1997), and since biomass increment is strongly related to leaf area (Sillett et al., 2015a,b; Koch et al., 2015), this implies declining leaf areas in old forests. Quantifying leaf area and productivity of forest plots is difficult, as the chronosequence approach often suffers from design considerations, and plot re-measurements often occur over relatively short intervals (Foster et al., 2014). Long-term research, however, has shown that this decline is not attributed to an age-related decline in tree-level productivity, but rather to changes in forest structure caused by mortality of large trees (Coomes et al., 2012; Xu et al., 2012). In these cases, limits on the longevity of individuals led to measured declines. In an example from northern Minnesota where tree rings were used to examine growth, an age-related decline was observed with an interesting exception. A low-productivity old-growth forest dominated by multi-cohort Quercus rubra containing a significant component of Thuja occidentals (Cupressaceae) exhibited an essentially asymptotic increase in biomass increment over time (Foster et al., 2014). In cases where the largest species in the forest can regenerate under forest conditions, aboveground biomass and leaf area may approach a theoretical maximum.

4.5. Conclusions

This is the first study to quantify the magnitude of aboveground biomass, leaf area, and carbon in Sequoia forests across the range of the species, whose grandeur has long captivated society. Our results provide an explanation of how established Sequoia forests achieve dimensions far beyond those of any other forest in the world and can continue to approach a theoretical maximum in per-
petuity. Sequoia forests excel at all of the key variables necessary for crown optimization – phenotypic plasticity of leaf form, tall structures on which to build emergent crowns, extremely decay-
resistant heartwood, and prolific capacity for reiteration, which permit recovery from crown damage and promote longevity. In addition, since Sequoia is not succeeded by other species, maxima in biomass, leaf area, and aboveground carbon are essentially asymptotic over time. Sequoia is unmatched in both the amount and type of carbon stored in old-growth forests. Because >95% of the original Sequoia forests have been cut at least once, manage-
ment of younger forests toward this goal will benefit from better predictions of biomass and leaf area. This study presents a snapshot of aboveground biomass, leaf area, and carbon in eleven plots based on a single, intensive field visit. We are also making five-
year re-measurements of every variable, including ground-based subsampling and within-crown measurements, to quantify above-
ground biomass increments and rates of carbon sequestration in these forests as well those dominated by Sequoia’s closest living relative, Sequoiadendron.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.foreco.2016.05.018.

References


COMPOSITION, INVASIBILITY, AND DIVERSITY IN COASTAL CALIFORNIA GRASSLANDS

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Abstract:

We present a detailed floristic study of coastal terrace prairies in central California that are poorly described in California’s ecological literature. Definitive native grasses include *Danthonia californica*, *Nassella pulchra*, and *Festuca rubra*. Definitive native forbs include *Baccharis pilularis*, *Viola*, *Sidalcea*, *Cammisonia* and *Acaena*. Species richness in the coastal prairies (1 m²) averaged 22.6, nearly twice that of relatively diverse serpentine California grasslands, and other North American grasslands. We sampled 33 coastal prairies and found 340 plant species including 258 forbs. Nearby plant communities (Monterey Pine, Coastal Scrub) had much lower species diversity at all spatial scales studied. Three distinct coastal grasslands, each associated with a land form, can be defined by distinct species composition; coastal terraces, uplifted “bald hills” and inland ridges. We compared 29 coastal terrace prairies (those without tree or shrubs) to 80 inland *Nassella* prairies with regard to 27 floristic variables (cover, number of natives/exotics, perennials/annuals, grasses/forbs) along a gradient from interior-coastal valley and from north to south along the coast. Coastal terrace prairies were invaded by exotics, but far less so than inland *Nassella* prairies. Species diversity (0.1 ha) and total cover were positively correlated. Relative cover of exotic species was negatively correlated with total cover, based on all sites. Number of exotic species was positively correlated with species richness in inland *Nassella* prairies but not coastal terrace prairies. Canonical correspondence analysis indicated that coastal terrace prairies with higher cover of non-native species had reduced total cover and/or reduced diversity of native perennial species of grasses and forbs. Native perennial grasslands, including coastal terrace prairies, are rare and have been eliminated by development.
along the narrow corridor of land between the sea and the inland ridges of central, coastal California. If protection of biodiversity is a management goal in land use plans, coastal grasslands should be protected as biodiversity “hotspots” with development focused in nearby relatively depauperate communities.
Introduction

Native perennial grasslands in California are among the most endangered ecosystems in the United States (Peters and Noss 1995). An area of approximately 7,000,000 ha (about 25% of the area of California) formerly in native grassland or foothill savanna, is now dominated by exotic grass species primarily of Mediterranean origin (Huenneke 1989). Typical annual grassland species include Bromus diandrus, B. mollis, B. rubens, Avena barbata, A. fatua, Erodium cicutarium, E. botrys and Vulpia myuros (Heady et al. 1988). Conversion to exotic annual vegetation was so fast, extensive, and complete that the original extent and species composition of most native perennial grasslands is unknown (Burcham 1957, Barry 1972, Keeley 1989, Heady et al. 1992, Holland and Keil 1995). Cover of exotics is often over 80% in this annual grassland vegetation type (Biswell 1956). Yet, small, isolated stands of native perennial grasslands still occur and these stands have been used to define “valley grassland” (White 1966b, 1967, Robinson 1971), presumably once dominated by Nassella (Heady et al. 1988). Extensive fragmentation of relict grasslands continues (Barry 1972) and even within protected natural areas, (Hastings, San Bruno Mountain, Jepson Prairie, Santa Rosa Plateau) relatively “pure” stands of native grasses occur in smaller, interior patches. Few studies have been published to describe the original grassland composition or that of presumed remnants. The widely held view that interior annual grasslands of California were originally dominated by perennial grasses (primarily Nassella) is based on limited evidence (Hamilton 1998). The view that succession proceeds in these interior grasslands to dominance by Nassella (Heady et al. 1988) is not supported by long-term studies (Stromberg and Griffin 1996) or a critical review of evidence (Hamilton 1998). Large areas of the interior “valley grassland” (Heady et al. 1988) may have been dominated by native, annual forbs (Schiffman 1994, Schiffman 2000). Identification of these rare, scattered patches of high biodiversity continues to be a critical activity for
conservation (Myers et al. 2000). GAP analysis and remote sensing serve as useful tool, but to identify the most important habitats at a finer geographic scale, we need intensive field surveys using classical methods, as presented here.

The purpose of this study is to demonstrate that California’s coastal grasslands are previously unrecognized biodiversity hotspots. We will do this by presenting patterns of diversity, describing major gradients in diversity within habitats and compare the coastal grasslands with other nearby habitats and other US grasslands.

California’s coastal grasslands are poorly described in the literature. “Coastal terrace prairie” has had widely varying interpretations. (Kuchler 1964) described “coastal grasslands” in a general way. Others have defined “north coast prairies” by listing dominant species that extend from the Mendocino coast south to Point Lobos (Heady et al. 1988). They described north coast prairies as being dominated by Festuca idahoensis, F. rubra and Danthonia californica; they used the term “coastal terrace prairie” to describe this community. “Northern coastal grassland community” with the same dominant grasses, as well as Calamagrostis nutkanensis and Deschampsia caespitosa, has been described as extending from San Francisco northward to the Klamath Mountains and in patches south to San Luis Obispo (Holland and Keil 1995). Holland (1986) used the term “coastal terrace prairie” to define similar communities. Finally, a “tufted hairgrass community” has been defined where Danthonia is dominant- this series is part of the “coastal prairie, which extends inland from terraces to bald hills” (Sawyer and Keeler-Wolf 1995). Such “bald hills” are a common feature along the coast and arise abruptly inland from the coastal terraces. Coastal prairies occur on poorly drained soils, often clays derived from serpentine outcrops, and often occur on a series of former coastal terraces that through geological action have been moved inland and uplifted. As one moves inland, “ecological staircases” grade into drier, higher interior ridges (Westman 1975, Cylinder 1995). Most of these interior ridges
are forested, but many sustain open grasslands. Further inland, conifer forests are replaced by oaks and typical “annual grassland” oak savanna (Barbour and Major 1995, Holland and Keil 1995). Monterey pine forests are often adjacent to coastal terrace prairies in the central coast of California. Shrubs (eg. Baccharis) (McBride and Heady 1968) or trees, eg. Pinus radiata (Callaway and Davis 1993) invade these coastal grasslands without fire or grazing. Pre-settlement fires in coastal grasslands were frequent, with 2-10 year return intervals (Greenlee and Langenheim 1990). Post-settlement disturbances have included year-round grazing by domestic livestock (Mack 1989). In most descriptions of coastal grasslands, Nassella pulchra is a co-dominant.

Native perennial grasslands persist along a continuum from dominance by non-native species to being relatively free from exotics (Harrison et al. 2001). In this case, we examined species composition, invisibility and diversity change along a gradient from central coast terraces inland to California’s central coastal mountain ranges (here, the Sierra de Salinas). Our previous studies of the inland Nassella prairies (INP) investigated the role of gophers, grazing and historic cultivation (Stromberg and Griffin 1996). Here, we extend our studies towards the coast to include grasslands that can be recognized as coastal terrace prairies by the constant presence of Danthonia californica and Nassella. We provide a background of data on the more general discussion of patterns in species diversity (Tilman et al. 1997, Huston et al. 2000, Kaiser 2000) and the relationship between species diversity, and invasive species (Symstad 2000) in landscape studies (Stohlgren et al. 1997).

Study Areas

Thirty-three stands of coastal terrace prairie were sampled, from Avila Beach, north along the Big Sur coast to Pebble Beach and then north from Santa Cruz to San Bruno Mountain
near San Francisco (Figure 1). Stands were selected based on previous extensive botanical surveys of central coastal California grasslands (Kephart 1993, Yadon 1995, Stromberg and Griffin 1996). Stands were not recently grazed or cultivated and were initially selected based on co-dominance of Deschampsia or Danthonia.

Data from other studies were discovered and used. In 1965 and 1966, 46 homogenous stands of Monterey Pine (Pinus radiata) forests were sampled from Cambria to Año Nuevo (White 1966a, Vogl et al. 1988). In 1993, 141 homogenous stands of coastal scrub were sampled from San Simeon to Point Lobos (Heuer 1994). In 1991, 80 inland Nassella prairies in the Sierra de Salinas were sampled (Stromberg and Griffin 1996). Species richness depends on the scale of sampling (Gross et al. 2000) so comparisons to other studies were made at similar scales (1 square meter).

**Methods**

Sampling was done at the peak of the flowering season, from mid-April through May in 1996 and 1997. At each grassland stand (Figure 1), we chose a homogenous area and flagged a 50 m x 20 m plot with the long axis parallel to topographic contours. We recorded presence of all plant species we could discover on the larger plots (0.1 ha). Starting from the midpoint of the short axis, we placed steel quadrats (20 cm x 50 cm; 0.1m²) at 2.5m intervals along the 50m long midline of the 0.1 ha plot (20 quadrats/plot). For each quadrat, we recorded a cover class for canopy cover of all plant species we observed (Daubenmire 1959). Quadrats were painted to facilitate recognition of Daubenmire cover classes. A cover value of 0.01 was assigned to each species seen only in the larger plot and not seen in any smaller quadrat. Cover for each species at each stand (site) was calculated by averaging midpoints of the cover classes assigned to each of species in the 20 quadrats. Stand were at least 200 m apart, and more often, many kilometers
apart. For each stand, we recorded aspect, elevation, distance inland from the coast, latitude and longitude (UTM), total number of plant species (Hickman 1993), soil type, land form, number of grasses and forbs, numbers of perennials and annuals, native and exotic. Species were counted based on scores in successive quadrats on original field sheets; one CTP data sheet was inadvertently lost after transcribing summary numbers so the species tally by area for one CTP is missing. Nine soil series were included (Cook 1978, Ernstrom 1984). Land forms of coastal terrace prairies include: 1) coastal terraces immediately adjacent to the ocean that are almost level; 2) grasslands on the sides of isolated bald hills arising inland and up at least 10 m from the terraces; these are sometimes locally known as “potreros”, and: 3) drier, inland ridges well over 100 m above the coastal terraces and bases of the inland mountain ranges. Statview 5.0 (SAS) was used for statistical comparisons. Bonferroni/Dunn post-hoc tests were included to show individual differences in pairwise comparisons (significance level at 5%). We used several methods to order stands based on species composition and with regard to measures of diversity, including CCA, DCA and Bray-Curtis ordinations (PC-ORD ver 4) (ter Braak 1987b, ter Braak 1987a, McCune and Mefford 1999). Stand coordinates in our ordination were based on species data. We dropped species that occurred in only one stand with a cover value less than 5% in order to reach a numerical solution for CCA. Computational problems (Tausch et al. 1995) have been addressed, and the method we used is inherently robust (Leps and Hadincova 1992).

Species composition of the herb layer was observed using similar methods in 46 stands of Monterey pine forests. Discovery of archival records (K. White, unpublished data, Hastings archives) allowed us to include observations from 40 to 80 quadrats (20 cm x 50 cm) that were read as above for plant cover. A larger area of .1 to 1 ha was then searched for additional species present and each was recorded (K. White, unpublished data, Hastings archives).
Discovery of additional comparable data allowed us to include comparisons to coastal shrub communities (Heuer 1994). Coastal shrub communities, often adjacent to coastal terrace prairies, were sampled with 16 square meter quadrats at 141 locations, again at the peak of the growing season, in 1993. No larger sampling areas were surveyed for additional species (Heuer 1994) and only the larger (16 sq. m) quadrats were used.

Inland Nassella prairies were described in detail previously (Stromberg and Griffin 1996). We included inland prairies in this study to examine the larger scale differences across the landscape as inland Nassella prairies share Nassella and other species with coastal terrace prairies, but occur at a drier, inland part of an environmental continuum occupied by native grasslands in coastal California. Data sets from this study will be made available (ESA Ecological Archives or NRS archives).

3. Results

Average species richness varies with the area sampled (Figure 2). For individual sites, most reach an asymptote by about 2 m (Figure 2a). No definitive asymptote is reached for the average CTP or MPF. Species counts at 0.1ha represents the best estimates for total species richness. Mean species numbers between all pairs are significantly different (paired t-tests, p < 0.001) for comparisons at 1 sq. m. and at 0.1 ha (Table 1).

This comparison of species richness with area leads to an interesting observation on the effects of a major human-directed use of the ecosystem. In a previous analysis of inland Nassella prairie stands with and without active grazing by domestic cattle, significantly fewer plant species were observed in grazed stands (Stromberg and Griffin 1996) based on areas of 0.1ha. In this analysis of species number at a smaller sampling scale (1 sq. m), this pattern in species richness was reversed and is clearly dependent on scale (Figure 2).
Coastal grasslands have much greater species richness in comparison to inland *Nassella* grasslands, coastal pine, or coastal scrub plant communities. A total of 82 species of grasses or sedges and 258 forbs (340 total) were found in 33 coastal terrace prairie stands. In 80 inland *Nassella* prairies stands, a total of 194 species were found; 136 plant species were found in 48 coastal Monterey pine stands (Vogl et al. 1988). Many fewer plant species (65 total) were found in 141 coastal scrub stands. Species richness (species / square meter) in coastal prairies is about 3.5 times greater than in adjacent Monterey pine forests (Table 1) and nearly 4 times greater than in adjacent coastal scrub.

Coastal prairies also have a much greater species richness compared to other grasslands in California and North America (Table 2) when each is presented at a comparable scale (1 sq. m).

Preliminary Bray-Curtis ordinations of the 33 stands revealed that both stands at Bird Rock and both forest stands in Pebble Beach (Poppy Hills, 24 Padre Lane- Table 4) were outliers. Although eliminated, they offer insights to dynamics of coastal prairies. Samples at Bird Rock had unusually high cover of *Carex pansa* (68% and 18% respectively). *Carex pansa* was only found in two other stands, and there it was not abundant (cover < 5%). Bird Rock 2 was the only stand to have more than 10% *Lolium multiflorum* with 34.4%. Padre Lane was the only stand where we found *Phalaris californica* and *Hierochloe occidentalis* and was one of only two stands with *Pinus radiata* (11%). Poppy Hills also had some *Pinus radiata* (2%), but was the only stand with *Rubus ursinus* or to have > 1% *Arctostaphylos hookeri* (10%). Because these four stands have such exceptional composition, they confound analysis of the other open coastal prairies and were subsequently dropped from more detailed analysis of coastal terrace prairies.

Ordinations of species composition data from the 29 coastal terrace prairies showed that different land forms (“inland ridges”, “coastal terraces” and “bald hills” above coastal terraces)
each have a relatively distinct species composition. This was supported by results of the analysis of variance for individual measures. Comparisons of the three land forms of coastal terrace prairies showed that bald hills have more species of grasses or sedges overall (Table 3-a), more native grasses and sedges (3-b) and more native forbs at both scales of sampling (3-c,d) and so more species of native plants overall (3-e). The cover of the native plants show a similar pattern- Bald Hills have more cover of natives (3-f), particularly more cover of native perennial forbs (3-g). Inland ridges, as will be seen in a pattern extending to inland \textit{Nassella} prairies (below) show more dominance by annual exotic forbs (3-h) and other exotics in general (3-i) than the more diverse, bald hill coastal terrace prairie.

Both inland \textit{Nassella} prairies and coastal terrace prairies show an increase in the number of native species with total species richness in 0.1 ha plots (Figure 6-a,b). The number of exotic species also increases with species richness in inland \textit{Nassella} prairies but not in coastal terrace prairies (Figure 6-c,d). The relative cover of exotics decreases in both inland \textit{Nassella} prairies and coastal terrace prairies with species richness (Figure 6-e,f). One relative outlier (Fig 6.f) is instructive. This stand, Piedras Blancas-1, is unusually low in both relative cover of exotics and species richness because it is the only stand with 95\% cover of one native, the perennial grass \textit{Deschampsia cespitosa} var. \textit{holciformis}. In some cases then, relative cover of exotics can be low (~1\%) even with low species richness (~34) if the total cover of the site is high. Including all coastal terrace prairies and inland \textit{Nassella} prairies, species richness (0.1 ha) and total cover were positively correlated ($R^2_{adj} = 0.18$, $F = 24.8$, $P < 0.001$, residual df = 107) and relative cover of exotic species is negatively correlated with total cover ($R^2_{adj} = 0.19$, $F = 25.6$, $P < 0.001$, residual df = 107). Native species richness (0.1ha) and exotic species richness were positively
correlated for inland *Nassella* prairies ($R^2_{adj} = 0.23$, $F = 24.6$, $P < 0.001$, residual df = 78) but not for coastal terrace prairies ($R^2 = 0.02$, $F = 0.67$, $P < 0.001$, residual df = 27).

Considering just the 29 open coastal terrace prairies, grasses and forbs differ in how they vary with species richness at 0.1 ha. On this scale, neither total vegetative cover or cover of native species are related to species richness. However, cover of all exotic species decreases significantly with increasing species richness ($R^2_{adj} = 0.15$, $F = 6.0$, $P < 0.05$, residual df = 27). This decrease in cover of exotics with an increase in species richness was largely due to the decrease in cover of exotic grasses. Cover of exotic grass was significantly negatively correlated with species richness ($R^2_{adj} = 0.12$, $F = 4.96$, $P < 0.05$, residual df = 27). Neither the cover of exotic forbs or the number of exotic forbs was correlated with species richness in coastal terrace prairies. The degree to which the grasses are native increases with species richness; the number of native grasses is correlated with species richness ($R^2_{adj} = 0.14$, $F = 5.56$, $P < 0.05$, residual df = 27) although the cover of native grass is not correlated. The degree to which forbs are native also increases with increasing species richness. In this case both cover and number of native forbs (0.1 ha) were significantly correlated with species richness (respectively, $R^2_{adj} = 0.29$, $F = 12.9$, $P < 0.001$, residual df = 27 and $R^2_{adj} = 0.83$, $F = 136$, $P < 0.001$, residual df = 27).

The summary of the 25 most frequent and dominant species of grasses and sedges in the coastal prairies (Figure 4) reveals that coastal prairies are heavily invaded with non-natives. The widespread fescue, *Vulpia spp.*, is in most samples and is often very abundant. *Danthonia californica, Nassella pulchra* and *Festuca rubra* are the native grasses that define this community. A summary of the 25 most frequent and dominant species of forbs in coastal prairies (Figure 5)
show a similar dominance by non-natives; in this case by widespread *Plantago*, *Erodium* and *Hypochaeris*, all of which extend well inland. Most important natives include the very similar *Plantago erecta* and *Baccharis pilularis*. These natives, along with *Viola*, *Sidalcea*, *Cammisonia* and *Acaena* are the native forbs that complete the definition of these coastal prairies. In this community, the dominance of grasses drops off rapidly (Figure 4), while the cover and frequency of the forbs is far greater for more species (Figure 5).

Dominance of exotic grasses and exotic forbs in coastal terrace prairie increases as one moves from the coastal terraces, inland to bald hills and then inland to the drier ridges (Table 3). For coastal prairies, the average ratio of the number of exotic grass or sedge species to total species present is 0.44, and the average ratio of exotic forb species is 0.33 (n = 33). Corresponding average ratios of exotic species in inland *Nassella* prairies are 0.79 and 0.19 (n = 80).

We used CCA to sort out which individual comparisons of community characteristics (measures of diversity and the degree to which the community has been invaded by exotic species) are most closely associated with vegetation composition across the landscape gradient from inland *Nassella* prairies to coastal terrace prairies. Some of these measures were highly correlated, so we proceeded with only 19 (Table 5). Plant species with total cover of less than .05% and which occurred in 5 or fewer stands were eliminated, leaving 192 species. With these simplifications (tolerance set to 0.100000E-12), PCord reached a CCA solution after fewer than 100 iterations. Inland *Nassella* prairies were clearly grouped to the left (Figure 7) and coastal terrace prairies were on the right. The highest "intraset correlation" (ter Braak and Smilauer 1998) with this first axis was the cover of native, perennial grass and on the second axis, the cover of exotic species (Figure 7). Coastal terrace prairies are characterized as having both more species and higher cover of native perennial grasses than any of the tightly grouped (thus similar)
inland Nassella prairies that are clearly placed to the left of the first axis where stands can be described as having higher cover of annual, exotic forbs (for example, *Erodium cicutarium*). The second axis distinguishes between coastal terrace prairies into those with relatively more dominance by exotic species (Piedras Blancas Light House, Fish Ranch, etc.) and those with relatively high cover of native, perennial forbs (San Bruno, Soda Springs, Piedras Blancas 1, etc.) (Figure 7- joint plot).

By restricting our focus to only coastal terrace prairies, we can examine the pattern of species composition and floristic characteristics at a smaller scale. By dropping the 80 inland Nassella prairies, the number of plant species (total cover > 0.5%) included in the CCA dropped to 149. Correspondingly, more of the floristic variables were highly correlated (Table 5) and only 12 were relatively independent. A joint plot (Figure 8) shows many coastal terrace prairies in a group with relatively high cover of exotic species. The highest intra-set correlation with the first axis was with cover of exotic species. The highest intra-set correlation with the second axis was with the number of native forbs. Stands such as San Bruno, Soda Springs, the stands near Avila Beach (Olson Hill, San Luis Hill) are exemplary coastal terrace prairies with fewer exotics and higher cover of native forbs. The Point Lobos Mima mound prairie and Piedras Blancas 1 are coastal terrace prairies with fewer exotics, higher cover of native forbs and more native grasses (Figure 8- joint plot) while stands clustered on the left side relatively more cover of exotic species.

Soils and locations of the various sites are described in Table 4. Fourteen of the coastal terrace prairies (44%) occurred on soils with a hard pan from 10-20 cm beneath the surface. An additional 3 coastal terrace prairies occurred on serpentine rock or clay with limited drainage. A hardpan that provides standing water during the winters was often present, but apparently not required. Coastal terrace prairies also occurred on sands, loams and clays.
4. Discussion

Diversity of plant species in coastal terrace prairies is among the highest in grasslands of North America (Stohlgren et al. 1999b). County and wildland planners often have selected coastal terrace prairies for development, perhaps not recognizing the biodiversity of coastal terrace prairies or because political support to protect forests or coastal scrub has been comparatively well organized. If protection of biodiversity is a goal, then coastal terrace prairies should be protected and development should be focused on relatively species-poor plant communities.

Invasions of natural communities by exotic species may occur more readily in areas of low species diversity than in areas of high species diversity (Darwin 1859). Plant communities with low species diversity (and total cover) may use resources less completely, allowing invasion by similar species (MacArthur and Wilson 1967, Pimm 1991, Tilman et al. 1997). Evidence for this relationship between diversity and invasions in grasslands depends on scale, and at a landscape scale, may be reversed (Stohlgren et al. 1999b). Based on the number of species, our studies do not support the theory that exotics are more abundant where species diversity is relatively low; inland Nassella prairies (but not coastal terrace prairies) with the highest diversity have more exotic species (Figures 6 c., d.). But, numbers of species probably do not reflect ecosystem function. Species occupying more space intercept more light, and presumably are more important in nutrient capture and storage. In both inland Nassella prairies and coastal terrace prairies, most species in our grasslands have cover < 5%. Two species may be equally counted as present, but one may occupy far more cover in the community. Based on relative cover (Fig. 6 e., f., 7) both diverse inland Nassella prairies and coastal terrace prairies have
reduced exotic dominance, supporting the theory that less diverse communities are more likely to be invaded.

Ordinations of the species and stands agree with our general understanding of the biology of individual species. The ordinations are also consistent with patterns seen by making pairwise statistical comparisons (Table 3, Figure 7). All coastal terrace prairies have been invaded to some degree by exotics, but the importance of exotic species is far greater in inland Nassella prairies. Two of the three grasses with the most cover (Figure 4) and the four forbs with the most cover in coastal terrace prairies are exotics (Figure 5).

Although the effects of grazing by large domestic herbivores on these grasslands were not specifically addressed, a re-analysis of inland Nassella prairie data at various scales of sampling (Figs. 2, 3) supports observations elsewhere (Chaneton and Facelli 1991, Olff and Ritchie 1998) that the loss in plant species diversity in grasslands grazed by herbivores is only seen at a scale larger than about 100 m². Grazing, or its removal, probably has little effect on species diversity in other California grasslands because grazing has been continuous for centuries, following European settlement (Harrison 1999a). At some scales, grazing may have little effect on native species richness in other North American grasslands (Stohlgren et al. 1999a). All grasslands in this study were probably grazed since European settlement. There is no evidence that herds of large herbivores co-evolved with the California coastal grasslands (Painter 1995). In general, domestic livestock grazing has had severe impacts on grassland ecosystems in western North America (Painter and Belsky 1993) and livestock removal has been suggested at various scales (Bock et al. 1993). However, grazing has been present for so long that careful consideration must be given before livestock are removed from coastal grasslands. On Santa Cruz Island, grasslands formerly grazed by cattle and sheep now support near monocultures of Foeniculum vulgare, an exotic plant formerly held in check by year-long grazing (personal
observation- M. Stromberg, (Mayfield et al. 2000). On other coastal parkland where grazing has been entirely removed after many years of year-round grazing (Andrew Molera State Park, Santa Clara County Parks, San Mateo County’s Mid-Peninsula Open Space District) we have seen extensive, rapid expansions of *F. vulgare*, *Baccharis pilularis* and *Dipsacus spp.*, where these plants continue to be relatively unimportant on nearby grazed lands.

Most coastal terrace prairies were clearly open grasslands, but the composition of several stands included trees and shrubs (e.g., Poppy Hills, Padre Lane). The presence of otherwise typical coastal terrace prairies grasses and forbs in these brushy or forested stands supports the concept of a dynamic tension between forest and grassland vegetation mediated by occasional fire (or grazing) in the coastal communities (Greenlee and Langenheim 1990). Currently, central California coastal grasslands are gradually seeing increased dominance by the native coastal shrub (*B. pilularis*) (McBride and Heady 1968) or oak woodland (Callaway and Davis 1993). Indeed, *B. pilularis* is a co-dominant, native of the coastal prairies.

California’s human population will double by 2040, and coastal development is much faster than that in interior California (Medvitz and Sokolov 1995). Although prescribed fires are the most cost-effective way to maintain the grasslands on a large scale (Kephart 2000), current and planned development almost precludes this option. Small scale, prescribed burns, mowing, and controlled grazing during the dry season should be included in management strategies to sustain the long-term viability of California’s coastal prairies.

Although some may attempt to assign names or define units of vegetation (Sawyer and Keeler-Wolf 1995) this may be impossible (Zedler 1997) because vegetation occurs on a continuum in the environment where each species has an individual distribution on the gradient from coastal to inland. Even if we could find identical environments, species composition would probably vary due to other factors that have undoubtedly influenced the abundance of individual
species in a given year (Fox and Fox 1986). Gradients may also be based on competition; from wet (coastal) to dry (inland) (Lane et al. 2000) or disturbance (fire frequency, grazing duration and intensity, gopher abundance, etc.).

Gopher tailings probably sustain a disturbance regime of inland California annual grasslands and old fields (Stromberg and Griffin 1996) where gopher density can be very high. On coastal terrace prairies however, gopher tailings rarely observed.

We did not sample all known high quality or relict stands in this study area. Terraces on the San Simeon Ranch, the grasslands just north of Santa Cruz adjacent to Wilder Ranch State Park, those on the San Mateo coast, and those north of Bodega Bay need more investigation.

Coastal prairies support a number of state or federally designated “rare” species and are often managed for protection of rare animals (Launer and Murphy 1994). Rare animals include several butterflies; the Mission Blue and San Bruno Elfin (McClintock et al. 1990, Weiss 1993). Conservation of the coastal terrace prairie on San Bruno Mountain includes the first “habitat conservation plan” approved by the federal government. Species considered as “special plants” by various regulatory agencies and observed in this study include Arctostaphylos hookerei, Astragalus tener var. titi, Allium hickmanii (in 23% of the coastal terraces sampled), Sanicula maritima, Trifolium polyodon, Psilocarphus tenellus var. globiferus, Cirsium occidentale var. compactum, Perideridia gairdneri, and Arabis blepharophylla. Each of these officially rare species occurred in only one stand, and then only sparsely in the larger plot (50 x 20m). We also found Ophioglossum californicum at Spruance Meadow, not seen in Monterey County since it’s original collection in 1910. Astragalus tener var. titi is listed as federally endangered and occurs only in one location (Bird Rock). We purposely included this site in the sampling as it occurs on an exceptional relict stand including Danthonia and Deschampsia cespitosa var. holciformus.
Land managers who can identify the species assemblages described here (Figures 4, 5) should expect other associated rare species.

5. Acknowledgments

We dedicate this paper to the memory of Oren Pollak who arranged funding for this study through The Nature Conservancy, California Office. Thanks to various landowners or managers who allowed us to study the grasslands under their care; Tom Gray- Santa Lucia Preserve, Diane Fish- Fish Ranch, Bill Barker and Danny Hoag- Barker Ranch, Pacific Gas and Electric Co., Ted Horton- Pebble Beach Company, Alan Williams- Cañada Woods, Galen Rathbun and Norm Scott, USFWS- Piedras Blancas & Cambria, who provided helpful access to land. Mike Markkula and Helen Johnson provided logistical support. Support from the Museum of Vertebrate Zoology, UC-Berkeley is gratefully acknowledged. Susan Harrison and Carla D’Antonio provided helpful advice and we appreciate Walter Koeing’s critical reviews.

Literature Cited


Ernstrom, D. J. 1984. Soil survey of San Luis Obispo County, California, Coastal Part. Soil Conservation Service, Forest Service, and University of California Agriculture Experiment Station., Berkeley, California.


Table 1. Comparison of species diversity between coastal terrace prairies (CTP), inland Nassella prairies (INP) and Monterey pine forests (MPF) based on first ten 0.1 sq. m observations (1 square m) in each sample. Coastal scrub species density was derived from 16 sq. m. quadrats at each stand, expressed here as species/ sq. meter using $S = cA^z$ where $z = 0.25$.

<table>
<thead>
<tr>
<th>Number of Species per square meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>Coastal Terrace Prairies</td>
</tr>
<tr>
<td>Inland Nassella Prairies</td>
</tr>
<tr>
<td>Monterey Pine Forests</td>
</tr>
<tr>
<td>Coastal Scrub</td>
</tr>
</tbody>
</table>

Comparison of Means (INP, CTP, MPF)

<table>
<thead>
<tr>
<th>DF</th>
<th>Mean Square</th>
<th>F Value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>2</td>
<td>2615.2</td>
<td>62.9</td>
</tr>
<tr>
<td>Residual</td>
<td>155</td>
<td>41.6</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Comparison of species richness (# species / 1 sq. meter, ± SD or ± SE) in California grasslands and other arid, western plant communities.

<table>
<thead>
<tr>
<th>Community Name</th>
<th>Species Density</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal Terrace Prairies</td>
<td>22.62, + 8.9</td>
<td>This study.</td>
</tr>
<tr>
<td>Napa Co.- L. Barryessa, Ca. Serpentine Meadows</td>
<td>12.3, + 2.3</td>
<td>(Harrison 1999a)</td>
</tr>
<tr>
<td>Napa Co.- L. Barryessa, Ca Non-Serpentine Meadows</td>
<td>10.3, + 2.2</td>
<td>(Harrison 1999a)</td>
</tr>
<tr>
<td>Monterey Co., Sierra de Salinas Annual Calif. Grassland</td>
<td>14.7, + 0.7</td>
<td>(Stromberg and Griffin 1996)</td>
</tr>
<tr>
<td>Bighorn Basin, C. Wyo. Agr spi/Art tri</td>
<td>10.2, + 0.5</td>
<td>(Stohlgren et al. 1999a)</td>
</tr>
<tr>
<td>Grant Teton, N.W. Wyo. Agr spi/Art tri</td>
<td>8.9, + 0.6</td>
<td>(Stohlgren et al. 1999a)</td>
</tr>
<tr>
<td>Gunnison, W. Colo. Sti let/Art tri</td>
<td>8.8, + 0.4</td>
<td>(Stohlgren et al. 1999a)</td>
</tr>
<tr>
<td>Wind Cave, W. So. Dakota Poa pra/Amo can</td>
<td>8.7, + 0.5</td>
<td>(Stohlgren et al. 1999a)</td>
</tr>
<tr>
<td>Charles Russell NWR, E. Mont. Agr smi/Art tri</td>
<td>4.6, + 0.5</td>
<td>(Stohlgren et al. 1999a)</td>
</tr>
<tr>
<td>Yellowstone, W. Wyo. Fes ida/Art tri</td>
<td>9.0, + 0.6</td>
<td>(Stohlgren et al. 1999a)</td>
</tr>
<tr>
<td>Pipestone N.M., So. Min. Tallgrass Prairie</td>
<td>12.2, + 0.7</td>
<td>(Stohlgren et al. 1999b)</td>
</tr>
<tr>
<td>Cheyenne, S.E. Wyo Mixed-Grass Prairie</td>
<td>10.7, + 0.5</td>
<td>(Stohlgren et al. 1999b)</td>
</tr>
<tr>
<td>Pawnee Butte, N.E. Colo. Short-grass Prairie</td>
<td>8.5, + 0.4</td>
<td>(Stohlgren et al. 1999b)</td>
</tr>
</tbody>
</table>
Species codes: Agr spi, Agropyron spicatum; Agr smi, Agropyron smithii; Amo can, Amorpha canescens; Art tri, Artemesia tridentata; Fes ida, Festuca idahoensis; Sti let, Stipa lettermanii; Poa pra, Poa pratensis.
Table 3. Based on open coastal grasslands, differences between mean values from coastal terraces (CT, \( n = 10 \)), coastal bald hills (BH, \( n = 10 \)) and interior dry ridges (IR, \( n = 9 \)) are shown based on analysis of variance. Bonferroni/Dunn post-hoc comparison (e.g. BH,CT) are shown only with a significance level of 0.05. Residual df = 26 in all 2-way ANOVA. Arcsin-square root transformation of ratio data were done before ANOVA; results expressed below in ratios.

a. Species of Grasses and Sedges .1 ha

\[ F = 3.61, P-Value = 0.04 \]

<table>
<thead>
<tr>
<th>Mean</th>
<th>Std. Error</th>
<th>BH, IR p ≤ 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>14.5</td>
<td>1.2</td>
</tr>
<tr>
<td>BH</td>
<td>15.4</td>
<td>1.4</td>
</tr>
<tr>
<td>IR</td>
<td>11.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

b. Species of Native Grasses and Sedges 2 sq. m

\[ F = 6.1, P-Value = 0.006 \]

<table>
<thead>
<tr>
<th>Mean</th>
<th>Std. Error</th>
<th>BH, IR p ≤ 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>14.5</td>
<td>1.2</td>
</tr>
<tr>
<td>BH</td>
<td>15.4</td>
<td>1.4</td>
</tr>
<tr>
<td>IR</td>
<td>11.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

c. Species of Native Forbs .1 ha

\[ F = 3.92, P-Value = 0.032 \]

<table>
<thead>
<tr>
<th>Mean</th>
<th>Std. Error</th>
<th>BH, CT p ≤ 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>17.6</td>
<td>2.6</td>
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<tr>
<td>BH</td>
<td>28.9</td>
<td>3.4</td>
</tr>
<tr>
<td>IR</td>
<td>20.4</td>
<td>3.0</td>
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</tbody>
</table>

d. Species of Native Forbs 2 sq. m

\[ F = 3.45, P-Value = 0.04 \]

<table>
<thead>
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<th>Mean</th>
<th>Std. Error</th>
<th>BH, CT p ≤ 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>9.7</td>
<td>1.9</td>
</tr>
<tr>
<td>BH</td>
<td>17.1</td>
<td>2.3</td>
</tr>
<tr>
<td>IR</td>
<td>13.4</td>
<td>1.9</td>
</tr>
</tbody>
</table>

e. Species of Native Plants .1 ha

\[ F = 4.39, P-Value = 0.02 \]

<table>
<thead>
<tr>
<th>Mean</th>
<th>Std. Error</th>
<th>BH, IR p ≤ 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>25.1</td>
<td>2.9</td>
</tr>
<tr>
<td>BH</td>
<td>36.7</td>
<td>3.8</td>
</tr>
<tr>
<td>IR</td>
<td>24.6</td>
<td>2.9</td>
</tr>
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</table>
### Table 3. (continued)

<table>
<thead>
<tr>
<th>f. Cover- Native Plants</th>
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<tr>
<td><strong>F</strong> = 7.02, P-Value = 0.036</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>Std. Error</td>
<td>CT, IR p &lt; 0.01</td>
</tr>
<tr>
<td>CT</td>
<td>67.7</td>
<td>8.8</td>
</tr>
<tr>
<td>BH</td>
<td>77.7</td>
<td>5.3</td>
</tr>
<tr>
<td>IR</td>
<td>42.9</td>
<td>4.6</td>
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<table>
<thead>
<tr>
<th>g. Cover Native Perennial Forbs</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>F</strong> = 3.89, P-Value = 0.035</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>Std. Error</td>
<td>BH, IR p &lt; 0.05</td>
</tr>
<tr>
<td>CT</td>
<td>12.2</td>
<td>2.7</td>
</tr>
<tr>
<td>BH</td>
<td>21.4</td>
<td>4.7</td>
</tr>
<tr>
<td>IR</td>
<td>8.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>h. Cover Annual Exotic Forbs</th>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td><strong>F</strong> = 6.84, P-Value = 0.004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>Std. Error</td>
<td>CT, IR p &lt; .05</td>
</tr>
<tr>
<td>CT</td>
<td>9.7</td>
<td>2.3</td>
</tr>
<tr>
<td>BH</td>
<td>6.9</td>
<td>1.7</td>
</tr>
<tr>
<td>IR</td>
<td>20.6</td>
<td>3.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>i. Ratio of Exotic Species/Total Forb Cover</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>F</strong> = 4.86, P-Value = 0.016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>Std. Error</td>
<td>BH, IR p &lt; 0.05</td>
</tr>
<tr>
<td>CT</td>
<td>.48</td>
<td>.069</td>
</tr>
<tr>
<td>BH</td>
<td>.37</td>
<td>.048</td>
</tr>
<tr>
<td>IR</td>
<td>.63</td>
<td>.025</td>
</tr>
</tbody>
</table>
Table 4. Stand names and locations (UTM) included in sampling of California coastal grasslands.

<table>
<thead>
<tr>
<th>No.</th>
<th>Stand Name</th>
<th>Abbreviation</th>
<th>East</th>
<th>North</th>
<th>Soil Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Barker Ranch, Laureles Ridge</td>
<td>Barker 1</td>
<td>614.291</td>
<td>4041.710</td>
<td>Sandy Loam</td>
</tr>
<tr>
<td>2</td>
<td>Barker Ranch, Laureles Ridge</td>
<td>Barker 2</td>
<td>613.835</td>
<td>4041.865</td>
<td>Sandy Loam</td>
</tr>
<tr>
<td>3</td>
<td>Bird Rock, Inland terrace</td>
<td>Bird Rock1</td>
<td>592.905</td>
<td>4050.277</td>
<td>Sand</td>
</tr>
<tr>
<td>4</td>
<td>Bird Rock, Inland terrace</td>
<td>Bird Rock 2</td>
<td>592.907</td>
<td>4050.278</td>
<td>Sand</td>
</tr>
<tr>
<td>5</td>
<td>Canada Woods Site No. 4</td>
<td>CW No. 4</td>
<td>603.776</td>
<td>4051.868</td>
<td>Clay Loam</td>
</tr>
<tr>
<td>6</td>
<td>Canada Woods, Garage Site</td>
<td>CW Garage</td>
<td>604.100</td>
<td>4047.500</td>
<td>Clay Loam</td>
</tr>
<tr>
<td>7</td>
<td>Canada Woods, Lower Pine Tree</td>
<td>CW Low Pine</td>
<td>603.500</td>
<td>4048.200</td>
<td>Clay Loam</td>
</tr>
<tr>
<td>8</td>
<td>Canada Woods, Pine Tree</td>
<td>CW Pine Tree</td>
<td>603.700</td>
<td>4050.100</td>
<td>Clay Loam</td>
</tr>
<tr>
<td>9</td>
<td>Canada Woods, Swale</td>
<td>CW Swale</td>
<td>603.800</td>
<td>4046.900</td>
<td>Clay Loam</td>
</tr>
<tr>
<td>10</td>
<td>Canada Woods, Big Pool</td>
<td>CW Big Pool</td>
<td>604.744</td>
<td>4046.848</td>
<td>Clay Loam</td>
</tr>
<tr>
<td>11</td>
<td>Fish Ranch, above Entrance Rd.</td>
<td>Fish Ranch 1</td>
<td>597.300</td>
<td>4042.694</td>
<td>Silty Loam</td>
</tr>
<tr>
<td>12</td>
<td>Fish Ranch, above Entrance Rd.</td>
<td>Fish Ranch 2</td>
<td>597.905</td>
<td>4042.692</td>
<td>Silt Loam</td>
</tr>
<tr>
<td>13</td>
<td>Fort Ord, opposite Toro Park</td>
<td>Ft. Ord Toro</td>
<td>595.670</td>
<td>4052.110</td>
<td>Sandy Loam</td>
</tr>
<tr>
<td>14</td>
<td>Jade Flat, Central Terrace</td>
<td>Jade Flat</td>
<td>638.283</td>
<td>3975.370</td>
<td>Serpentine Clay</td>
</tr>
<tr>
<td>15</td>
<td>Laureles Grade, Laureles Ridge</td>
<td>Laureles</td>
<td>611.870</td>
<td>4043.319</td>
<td>Sandy Loam</td>
</tr>
<tr>
<td>16</td>
<td>Molera State Park, N. Terrace</td>
<td>Molera</td>
<td>600.763</td>
<td>3905.689</td>
<td>Sand Loam</td>
</tr>
<tr>
<td>17</td>
<td>Olson Hill, Diablo Canyon</td>
<td>Olson Hill</td>
<td>698.859</td>
<td>3896.149</td>
<td>Loam</td>
</tr>
<tr>
<td>18</td>
<td>Pebble Beach, 24 Padre Lane</td>
<td>Pebble For</td>
<td>592.366</td>
<td>4048.055</td>
<td>Loamy Sand</td>
</tr>
<tr>
<td>19</td>
<td>Plaskett Ridge, Above Camp</td>
<td>Plaskett Rdg</td>
<td>600.832</td>
<td>3975.359</td>
<td>Serpentine Rock</td>
</tr>
<tr>
<td>20</td>
<td>Point Lobos, Escobar Flat</td>
<td>Pt Lobos Flat</td>
<td>597.250</td>
<td>4042.194</td>
<td>Sandy Loam</td>
</tr>
<tr>
<td>21</td>
<td>Point Lobos, Mima Mounds</td>
<td>Pt Lobos Mima</td>
<td>584.70</td>
<td>4041.30</td>
<td>Clay Loam</td>
</tr>
<tr>
<td>22</td>
<td>Poppy Hills, Opposite Golf Club</td>
<td>Poppy Hills</td>
<td>595.465</td>
<td>4048.980</td>
<td>Sandy Loam</td>
</tr>
<tr>
<td>23</td>
<td>Pt. Piedras Blancas Light House</td>
<td>Piedras LH</td>
<td>646.262</td>
<td>3948.422</td>
<td>Sand</td>
</tr>
<tr>
<td>24</td>
<td>Pt. Piedras Blancas Terrace 1</td>
<td>Piedras 1</td>
<td>654.425</td>
<td>3951.349</td>
<td>Loam</td>
</tr>
<tr>
<td>25</td>
<td>Pt. Piedras Blancas Terrace 2</td>
<td>Piedreas 2</td>
<td>654.347</td>
<td>3951.341</td>
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<tr>
<td>26</td>
<td>Rancho San Carlos, Animas Entr.</td>
<td>Danthonia RSC</td>
<td>603.586</td>
<td>4040.213</td>
<td>Clay Loam</td>
</tr>
<tr>
<td>27</td>
<td>Rancho San Carlos, Animas Rdg.</td>
<td>Animas RSC</td>
<td>600.971</td>
<td>4041.197</td>
<td>Clay Loam</td>
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<tr>
<td>28</td>
<td>San Bruno Mt., Great Meadow</td>
<td>San Bruno 1</td>
<td>548.059</td>
<td>4180.678</td>
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</tr>
<tr>
<td>29</td>
<td>San Bruno Mt., Great Meadow</td>
<td>San Bruno 2</td>
<td>549.274</td>
<td>4171.733</td>
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<tr>
<td>30</td>
<td>San Louis Hill, Diablo Canyon</td>
<td>San Luis Hill</td>
<td>703.59</td>
<td>3896.915</td>
<td>Clay Loam</td>
</tr>
<tr>
<td>31</td>
<td>Soda Springs, Bluff W. of Hwy 1</td>
<td>Soda Spring</td>
<td>637.957</td>
<td>3965.330</td>
<td>Serpentine Rock</td>
</tr>
<tr>
<td>32</td>
<td>Spruance Meadow, Spruance Dr.</td>
<td>Spruance</td>
<td>595.241</td>
<td>4047.953</td>
<td>Loamy Sand</td>
</tr>
<tr>
<td>33</td>
<td>Work Ranch, Hwy 68</td>
<td>Work Ranch</td>
<td>615.953</td>
<td>4048.821</td>
<td>Sandy Loam</td>
</tr>
</tbody>
</table>
Table 5. Floristic variables considered in analysis of species richness in California grasslands. Highly correlated variables were dropped, leaving 19 variables (middle column) with sufficiently minimal correlation required to compute canonical correlation analysis (Figure 6). When only 29 coastal terrace prairies are compared, only 12 floristic variables were included in the analysis (Figure 7). For example, in a CCA including 80 INP and 29 CTP, variable 1 (No. of Species in 2 sq. m) was dropped as it had a high correlation with variable 21 (No.of all Native Species).

<table>
<thead>
<tr>
<th>No.</th>
<th>Variable Name</th>
<th>80 INP, and 29 CTP</th>
<th>29 CTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No. of Species in 2 sq. m</td>
<td>21, .94</td>
<td>21, .92</td>
</tr>
<tr>
<td>2</td>
<td>No. of Species in .1 ha</td>
<td>25, .87</td>
<td>25, .91; 27, .95</td>
</tr>
<tr>
<td>3</td>
<td>Total Vegetative Cover</td>
<td>included</td>
<td>included</td>
</tr>
<tr>
<td>4</td>
<td>Cover of all Exotics</td>
<td>included</td>
<td>included</td>
</tr>
<tr>
<td>5</td>
<td>Cover of all Natives</td>
<td>8, .78; 17, .79; 6, .86</td>
<td>6, .80</td>
</tr>
<tr>
<td>6</td>
<td>Cover of Native, Perennial Grass</td>
<td>included</td>
<td>included</td>
</tr>
<tr>
<td>7</td>
<td>Cover of Native, Perennial Forbs</td>
<td>included</td>
<td>included</td>
</tr>
<tr>
<td>8</td>
<td>No. of Native, Perennial Grasses (.1 ha)</td>
<td>17, .92; 23, .99</td>
<td>23, .99</td>
</tr>
<tr>
<td>9</td>
<td>No. of Native, Perennial Forbs (.1 ha)</td>
<td>included</td>
<td>25, .91</td>
</tr>
<tr>
<td>10</td>
<td>Cover of all Exotic Grasses (.1 ha)</td>
<td>included</td>
<td>4, .91</td>
</tr>
<tr>
<td>11</td>
<td>Cover of all Exotic Forbs (.1 ha)</td>
<td>included</td>
<td>included</td>
</tr>
<tr>
<td>12</td>
<td>Cover of Annual, Exotic Grasses</td>
<td>4, .99</td>
<td>4, .90</td>
</tr>
<tr>
<td>13</td>
<td>No. of Annual, Exotic Grasses (.1 ha)</td>
<td>included</td>
<td>16, .84; 22, .94</td>
</tr>
<tr>
<td>14</td>
<td>Cover of Annual, Exotic Forbs</td>
<td>included</td>
<td>included</td>
</tr>
<tr>
<td>15</td>
<td>No. of Annual, Exotic Forbs (.1 ha)</td>
<td>included</td>
<td>24, .92</td>
</tr>
<tr>
<td>16</td>
<td>No. Exotic Grasses (2 sq. m)</td>
<td>included</td>
<td>22, .88</td>
</tr>
<tr>
<td>17</td>
<td>No. Native Grasses (2 sq. m)</td>
<td>8, .94</td>
<td>8, .82; 23, .87</td>
</tr>
<tr>
<td>18</td>
<td>No. Exotic Forbs (2 sq. m)</td>
<td>included</td>
<td>20, .86</td>
</tr>
<tr>
<td>19</td>
<td>No. Native Forbs (2 sq. m)</td>
<td>included</td>
<td>included</td>
</tr>
<tr>
<td>20</td>
<td>No. all Exotics (2 sq. m)</td>
<td>included</td>
<td>included</td>
</tr>
<tr>
<td>21</td>
<td>No. all Natives (2 sq. m)</td>
<td>included</td>
<td>included</td>
</tr>
<tr>
<td>22</td>
<td>No. of all Exotic Grasses (.1 ha)</td>
<td>13, .96</td>
<td>13, .94</td>
</tr>
<tr>
<td>23</td>
<td>No. of all Native Grasses (.1 ha)</td>
<td>included</td>
<td>included</td>
</tr>
<tr>
<td>24</td>
<td>No. of all Exotic Forbs (.1 ha)</td>
<td>included</td>
<td>26, .86</td>
</tr>
<tr>
<td>25</td>
<td>No. of all Native Forbs (.1 ha)</td>
<td>included</td>
<td>included</td>
</tr>
<tr>
<td>26</td>
<td>No. of all Exotics (.1 ha)</td>
<td>included</td>
<td>included</td>
</tr>
<tr>
<td>27</td>
<td>No. of all Natives (.1 ha)</td>
<td>25, .94</td>
<td>25, .95</td>
</tr>
</tbody>
</table>
Figure Captions

Figure 1. Map of study sites on coastal California.

Figure 2. a) Average number of species present as sampling areas are added in three coastal, California plant communities, ± 1 standard error. b) Species/area curves for individual sampling localities.

Figure 3. Average number of species present as sampling areas are added in 43 ungrazed (1937-1991) inland *Nassella* prairies and 37 grazed (1880-1991) inland *Nassella* prairies (Stromberg and Griffin 1996)

Figure 4. Importance value (frequency  x average percent cover) of the 25 most dominant species of grasses and sedges, averaged from 29 coastal terrace prairies in central, coastal California.

Figure 5. Importance value (frequency  x average percent cover) of the 25 most dominant species of forbs, averaged from 29 coastal terrace prairies in central, coastal California.

Figure 6. Spearman rank correlation between species richness and number of all native plant species for a.) 80 inland *Nassella* prairies and b.) 29 coastal terrace prairies. Spearman rank correlation between species richness and number of all exotic plant species for c.) 80 inland *Nassella* prairies and d.) 29 coastal terrace prairies. c. Spearman rank correlation between species...
richness and relative cover of exotic plant species for e.) 80 inland *Nassella* prairies and f.) 29 coastal terrace prairies.

Figure 7. Canonical correspondence analysis (ter Braak 1994) of 80 inland *Nassella* prairies and 29 coastal terrace prairies, based on cover of 197 plant species and 19 floristic variables. Inset: joint plot of stands and correlated floristic variables for all stands; length of vector associated with each variable is related to correlation with position of stand on canonical axes; highly correlated floristic variables are plotted near each other.

Figure 8. Canonical correspondence analysis of 29 coastal terrace prairies based on cover of 149 plant species and 12 floristic variables. Inset: joint plot of floristic variables for axes one and two.
San Francisco
Monterey Bay
Morro Bay

California

Km

0 95 190 380
Coastal Terrace Prairies
Inland Nassella Prairies
Monterey Pine Forests
Dominant Grasses/Sedges - Coastal Grasslands

Importance Value - log (Freq. x Cover)

Species Importance Order

- Vulpia myuros
- Danthonia californica
- Bromus hordeaceus
- Nassella pulchra
- Festuca rubra
- Aira caryophyllea
- Briza minor
- Elymus glaucus
- Juncus bufonius
- Lolium multiflorum
- Avena barbata
- Nassella cernua
- Hordeum branchyantherum
- Deschampsia c. cespitosa
- Bromus carinatus
- Hordeum marinum
- Deschampsia c. holciformis
- Lolium perenne
- Avena fatua
- Juncus pheocephalus
- Bromus diandrus
- Distichlis spicata
- Leymus triticoides
- Briza maxima
- Nassella lepida

Native
Non-Native

Coastal California Grasslands
Stromberg, Kephart, Yadon
p. 41
Figure 6, a. b.

Inland *Nassella* Grasslands

Rho = .96, P < .001

Coastal Grasslands

Rho = .94, P < .001
Figure 6, c. and d.

**Inland Nassella Grasslands**

- Number of Exotic Species vs. Total Species Richness (1000 sq. m)
- Rho = 0.56, P < 0.001

**Coastal Grasslands**

- Number of Exotic Species vs. Total Species Richness (1000 sq. m)
- Rho = 0.08, P = 0.65 (n.s.)
Figure 6, e. and f.

Inland *Nassella* Grasslands

Rho = -.47, P < 0.001

Coastal Grasslands

Rho = -.44, P = 0.02
GOES-derived fog and low cloud indices for coastal north and central California ecological analyses

Alicia Torregrosa, Cindy Combs, and Jeff Peters

1Western Geographic Science Center, U.S. Geological Survey, Menlo Park, California, USA, 2Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado, USA

Abstract Fog and low cloud cover (FLCC) strongly influences the water, energy, and nutrient flux of coastal ecosystems. Easy-to-use FLCC data are needed to quantify the impacts of FLCC on ecosystem dynamics especially during hot and dry Mediterranean climate summers. Monthly, annual, and decadal FLCC digital maps (indices) were derived for June–September 1999–2009 for coastal California, latitude 34.50°N (south of Monterey Bay) to latitude 41.95°N (north of Crescent City) from 26,000 hourly night and day Geostationary Operational Environmental Satellite (GOES) images. Monthly average FLCC ranges from <2 to 18 hours per day (h/d). Average FLCC over the ocean increases from north (9 h/d) to south (14 h/d), whereas on land, FLCC is highest where land juts into the prevailing NW winds and is lowest in the lee of major capes. FLCC advects farthest inland through low-lying NW ocean-facing valleys. At night, average total hours of FLCC are higher more frequently on land than over the ocean. The interannual FLCC coefficient of variation shows long-term geographic stability that is strongly associated with landform position. FLCC hours per day mapped contours, derived from decadal average FLCC, delineate the commonly used term “fog belt” into FLCC zones with increased locational precision. FLCC indices are available for download from the California Landscape Conservation Cooperative Climate Commons website (http://climate.calcommons.org/datasets/ summertime-fog). FLCC indices can improve analyses of biogeographic and bioclimatic species distribution models; understanding meteorological mechanisms driving FLCC patterns; solar energy feasibility studies; investigations of ecohdrology, evapotranspiration, and agricultural irrigation demand; and viticulture ripening models.

1. Introduction

This study focuses on fog and low clouds (FLCs) of marine origin, the most common cloud type in coastal California during the seasonally arid Mediterranean climate summer months (June–September) [Palmer, 1917; Leipper, 1994; Pilié et al., 1979; Koracin et al., 2014; Torregrosa et al., 2014]. The product of this study is a suite of FLCC indices that simplify a complex phenomenon by providing a spatiotemporally coherent data set of fog and low cloud cover (FLCC). The indices were developed to explore patterns of coastal FLC that arise from interactions of air, ocean, and land surface processes and to quantify FLC as an input for ecological investigations.

1.1. Marine Fog in Coastal California

Fog is a category of low cloud that is variously defined by its meteorological formation process, the obstruction it presents to transportation, or its functional contribution to ecosystems. The primary definition of fog is a cloud whose base touches the ground [Houze, 2014]. Colloquially, the term fog is used to describe the layer of marine stratus and stratocumulus clouds with base heights of up to 2 km that are commonly perceived by coastal residents to produce a foggy summer morning. The American Meteorological Society [2014] and Federal Aviation Administration [2013] define fog as suspended water droplets close to the Earth that reduce visibility below 1 km (0.62 miles).

The dominant summer cloud pattern is driven by an eastern North Pacific high-pressure system (High) formed by the warm and dry descending branch of the Hadley cell. The subsiding air mass of the High caps the marine atmospheric boundary layer (MABL), a layer of air close to and strongly influenced by the cold Pacific Ocean surface and the periodically colder oceanic currents upwelled to the ocean surface by northwest winds [García-Reyes and Largier, 2012]. Within the MABL, water vapor in the buoyant ascending air masses gets cooled by expansion and condenses on salts from sea spray and other suspended aerosols to form an expansive marine stratus cloud that can, at times, convect into a multitude of individual
stratocumulus clouds [Wood, 2012]. The vertical thickness of the low cloud layer remains relatively constant as dissolution and formation processes balance each other out. The cloud loses thickness when moist air at the top becomes entrained into the warmer, drier air aloft. The cloud gains thickness from below when buoyant moist air near the ocean surface rises to its “lifted condensation level” replenishing the condensed droplets lost at the cloud top. Buoyancy and land surface heating lifts the cloud away from the Earth’s surface, but the upper air inversion acts to keep it lowered. The low cloud layer will dissipate with sufficient turbulence, wind shear, and cloud top radiative cooling [Lilly, 1968; Lester, 1985; Wood and Bretherton, 2006; Pruppacher and Klett, 2010; Wood, 2012; Houze, 2014].

A strong coastal to inland temperature gradient forms when the land surface heats or cools. The gradient drives both offshore and onshore breezes that advect the marine layer across the landscape. The coastal mountains add terrain complexity to the air-ocean-land system [Dorman et al., 2013]. The variations in elevation and slope steepness, low-lying gaps that funnel winds, and differential heating of north versus south facing slopes modify the temperature and pressure gradients that form, move, and dissipate FLC [Terjung et al., 1969; Filonczuk et al., 1995; Koračin et al., 2005, 2014; Taylor et al., 2008; Nicholson, 2011].

Many unknowns remain about the details of FLC formation and dissipation. As a result, FLC continues to be difficult to forecast on both long and short time scales [Kann et al., 2015]. Daily and diurnal patterns are chaotic, turbulent, and, because of the importance to air traffic, well recorded. From these records, strong correlations show up between the formation and transport of FLC and the strength of seasonal drivers that fluctuate in concert with global atmospheric and oceanic cycles [Trenberth and Hurrell, 1994; García-Reyes and Largier, 2012; Seo et al., 2012; Johnstone and Mantua, 2014; Redmond and Abatzoglou, 2014; Schwartz et al., 2014].

Airport FLC records have been very useful as primary sources for air quality and ecological research [Beer and Leopold, 1947; LaDochy and Witiw, 2012; Johnstone and Dawson, 2010; Williams et al., 2015]; however, these are point data and insufficient to answer many spatial ecological questions by themselves. The temporally and spatially continuous grid format of the data set described in this study offers an alternative analytic approach.

1.2. Clouds and Coastal Ecosystems

Clouds cycle water and alter the incoming and outgoing flux of energy thereby regulating ecosystem dynamics at local to global scales [Wielicki et al., 1996; Trenberth et al., 2009]. In coastal California FLC adds water and lowers temperatures during the hot and dry Mediterranean climate summer affecting the pattern of species distribution across the landscape [Leipper, 1994; Gilliam, 2002; Azevedo and Morgan, 1974; Hiatt et al., 2012; Iacobellis and Cayan, 2013]. As a consequence FLC is a key feature of coastal ecosystem and has numerous and strong impacts on ecological processes [Weathers, 1999; Mooney et al., 2001].

Increased relative humidity from FLC and lowered temperatures from blocked shortwave radiation reduce plant evapotranspiration stress [Fischer et al., 2009; Baguskas et al., 2014]. Fog water droplets coalesce on surfaces such as pine needles, fern fronds, and spider webs accumulating and dripping into the soil adding occult precipitation to shallow root systems [Katata et al., 2010; Valiente et al., 2011] and increasing belowground microbial community productivity [Carbone et al., 2013]. Fog drip also increases streamflow [Gurnell, 1976; Harr, 1982]. During extreme late summer low streamflow conditions, fog events can result in sufficient fog drip and reduced evapotranspiration to increase streamflow by 200% [Sawaske and Freyberg, 2014]. Plants capable of direct water uptake into internal tissues from their leaf or bark surfaces benefit to varying degrees from fog events [Slatyer, 1960; Dawson, 1998; Limm et al., 2009; Earles et al., 2015].

In addition to direct water, nutrient, and particulate inputs [Gundel et al., 1994; Weathers et al., 2000; Collett et al., 2002; Herkes et al., 2013], FLC also has cascading ecosystem benefits. Reduced net radiation lowers stream temperature during critical times of low streamflows, benefitting salmonids and other fish species that require cool stream temperatures [Madej et al., 2006; Madej, 2010]. Frequent FLC reduces the likelihood of forest fires [Norman et al., 2009] and extreme heat events [Iacobellis and Cayan, 2013], the latter correlated with increased instances of emergency medical requests from vulnerable human populations [Gershunov and Johnston, 2011]. Summer heat waves, such as those that occurred during the relatively FLC-free month of July 2006, increased the risk of mortalities in all ecosystem populations, from human [Knowlton et al., 2009] to intertidal invertebrates [Helmut et al., 2007]. Marine life is at increased risk of catastrophic die-off when summer low tides coincide with cloud-free summer days [Mislau et al., 2009]. FLC intensifies coastal-to-inland oceanic gradients of temperature and moisture [Mass et al., 1986; Bailey, 2009]. The combination of steep oceanic gradients and
complex coastal terrain increases bioclimatic diversity [Torregrosa et al., 2013]. All these effects have landscape-level impacts on vegetation patterns, species distribution, species refugia, carbon sequestration, agricultural irrigation demand, and urban energy use [Borthagaray et al., 2010; Baguskas et al., 2014; Barbour et al., 2014; Vasey et al., 2014].

The inland incursion of the marine stratus and stratocumulus layer has a long history as an explanatory factor for coastal vegetation distribution patterns. By the turn of the last century, the term fog belt was described as “well known” in scientific literature [Cannon, 1901] and a factor for coastal redwood distribution but with no precise definition. The term fog belt has continued to be used without being well defined [Shreve, 1927; California Department of Water Resources, 2012].

Higher-resolution maps that can better define the spatial and temporal variability of FLCC will improve our understanding of landscape-level ecosystem dynamics of coastal California systems; however, generating these maps is challenging. FLCC is extremely variable affecting ecosystem processes through different pathways. FLCC varies in duration sometimes lasting for days or disappearing within minutes. FLCC varies spatially with a horizontal range of 0 to 5000 km wide, vertical thickness range of tens to hundreds of meters (m), and a cloud base at 0 to 2000 m from the Earth’s surface. FLCC varies in droplet density and chemical composition. Further complicating FLCC-related landscape-level mapping and analysis is the voluminous amount of data, “big data,” that are needed to capture ecologically relevant patterns. The goal of this study is to provide FLCC indices that compress large quantities of data into manageable units that are useful for landscape-level analysis.

1.3. Satellite-Derived Fog and Low Cloud Frequency

Many satellite sensors have been used to investigate FLC. Sensors on satellite platforms that move in a Sun-synchronous orbit such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and the advanced very high resolution radiometer (AVHRR) provide views of FLC once or twice daily and have been used to investigate annual and decadal FLC variability [Platnick et al., 2003; Bendix et al., 2006; Jensen et al., 2008]. The National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES) maintains a “stationary” Earth view and provides continuous imagery every 15 or 30 minutes, day and night. An impressive effort to evaluate locations for fog water harvesting in Chile by Cereceda et al. [2003] classified pixels for 11,000 daytime GOES images from May 2001 to April 2003 as either clear sky or cloud to generate fog probability data. That study was an early inspiration for this work.

Most cloud mapping, including all the examples in the previous paragraph, uses data from the visible light channel (constrained to daytime). Shortwave and thermal infrared channels can also be used to classify pixels as clear sky or cloud at night. Low stratus/stratocumulus and high cirrus clouds have nearly opposite thermal properties that can be used to differentiate pixels of fog and low cloud (FLC) from high clouds [Ellrod, 1995; Jedlovec et al., 2008; Jedlovec, 2009]. Cirrus is a high, cold, and wispy cloud that is relatively transparent to shortwave radiation with low albedo. Stratus and stratocumulus are lower, warmer clouds with more water vapor and liquid droplets that strongly reflect shortwave radiation (high albedo). Both are effective at absorbing outgoing longwave radiation [Chen et al., 2000].

Classifying pixels in an image based on differences in thermal properties is computationally demanding due to the need to include in the computation the high temporal and spatial variability of the underlying land surface temperature [Lee et al., 1997; Jedlovec, 2009]. The absolute temperature difference between low clouds and the Earth’s surface changes as the Earth’s surface temperature changes. Both the Earth’s surface and the cloud temperatures are continuously changing during the day because they are receiving, reflecting, and, based on their temperature and composition, reemitting differing amounts of solar radiation. Throughout the day and night, clouds can absorb and reemit the infrared radiation reemitted from the land or ocean surface. In addition, the land surface is not homogeneous. Each land surface cover type has a different emissivity at the same temperature. Interannual, seasonal, and diurnal differences in solar radiation received at the surface add additional thermal variation. For cloud mapping this means that accurate classification of pixels into low, high, and no cloud categories requires changing temporal and spatial baselines, as is done in this study.

The NOAA Comprehensive Large Array-Data Stewardship System (CLASS) archive is a rich source of raw and derived satellite data and products; however, the data are not easy to process without atmospheric science
Table 1. Ecological Questions Driving the Development of FLCC Indices

<table>
<thead>
<tr>
<th>Question</th>
<th>FLCC Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Are fog and low cloud cover (FLCC) frequency patterns and plant species distribution correlated? If so, for which species and how strongly?</td>
<td>Percent FLCC over the regeneration period of the vegetation in question (years to decades)</td>
</tr>
<tr>
<td>What is the relative impact of FLCC on maximum stream and air temperatures? Can a generalized climatological relationship be extracted for use in future climate modeling and historical reconstructions?</td>
<td>Percent FLCC on a daily, monthly, annual, and decadal interval</td>
</tr>
<tr>
<td>Does FLCC affect late summer climatic water deficit?</td>
<td>Cumulative summer season FLCC and end-of-season (September) FLCC</td>
</tr>
<tr>
<td>How much does FLCC alter incident solar radiation (total intensity, direct, and diffuse)? How much does the FLCC-reduced radiation affect evapotranspiration? Does nighttime fog drip impact evapotranspiration?</td>
<td>FLCC daytime versus nighttime periods (daily, monthly, seasonal, and decadal)</td>
</tr>
<tr>
<td>How much does FLCC impact watershed hydrological variations measured against stream gage flow?</td>
<td>FLCC at intervals corresponding to stream gage data (diurnal, daily, monthly, and summer cumulative)</td>
</tr>
</tbody>
</table>

software platforms such as the Man Computer Interactive Data Access System (McIDAS) [Santek et al., 2006]. Nonetheless, GOES data are being used increasingly for more than their original purpose of real-time weather forecasting. Iacobellis and Cayan [2013] derived daytime GOES cloud reflectivity (cloud albedo) as a proxy for cloudiness and, in conjunction with radiosonde-derived vertical environment profiles, found inversion base height to be a key driver of inland FLC incursion.

Near-real-time FLC products are made available for aviation and weather forecasting purposes, but long-term archived data suitable for historical analysis of interactions between coastal fog and ecological systems are not. As a result, the natural resource management community of north and central California still lacks quantitative assessments of fog frequency and distribution suitable for ecological analysis. The data products produced by this study use archived night and day GOES imagery, with high temporal frequency, to produce indices relevant to both diurnal and nocturnal processes and suited to investigate ecological impacts associated with variations in FLC.

1.4. FLCC Indices for Ecological Application

As previously described, FLCC impacts coastal ecosystems by modifying the basic constituents of ecosystem processes: water and energy. This suggests that improved quantification of FLCC is relevant to a potentially wide and overwhelming range of ecological applications, from empirical and fundamental biogeographical questions about FLCC thresholds associated with geographic distributions of coastal species to mechanistically based predictions about how changes in an FLC regime impact ecological function.

Many different indices could be extracted from satellite data to describe key FLC and FLCC parameters to facilitate ecological analyses. Understanding FLCC-related processes with distinct temporal mechanisms requires that FLCC data sets be extracted into indices for those relevant time periods. To make the study more tractable, a set of key ecological questions (Table 1) were identified by an interdisciplinary group of land managers and scientists during the April 2012 Pacific Coastal Fog Workshop, Menlo Park, California (see http://geography.wr.usgs.gov/fog/archives.html). The questions were used as a starting point to identify specific temporal intervals of FLCC variability that would be ecologically relevant and the specific type of information to be contained within the index for that time interval.

Questions related to broad distributional patterns such as “what are the FLCC thresholds associated with landscape patterns of maritime chaparral, redwood forest, and other coastal California natural communities?” could be addressed with maps of FLCC patterns from a decadal time frame. Questions that are associated with radiation budgets such as “what is the relative impact of FLCC on stream temperatures?” or those related to evapotranspiration would require FLCC indices for both the daytime period of direct solar irradiance and the nighttime period of reemitted infrared. In the Mediterranean climate landscape a strong indicator of relative impact on plant growth is the climatic water deficit (CWD) during September, usually the hottest and driest time of the year. Two time periods that would contribute to investigations of the impact of FLCC on CWD are cumulative summer season FLCC and September FLCC. The latter would help assess how much FLCC attenuates the arid conditions at the end of the summer season.

In addition to the challenge of defining time intervals for indices is the challenge of defining the unit of analysis for the indices. Table 1 lists several different units associated with different questions. For example,
questions relevant to broad decadal patterns list percent cover as the unit of analysis, whereas questions regarding CWD require cumulative hours of FLCC over the entire specified time interval. For this study we use “hours per day” (h/d) as the unit of analysis. This measure is similar to percent cover in that it provides a relative percentage of cover; however, rather than a base of 100, it uses a base of 24 h. Either measure could be used; however, our use of h/d is intended to facilitate an intuitive grasp of the amount of FLCC affecting the ecological process of interest on a daily time step.

The indices are intended to repurpose FLCC data into an easy-to-use format that can be added directly into models, algorithms, or digital maps. The indices represent an important climate variable that can be used to help answer questions about the impact of FLCC on coastal ecosystems in both wild and urbanized settings.

2. Methods

The geographic study area is the California coast from latitude 34.50°N, Point Arguello, Santa Barbara County, to latitude 41.95°N, north of Crescent City, Del Norte County. The study focuses on the dry season defined as June–September when the impact from FLCC is greatest and the co-occurrence of other cloud types such as cirrus and rain clouds is minimal.

2.1. The CIRA Cloud and No Cloud Image Archive

Producing a cloud composite climatology is conceptually simple but operationally time consuming [Reinke et al., 1992].

The set of hourly cloud maps derived from NOAA GOES data for meteorological purposes using the image processing method as described in Combs et al. [2004, 2010] was used for this study. The image processing method is repeated in condensed form below to support the informed use of FLCC indices. Users are encouraged to review the published methods for greater detail about the algorithms and the method in general. The image processing steps use data from three GOES channels to classify each pixel as clear sky, low cloud, or high cloud. As described in section 1.3 both temporal and spatial comparisons are needed to accurately differentiate clouds from the Earth and ocean surface. Crucial to the description below is the concept of a “month-hour.” Due to Sun angle, thermal loading, and other conditions that change hourly throughout the day, satellite images taken at 10 A.M. local time during June will be more similar to each other than to images from June midafternoon. The June 10 A.M. images will also be more similar to July 9 A.M. images than to June midafternoon images. To improve the image classification process, image files are separated by month and by hour into month-hour groups.

The Cooperative Institute for Research in the Atmosphere (CIRA) ground station collects GOES data daily. The data are the same as those collected by other ground stations and available for download from NOAA CLASS. Data from June 1999 to September 2009 were used to derive hourly cloud maps for the study period. Cloud classifications were generated using GOES West Imager sensor data from channel 1, visible wavelengths (0.55–0.75 μm); channel 2, shortwave infrared (3.6 μm); and channel 4, longwave infrared (10.7 μm) wavelengths. Channel 1 spatial resolution is 1 km, whereas channels 2 and 4 are 4 km. The 1 km channel 1 data were resampled to match the 4 km resolution of channels 2 and 4 after processing. Channel 1 data were compiled for daylight hours and channels 2 and 4 for all hours. Daytime imagery was classified using all three bands, whereas nighttime imagery, with no data in the visible channel, was classified using just the two infrared channels, shortwave channel 2 and longwave channel 4.

Low clouds tend to be the same temperature as the ground; however, their emissivity differs from the ground, especially at night. The difference in cloud emissivity is picked up by using two infrared bands each sensitive to energy transmitted within different wavelengths (3.6 μm or 10.7 μm). Solar energy, with its daily, seasonal, and interannual variation changes, changes the temperature of the Earth’s surface. Matching image pairs by hour, month, and year, as described below, compares images with similar seasonal and time of day conditions. [Jedlovec and Laws, 2003].

Using the Jedlovec and Laws [2003] algorithm, channels 2 and 4 image files were matched according to time (an image pair for each hour of each month for each year) and divided into month-hour sets. For example, 30 channel 2 images were paired with their 30 temporally equivalent channel 4 images generating 30 image
Table 2. Temporal Summaries of GOES-Derived Hourly Fog and Low Cloud Data for the Dry Season (June–September) for 1999–2009

<table>
<thead>
<tr>
<th>Index Number</th>
<th>Index Descriptiona</th>
<th>Data Compression Ratio</th>
<th>Total Maps in Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Summertime fog and low cloud cover frequency for summer (June–September)</td>
<td>Decadal (1999–2009) average FLCC average hours/day</td>
<td>26,352:1</td>
</tr>
<tr>
<td>1.2</td>
<td>Total FLCC (1999–2009)</td>
<td>Total FLCC hours over summer over 9 years (1999–2009)</td>
<td>26,352:1</td>
</tr>
<tr>
<td>2.1</td>
<td>Annual summer FLCC frequency (June–September)</td>
<td>Average annual (1999–2009) daily summer</td>
<td>2,928:1</td>
</tr>
<tr>
<td>2.2</td>
<td>Total summer season FLCC (1999–2009)</td>
<td>Total FLCC hours each summer for 9 years (1999–2009)</td>
<td>2,928:1</td>
</tr>
<tr>
<td>3</td>
<td>Diurnal summer season FLCC</td>
<td>Summer season FLCC h/12 h period (day and night)</td>
<td>1,464:1</td>
</tr>
<tr>
<td>4</td>
<td>Monthly FLCC</td>
<td>Total FLCC each month</td>
<td>720 or 744:1</td>
</tr>
<tr>
<td>5</td>
<td>Diurnal monthly FLCC</td>
<td>Monthly FLCC h/12 h period (day and night)</td>
<td>360 or 372:1</td>
</tr>
<tr>
<td>6</td>
<td>Hourly summer FLCC</td>
<td>For each summer, number of days with FLCC on an hourly basis</td>
<td>122:1</td>
</tr>
<tr>
<td>7</td>
<td>FLCC hourly by month</td>
<td>For each month, total number of day with FLCC on an hourly basis (e.g., 24 h/d)</td>
<td>30 or 31:1</td>
</tr>
</tbody>
</table>

*There are two versions of all maps: “all clouds” (1999–2009) and “low clouds” (1999–2005); see text for further explanation.
*bThis is the number of maps per permutation (e.g., day or night).
*cThese maps are also available in “total hours” units.

For each image pair, a difference value was calculated for each pixel by subtracting the 3.6 μm brightness temperature value from the 10.7 μm brightness temperature value. Next, three new image files are generated for each hour by selecting, from the 30 (or 31) image pairs, (1) the largest negative difference (LND), (2) the smallest positive difference (SPD), and (3) the warmest 10.7 μm temperature value (WTV) for each pixel location. These three image files were then used to perform two threshold tests. The first is the minimum difference test. If the 10.7 μm to 3.6 μm temperature difference value for a given pixel in an image pair is negative, and the difference is less than the LND value minus a threshold value (in this case 5.1K over land, 4.1 K over ocean), it is tagged as cloud. Otherwise, it is considered clear. If the difference is positive and if the difference minus the SPD value is greater than the LND value minus a threshold value (in this case 5.1 K over land, 4.1 K over ocean), it is tagged as cloud.

During daytime hours when visible channel 1 data are available, an additional test is used to catch any pixels that were misclassified as clear using the channel 2 and channel 4 difference test. Misclassification during the day can occur because shortwave channel 2 receives reflected shortwave solar radiation unlike nighttime conditions when only reemitted shortwave is received. This last test that uses the Reinke et al. [1992] method is performed on pixels classified clear in the previous steps. For each pixel location, all channel 1 images within a given month-hour set are compared and the minimum value (excluding values within suspected cloud shadow regions) is determined. This results in a cloud-free image called a “background.” Then each image in the group is compared to the background image. Previous clear pixels were retagged cloudy if their value was greater than the background plus a threshold value for that location.

The final step was to assign cloud height. Each cloud pixel is further identified as “low” or “high” depending on whether the 10.7 μm temperature is below or above a threshold of 273 K. A pixel identified as high does not necessarily mean that there is not a low cloud below the high cloud, just that the satellite “sees” only the high cloud.

The GOES images were processed using the above algorithms written in Fortran to produce hourly cloud maps [Combs et al., 2004, 2010] and ingested into the geographic information system (GIS) conversion process as McIDAS area files.

2.2. Calculated Statistics

Each FLCC index (Table 2) is the result of a data compression of hourly classified image files into a single georeferenced digital raster. The value of each pixel in the raster (map) is the calculated result of spatial statistics routines coded as Python scripts and run in ArcMap (Environmental Systems Research Institute, ESRI, v10.2.2, 2014). Individual hourly image files from CIRA were used in their native binary format to quality control the indices and to identify specific image files to remove from the calculations. The most common reason for
removal was poor image quality during dusk and dawn when extreme Sun angles impact brightness values. Substitutions for removed hour data were made by averaging the hour before and hour after. Monthly averaged hour (month-hour) files from the CIRA archive for the summer season were converted into geographic information system (GIS) raster file format using McIDAS and the public domain National Oceanographic and Atmospheric Administration [2015] [Ansari et al., 2010] and GIS software [Environmental Systems Research Institute (ESRI), 2014]. The summer season included September because it exhibits a combination of high temperatures and negligible rainfall, resulting in high cumulative water deficit. For years 2006–2009, image files with only a binary classification of cloud-no cloud (e.g., no low cloud class) were used in GIS processing. Month-hour FLCC rasters for 1999–2005 (both high and low cloud classes) and 1999 through 2009 (one cloud class) were aggregated into seven different indices (Table 2) to investigate diurnal, monthly, seasonal, interannual, and decadal patterns. Diurnal indices are defined by two 12 h periods. Nighttime hours are 3:00 to

<table>
<thead>
<tr>
<th>Location Number</th>
<th>Location (North to South)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Eureka/Humboldt Bay</td>
</tr>
<tr>
<td>2</td>
<td>Cape Mendocino</td>
</tr>
<tr>
<td>3</td>
<td>Point Arena</td>
</tr>
<tr>
<td>4</td>
<td>Petaluma Gap</td>
</tr>
<tr>
<td>5</td>
<td>Point Reyes</td>
</tr>
<tr>
<td>6</td>
<td>Montara/Half Moon Bay</td>
</tr>
<tr>
<td>7</td>
<td>Año Nuevo</td>
</tr>
<tr>
<td>8</td>
<td>Monterey Bay</td>
</tr>
<tr>
<td>9</td>
<td>Salinas Valley</td>
</tr>
<tr>
<td>10</td>
<td>Big Sur Coast</td>
</tr>
<tr>
<td>11</td>
<td>Los Osos Peninsula</td>
</tr>
<tr>
<td>12</td>
<td>Point Arguello</td>
</tr>
</tbody>
</table>

Table 3. List of Locations With FLCC Spatial Patterns of Particular Interest

Figure 1. Hours of summer high clouds (June–September) averaged over six summers, 1999–2005. The majority of the California study area boundary (dashed line) has less than 48 h of summer high clouds (1%). The northern portion of the study area has up to 96 h of summer high clouds (3%).
14:00 coordinated universal time (UTC), local time 7 P.M. to 6 A.M. Pacific daylight time (PDT). Daytime hours are 15:00 to 23:00 and 0:00 to 3:00 (7 A.M. to 6 P.M. PDT). Henceforth, local time will be used.

Data were missing for August 2001 and June 2006 leaving only nine full summers for interannual and decadal calculations. Monthly averages from all 11 years were used when available. Data compression ratios range from 26,352 h for the 9 year summertime FLCC index to 30 or 31 h for one month-hour index. Spatial patterns of interannual variability are characterized by standard deviation (SD) and coefficient of variation (CV).

Two groups of sites were selected to describe patterns found in the indices for the results and discussion sections. The first group, 12 generalized locations, was selected based on spatial and temporal patterns of interest (Table 3). The second group of six locations was selected for pixel-based time series analysis. Each

Figure 2. Decadal FLCC index. Mean FLCC h/d averaged over nine summer seasons (June–September, 1999–2000, 2002–2005, and 2007–2009) for the north and central California coast. Black outlines depict coastal counties, from north to south (and clockwise around the San Francisco Bay-Delta coastline): Del Norte, Humboldt, Mendocino, Sonoma, Marin, Napa, Solano, Contra Costa, Alameda, Santa Clara, San Mateo, San Francisco, Santa Cruz, Monterey, San Luis Obispo, and Santa Barbara. Numbered map locations are also listed in Table 3: 1 = Eureka/Humboldt Bay, 2 = Cape Mendocino, 3 = Point Arena, 4 = Petaluma Gap, 5 = Point Reyes, 6 = Montara/Half Moon Bay, 7 = Año Nuevo, 8 = Monterey Bay, 9 = Salinas Valley, 10 = Big Sur Coast, 11 = Los Osos Peninsula, and 12 = Point Arguello.
pixel location corresponds to a colocation site where various fog-related research projects are being conducted [Torregrosa et al., 2014].

2.3. Difference Map

To explore the impact on FLCC calculations using data that do not differentiate between high and low clouds, a difference map was generated using two data sets for the same six summers, 1999 to 2006. One data set quantified cloud cover based on three classes: clear sky and two cloud classes (high cloud and low cloud). The other data set quantified cloud cover using two classes: clear sky and cloud.

2.4. FLCC Contours and Elevation Profile

The 9 year summertime average FLCC raster (decadal index) was interpolated into a contour vector map using the ArcGIS Spatial Analyst functions with bilinear convolution [ESRI, 2014]. The contour map delineates 13 zones of FLCC from < 2 hours per day (h/d) to more than 14 h/d. An exploratory analysis of the relationship between FLCC contours and elevation was conducted to expand and provide precision for the concept of a “fog belt.” Elevation pixels with 270 m resolution were extracted along decadal FLCC h/d contour lines using the ArcGIS Zonal Histogram Spatial Statistics function [ESRI, 2014]. These were binned into 100 m elevation intervals to examine the elevation profile along an FLCC h/d contour.

3. Results

3.1. Low Versus High Cloud Cover

The difference map of low clouds subtracted from all clouds (Figure 1) shows a north-south gradient with more high clouds in the north and a curved west to southeast pattern. The latitudinal zonation corresponds
to increased summer storms from the Pacific that contribute more high clouds at increasing latitude. The influence of the Cascades and Sierra Nevada mountain ranges, both situated at longitudes well inland from the study area, contributes to the curved pattern east of the study boundary. The majority of the California coast averages high clouds for less than 48 of the 2928 h of summer (1.6%). The north section of the coast averages 3% high cloud cover. As an average, high clouds contribute from 0.5 h/d in the south to 2.25 h/d at the Oregon border. Given the low occurrence of high clouds and the improved statistical robustness from using an additional 5 years of data, the 11 year single-cloud-class data set is used to explore FLCC patterns, except where specified. Subregions of particular interest, such as the San Francisco Bay Area, are in the zone least affected by high clouds during the summer.

3.2. Decadal Summertime FLCC Patterns

The decadal (1999–2009) summer FLCC index (Figure 2) for coastal north and central California shows a zone of FLCC incursion onto land. Twelve locations (Table 3) are used to describe localized patterns that form in response to specific interactions between the atmosphere, ocean, and land processes that drive FLCC formation, movement, and dissipation. These locations will be referred to in the text by their location number (LN).

3.2.1. Average FLCC Hours per Day

The decadal FLCC pattern over the ocean does not exhibit as much spatial variation as the FLCC pattern over land. In general, over the ocean and parallel to the coast, there is a NW to SE increase in FLCC h/d from 9 to 10 h/d at the 41° latitude to more than 14 h/d at the southern edge of the study area at the 34.5° latitude. The open ocean NW to SE pattern changes to a NE to SW pattern south of major capes such as Cape Mendocino (LN 2), Point Arena (LN 3), Point Reyes (LN 5), and Año Nuevo (LN 7). A similar NE to SW pattern also extends close to the Big Sur coast (LN 10) past Los Osos (LN 11). This latter NE to SW FLCC feature is parallel to a steep stretch of high-elevation coastal mountains abutting the ocean. The FLCC ocean contours near Humboldt Bay

Figure 4. Interannual variation mapped across the landscape: (a) standard deviation and (b) coefficient of variation both derived from the decadal FLCC index of mean h/d for nine summers (June–September 1999–2001, 2002–2005, and 2007–2009). Geographic locations are numbered as in Figure 2 and Table 3.
and along the San Mateo coast (LN 6 to LN 7) are similarly parallel; however, rather than increasing h/d bands NE to SW, FLCC increases from SW to NE, reaching >14 h/d at the coastline. The open ocean area with the least FLCC (8–9 h/d) is the large area south of Cape Mendocino (LN 2) extending well off the coast.

The FLCC patterns are more complex over land and out on the ocean within 20 km of land. FLCC patterns are strongly associated with terrain features and orientation of terrain to the prevailing NW wind. Stretches of coastline that face NW have the highest FLCC, Humboldt Bay (LN 1), Mendocino Coast north of Point Arena (LN 3). Point Reyes (LN 5), San Francisco-San Mateo Coast (LN 6 and LN 7), Monterey Peninsula/Salinas River mouth (LN 8 and LN 9), Morro Bay (near LN 11), and the Los Osos Peninsula north of Point Arguello (LN 12). Conversely, stretches of coastline with least FLCC are those facing SW, south, and in the lee of major capes, notably south of Cape Mendocino (LN 2), Point Arena (LN 3) to Bodega Bay (north of LN 5), Año Nuevo (LN 7) to Monterey (LN 10), and the Big Sur coast (LN 10) south of Monterey Bay.

The greatest inland incursion of FLCC is through low-elevation NW to SE valley systems open to the ocean. These long incursions include Humboldt Bay-Eel River (100 km, LN 1), Petaluma Gap-Russian River (75 km, LN 4), San Francisco Bay and offshoot valleys (maximum 85 km, between LN 5 and LN 6), Monterey Bay-Pajaro River (60 km, LN 8), Salinas River Valley (140 km, LN 9), and Los Osos-Santa Maria River (20+ km, LN 11 and beyond map extent).

Stretches of NW to SE oriented coastlines with high, steep mountains have very low FLCC. Three examples in the study area are the Big Sur coast (LN 10), the Sonoma coast north between Petaluma Gap (LN 4) and Point Arena (LN 3), and the southern end of the King Range south of Cape Mendocino (LN 2). Contrary to common perception, not all steep coastal mountains are good at blocking advecting marine stratus. The orientation and length of the mountainous stretch of coastline is important. Three areas with high steep coastal mountains that rise precipitously from the ocean have high FLCC including the northern 30 km stretch of the King Range next to Cape Mendocino (LN 2), the coastal mountains north (LN 5) of the entrance to San Francisco Bay (SF Bay), and south (LN 6) of the SF Bay entrance.

Figure 5. Diurnal pattern of decadal FLCC along the north and central California coast: (a) mean FLCC h/d for the 12 h/d period (7 A.M. to 6 P.M.), (b) the 12 h night period (7 P.M. to 6 A.M. local time), and (c) the fraction of FLCC that occurs at night. See Figure 1 for identification of counties outlined on the map and the seven numbered areas.
3.2.2. FLCC in Complex Terrain

A closer view of FLCC at the regional scale (Figure 3) shows a more complex pattern. The highest FLCC contour (>14 h/d) along the central coast touches land at Montara and Año Nuevo south of San Francisco. A series of mountainous barriers (listed clockwise) restricts the inland incursion of FLCC: Sonoma Coast Range, Mayacamas Mountains (Mtns), Mount Diablo, Mount Hamilton Range, Santa Cruz Mtns, and in the middle Mount Tamalpais. Between these barriers FLCC has highs of 13 h/d at three low-lying gaps closest to the ocean: Petaluma, San Francisco, and the coastal plains at the entrance to Salinas and Pajaro Valleys. Except for the low FLCC values in the shadow of Mount Tamalpais, FLCC is highest closest to the ocean and in a continuous line east and into valleys across from the gaps. Russian River and Santa Clara Valleys mirror each other with highs of 7 to 10 h/d. The East Bay Hills have high FLCC (9–10 h/d) due to their position east of the San Francisco gap along a straight line to the low-lying delta. Napa and Livermore Valleys, more distant from the ocean, have 5 h/d FLCC.

The Santa Cruz Mtns produce a complex fog pattern. The northern section of coast from Montara to Año Nuevo receives 9 to 14 h/d, whereas the southern section of coast from Año Nuevo to Santa Cruz receives half that amount, 4 to 7 h/d. The northern section is west facing, whereas the southern section is SW to south facing. The higher elevations (400 to 1000+ m) of the southern Santa Cruz Mtns form a relatively fog free island (3 to 5 h/d) compared with the northern Santa Cruz Mtns (5 to 8 h/d). The bayside flats and foothills (<100 m) experience 9 h/d in the north and 4 h/d south toward the Santa Clara Valley.

The Santa Clara Valley also funnels fog south from San Francisco Bay with a gradient from 6 h/d at the south end of SF Bay to 3 h/d in Coyote Valley. The lower elevations (100 to 300 m) of the Mount Hamilton Range are still in the fog belt, but the higher elevations (>400 m) experience <3 h/d, similar to other highlands of the Inner Coast Range.

Figure 6. Site-based FLCC statistics at six locations. (a) Decadal average FLCC for the month of July (1999–2009) with six sites mapped from north to south: Trinidad Head, Pepperwood Preserve, Bodega Bay Marine Labs, Montara Lighthouse, Santa Cruz, and Marina Airport. (b) Interannual FLCC coefficient of variation, top scale, and bottom scale, hours per day, for decadal seasonal mean FLCC and decadal FLCC range (June–September) for nine summers (1999–2000, 2002–2005, and 2007–2009) for the six sites shown on map in Figure 6a. (c) Mean decadal FLCC for nighttime (7 P.M. to 6 A.M.) and daytime (7 A.M. to 6 P.M.) at six locations.
3.2.3. Interannual Variability

The area of FLCC standard deviation (SD) that is highest (>2.5 h/d) and largest (Figure 4a) occurs over the ocean near the steep Big Sur coast (LN 10). The largest cluster of high SD on land occurs at the mouth of the Salinas Valley (LN 9) and continues offshore over Monterey Bay (LN 8). Smaller clusters of very high SD occur on the inland curving portion of SW facing coastal features (south of LN 3, LN 5, LN 7, LN 11, and LN 12). A few areas of moderately high SD (>0.9) are north of Point Arena (LN 3) and Humboldt Bay (LN 1). Coastal areas with the lowest SD are the same areas where average decadal FLCC is lowest (south of LN 2, Santa Cruz north of LN 8, and inland of LN 10) and the higher elevations east of LN 10 (Figure 2); however, not all areas of low FLCC have low SD.

The coefficient of variation (CV) provides a complementary measure of interannual variability as a function of FLCC (Figure 4b). Uniformly low CV (<0.10) occurs, in general, in areas with greatest FLCC (6 to 14 h/d, Figure 2). Along the immediate coast, the highest values of CV (>0.35) occur along the Big Sur coast (LN 10) almost to Los Osos (LN 11) where FLCC is low (<3 h/d). Moderately high CV (0.20 to 0.35) occurs where FLCC is low (3 to 4 h/d), and SD ranges from 0.75 to 1.0 h/d, except for the patch just south of Cape Mendocino (LN 2). Interannual CV is highest in the areas of lowest FLCC (<2 h/d), and SD < 0.5 h/d.

3.2.4. Diurnal Patterns

The FLCC daytime and nighttime pattern (Figure 5a) is different over ocean and land. Over the ocean FLCC is higher (6 to 9 h/d) during the day period than the night period (4 to 6 h/d), whereas over land, the range in

Figure 7. Monthly variation (June–September) in FLCC at six sites over nine years, 1999–2000, 2002–2005, and 2007–2009. (a) Monthly mean FLCC h/d, (b) 9 year monthly mean FLCC, and (c) 9 year mean FLCC interannual CV.
FLCC is equivalent during the two periods (5–9 h/d), but there is more land area that is covered with FLC (LN 4, LN 7, LN 9, LN 11, and LN 12). The nighttime fraction of FLCC shows this most clearly. When there is FLCC over land, it is present more often at night than during the day (Figure 5c). Nighttime fraction of FLCC is high (0.6) along most coastal areas with notable exceptions, the Big Sur coast (LN 10) and south of Cape Mendocino (LN 2).

### 3.3. Time Series at Selected Points

The time series analysis of FLCC month-hour means for June 1999 to September 2009 at six point locations (Figure 6a) shows strong spatial trends. Trinidad Head (Trinidad) represents the Humboldt Bay system. Bodega Bay Marine Labs (Bodega Bay) and Pepperwood Preserve (Pepperwood) span a regional coast-to-inland gradient. Montara Lighthouse (Montara), as previously described, is the landfall location for the highest contour of the decadal FLCC index. The Santa Cruz and Marina Airport (Marina) sites contrast conditions within Monterey Bay.

The statistical summary (Figure 6b) of seasonal averages shows that Pepperwood had the most interannual CV (0.215) and Trinidad the least (0.06); Marina had the greatest range (4.25 h/d) and Santa Cruz the least (1.3 h/d); and Montara had most FLCC (13.9 h/d) and Pepperwood the least (3 h/d). In contrast with the pattern of higher night fraction FLCC in inland areas with low mean FLCC (Figure 5c), all sites had more FLCC hours during the daytime period.

The monthly 9 year climatology for these sites (Figure 7a) provides more detail. Month-year FLCC h/d averages have a wider range than FLCC seasonal averages (Figure 6b). The site with the highest month-year FLCC was Montara in July 2001 (19 h/d), and the site with the lowest was Pepperwood in lowest relative monthly variability June 2002 (0.6 h/d). In general, Montara, Trinidad, and Marina have the highest FLCC h/d (Figure 7b). Pepperwood and Santa Cruz have the lowest FLCC h/d. Trinidad and Montara have the lowest relative monthly variability (Figure 7c). June and September are generally more variable across sites than July and August. The pattern of relative monthly variability is strongly site specific.

### 4. Discussion

The data presented here provide first-order FLCC climatology across the north and central California coast with high spatial resolution (~4 km), based on hourly satellite images. The spatial and temporal continuity of the data set is unique. Satellite observations provide wall-to-wall coverage of FLC, which eliminates the need for interpolation. Wall-to-wall coverage also provides a base for deriving statistical relationships with topography, synoptic meteorology, and other spatially explicit modeling methods and allows for the extraction of fog climatology and monthly time series at any point location within the landscape. The hourly time step and the ability to calculate total FLCC h/d contrast with other satellite records that take snapshots (i.e., daily MODIS at 10:30 and 14:30 [Fischer et al., 2009; Sawaske and Freyberg, 2014]) and do not resolve clouds at night when the majority of the deepest FLCC inland incursion occurs (Figure 5c). At the inland edge of FLCC incursion, FLCC often dissipates earlier than 10:30 A.M. and is therefore not fully captured by MODIS or AVHRR.

Point records, including airport observations and station data, have high temporal resolution but not continuous spatial coverage. Maps of FLCC zones based on high-frequency interpolated solar radiation data, such as the fog belt zones derived from the California Irrigation Management Information System (CIMIS) meteorological stations, tend to have coarse-scale spatial resolution (http://www.cimis.water.ca.gov/Content/PDF/CmisRefEvapZones.pdf). Importantly, solar radiation measurements only resolve daytime clouds. Other sources, as discussed below, may provide ancillary information for better calibration and analysis of FLCC effects on temperature, humidity, and vegetation.

#### 4.1. FLCC Spatial and Temporal Structure

##### 4.1.1. Terrain and Wind-Driven Patterns

Continuous FLCC coverage reveals many consistent spatial patterns. FLCC has generally been linked to topographic effects. We show in this study that indeed the primary factor for FLCC spatial pattern is topography; however, terrain feature placement with respect to wind direction and length of terrain feature is also of primary importance. Under the current decadal wind regime, terrain features less than 30 km do not tend to divert FLCC.
Windward (W-NW facing) coastlines have more FLCC than leeward coastlines (SW-S). There are "FLCC shadows" downwind of major headlands/peninsulas, and these areas tend to have higher interannual variability (CV). The occurrence of FLCC in these pockets is reliant on southerly surges of FLCC, which irregularly occur through the summer in contrast with the strong prevailing W-NW winds. During June–September 2006 to 2014 at Point Reyes, the most exposed land station, W-NNW winds occur 60% of the time, but southerly (SSW-SE) winds occur 32% of the time (Figure 8) [Western Regional Climate Center, 2015]. Several authors have identified these southern surges with cyclonic vorticity resulting from a bend in the relative angle of the coastline producing changes in low-level wind speed and direction such as the Catalina eddy in the California Bight off the coast in Southern California and the recently named Santa Cruz eddy [Archer et al., 2005; Hu and Liu, 2002; Parish et al., 2013].

4.1.2. FLCC Zones

The histogram of elevation pixels extracted along the 3 h/d FLCC contour of the Inner Coast Range south from 39.6 N (Figure 9a) shows a distinct dropoff in FLCC above 500 m, although the tail of the distribution extends above 1000 m. A similarly constructed histogram for the Santa Lucia Range (Figure 9b) shows a more gradual decline in the elevations along the 3 h/d FLCC contour, with the sharpest drop at >600 m, a tail extending to 1400 m, and highest elevations on the NW flank of the mountains downwind of the high fog Monterey Peninsula. These results are broadly consistent with the mechanisms [Wood and Bretherton, 2006; Wood, 2012] described above and the inversion heights reported by Iacobellis and Cayan [2013].

A comparison of annual average h/d FLCC derived from GOES with records of cloud ceilings below 400 m compiled by Johnstone and Dawson [2010] from Arcata and Monterey airport observations shows a strong and highly significant correlation between GOES-derived FLC and Monterey airport records with an intercept of −1.66 h and p value of 0.0005 (Figure 10). The correlation with Arcata airport records is weak as expected given the higher amount of high clouds at that latitude (Figure 1). Our maps are also consistent with the spatially explicit results from Iacobellis and Cayan [2013].

Figure 8. Wind Rose, Point Reyes, California. The predominant summertime wind direction is NW during the period of the GOES-derived cloud cover archive for 2000–2014.
The mechanisms described by Wood and Bretherton [2006] and Wood [2012] are consistent with the GOES-derived FLCC maps. Marine stratocumulus increases in frequency and lasts longer under the vertical barrier of a strong inversion that also acts to lower the FLC base heights. Inversion heights reported by Johnstone and Dawson [2010] averaged ~400 m, based on soundings at Oakland. Taken together, this information suggests that the landscape coherence in high interannual variability, expressed by the CV, (Figure 4b) at the inland limits is likely a function of inversion heights, whereas the high interannual variability expressed by the SD (Figure 4a) is more strongly related to the constraining topographic barrier to advection. Inversion heights vary through the season with the intensity of subsidence, often driven by upper level low-pressure systems that pass on an irregular basis. These systems first thicken the FLC layer, allowing higher-elevation incursions, but when inversion heights rise too high, FLC dissipate. Incursion into the higher elevations is limited to those periods when the inversion has lifted enough, but not too much. At the inland fringe, especially at lower elevations, a higher evaporative demand relative to cloud droplet condensation results in very low FLCC h/d beyond the San Francisco Bay-Delta across the Carquinez Strait. Each of the FLCC contour lines (Figures 2 and 3) represents the results of these interacting processes of FLC formation and dissipation and can be thought of as FLCC zones or more colloquially fog belt zones.

Visually integrating the geography of FLCC h/d contours of inland incursion in Figures 2 and 3 with the geography of CV reveals that the 3 h/d FLCC contour has the greatest correspondence with several delineations of fog belt zones documented by Logan [2006] and the fog belt zones in the CIMIS evapotranspiration map (http://www.cimis.water.ca.gov/Content/PDF/CimisRefEvapZones.pdf).

Throughout this study the term FLCC has been used to aggregate advecting marine stratus, stratocumulus, and fog clouds that are visible from a satellite point of view. The FLCC data set presented in this study does not resolve the vertical structure of the clouds nor their distance from the ground. This data set does empirically resolve the inland limits and h/d zones of FLCC incursion. The results of GOES-derived FLCC are in line with results from other sources that do estimate vertical structure.

### 4.1.3. Nighttime FLCC

Each FLCC index frames a specific period of time to reveal FLCC patterns that can be used to explore ecological mechanisms of interest (Table 1). The nighttime versus daytime pattern, although well known to meteorologists and anecdotally

![Figure 9](image-url) - Number of pixels extracted along the 3 h FLCC contour and binned into 100 m elevation bands (100 m to 1600 m) for (a) inner coast range and (b) Santa Lucia range.

![Figure 10](image-url) - Correlation between airport observations of fog hours and satellite-derived FLCC per day at Arcata and Monterey.

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**Figure 9.** Number of pixels extracted along the 3 h FLCC contour and binned into 100 m elevation bands (100 m to 1600 m) for (a) inner coast range and (b) Santa Lucia range.

**Figure 10.** Correlation between airport observations of fog hours and satellite-derived FLCC per day at Arcata and Monterey.
The strong pulse of nighttime FLCC into coastal ecosystems (Figure 5) provides an additional metric for delineating FLCC zones and suggests areas of expected fog cover. The pattern of high FLCC nighttime fraction, although similar to the spatial pattern of mean decadal FLCC h/d, has intriguing differences. Of the five areas with the highest FLCC h/d (Figure 2), Trinidad (LN 1), Montara (LN 6), Petaluma Gap (LN 4), Salinas Valley (LN 9), and Los Osos (LN 11), only Petaluma (LN 4) and Salinas (LN 9) have significantly high night fraction of FLCC. The opening to the San Francisco Bay through the Golden Gate has an unexpectedly low night fraction of FLCC. Nighttime FLCC incursion will bring a different set of impacts to ecosystem processes than daytime FLCC. The novel data set generated through this study will provide an opportunity to explore differences and help investigate the diurnal components of energy and water balance in these ecosystems. The vertical dimension of nighttime FLCC has received significant attention in Southern California with evidence suggesting that the observed reduction in fog frequency close to urban areas is associated with greater nighttime warming that raises ground level dew point temperature with subsequent lifting of cloud base heights [Williams et al., 2015].

### 4.2. Application of FLCC Indices

A primary motivator for developing FLCC indices was the need voiced by natural resource managers, fog water harvesters, farmers and vintners, and scientists for data that could be used to map FLCC across the landscape. The reported 33% reduction in fog over the last century [Johnstone and Dawson, 2010], although now placed in the context of known coupled cycles of ocean and atmosphere systems [Johnstone and Mantua, 2014], was startling and brought attention to the importance of retrieving FLCC records. The current California drought and increasing summer temperatures have heightened interest in understanding long-term and future trends of FLCC. The indices we have developed have many potential applications as well as limitations.

In a letter of support for the development of FLCC indices, Kirk Lenington, Senior Resource Planner, Mid-Peninsula Open Space District, sums up several potential uses for the indices.

“Spatial and temporal fog patterns significantly influence species distributions and ecological dynamics of California coastal ecosystems. The District owns over 8,000 acres of San Mateo County Coastland with a diverse range of plant and animal species, many of which are rare, threatened, or endangered. A historical reference of fog distribution and framework for long term fog monitoring system would greatly improve our ability to evaluate locations of unique or climatologically sensitive habitats, and develop more informed strategies for land management and future land acquisitions. Such products are particularly urgent given potential changes to fog patterns caused by climate change.”

“Fog distribution information is also crucial for making well-informed decisions regarding native plant restorations. In cases where the District has acquired land with severe ecological disturbance, lack of information of fog frequency and location has made identifying target restoration species challenging. Products from (this) project would be of immediate use in determining the restoration objective for a disturbed site by selecting an appropriate nearby reference site that has similar fog patterns” (8 April 2011).

FLCC indices can be especially useful when merged with other data such as climatic water deficit (CWD) maps [Flint and Flint, 2014]. An overlap of FLCC and CWD maps would provide additional climatic resolution to identify areas of highest aridity, e.g., high CWD values and low FLCC values, from those of lesser aridity, e.g., high CWD and high FLCC. This information could be useful for habitat restoration. Other ancillary information such as data from ground fog monitoring stations would also improve the usefulness of FLCC indices to land managers.

FLCC indices are an aggregate of three types of clouds, those touching the ground (fog), fog as defined by airport observations (e.g., clouds with an aboveground base < 400 m), and warm low clouds with an undetermined base height and a cloud top height usually below 1000 m (as previously described). The combination of a cloud touching the ground (fog) and high relative humidity does not always result in fog drip. Many factors influence the dynamics of water delivery from clouds: water droplet size and density, aerosol composition, wind speed, and all the atmospheric dynamics that affect an air parcel's trajectory and evolution [Gonser et al., 2012; Wilkinson et al., 2013; Degefe et al., 2015a, 2015b].
Under favorable conditions, fog drip can produce substantial local moisture for restoration and other uses [Estrela et al., 2009; Domen et al., 2014; Katata, 2014; Batisha, 2015]. Fog events vary in liquid water content and droplet size [Yin et al., 2014]. The amount of fog drip that will result from a fog event depends first on the relative exposure of the site where the fog cloud intercepts the land surface then on local topography and vegetation structure. Onshore winds drive a “conveyor-like belt” of clouds onto windward slopes, producing large amounts of fog drip. Leeward slopes have reduced fog drip [Sawaske and Freyberg, 2014].

Fog drip produced during the nighttime period can proceed with minimal evaporation. The elevation band between the cloud base and cloud top will be in contact with the land surface. Analysis of cloud base observations from airports and soundings colocated to the GOES data and a digital elevation model can identify areas of high potential fog drip. In addition to ameliorating summer drought for vegetation, fog drip hot spots can contribute enough moisture to affect low flows in coastal streams [Sawaske and Freyberg, 2014]. The identification of fog drip hot spots could inform vegetation management to maximize fog drip potential by retaining large trees that are particularly efficient at intercepting fog.

As mentioned earlier there are many potential uses for FLCC indices. One example that bears mention for its relevance to endangered species restoration activities, for the recently released Coho Salmon Recovery Plans for the Central California Coast and Northern California/Southern Oregon Coast [National Marine Fisheries Service, 2012], is the use of FLCC indices to identify areas where FLCC acts to strongly reduce incident solar radiation to streams and lower riparian evapotranspiration. The cascading effect of the shade and fog drip provided by FLCC includes increased low flows and reduced maximum stream temperatures in late summer. Steam temperature is a fundamental constraint on cold water fisheries, especially endangered coho salmon and threatened steelhead trout. FLCC indices could be used to identify areas with low long-term interannual variability and high FLCC h/d, two metrics that show promise as measures of climatic resilience.

### 4.3. Future Directions

Several future research areas that focus on improving FLCC indices have been identified in the preceding sections: integrating cloud ceiling height to improve the vertical dimension; extending the temporal period for the FLCC indices by adding earlier and more recent GOES data; and increasing the spatial resolution, perhaps through multisensor fusion. Other future research areas focus on the application of these indices or changing conditions that will affect the stationarity of FLCC indices such as global warming or the localized effects of urban heat island warming.

Millions of people live in coastal areas of California that are climatically influenced by FLCC. The term climatically influenced, for the purpose of this qualitative description, is defined as zones of decadal July FLCC index >9 h/d (Figure 6). In these areas, the difference in temperature between days with FLCC and days of no-cloud cover can be a matter of life or death. For more details about the higher proportion of fatalities that occurred among coastal residents during and after the July 2006 heat wave, see Knowlton et al. [2009].

Recently, record-breaking high temperatures were recorded on cloud-free 16 August 2015: 32°C in San Francisco and 40°C in Napa. On 21 August 2015, after several days of increasing FLCC, maximum temperatures had fallen back to 21°C in San Francisco and 22°C in Napa (http://www.timeanddate.com/weather/). Many are now asking: How will global climate change affect the frequency and distribution of FLCC? Although this climate change question could be thought of as just one of the many future directions for FLCC research, an approach that integrates many separate research directions may meet the challenge of answering this question more effectively.

An interdisciplinary approach for future research directions would have many of the same benefits as colo-cating disparate research projects. Spatially and temporally coincident measurements of individual system elements provide data not only for the individual system element but also for understanding system-level dynamics. Coincident measurement in a system dynamic context would advance our understanding of spatial and temporal patterns of FLCC on many fronts simultaneously.

FLCC patterns result from multiple interacting factors across multiple scales [Koračin et al., 2014; Torregrosa et al., 2014]. Recent work that quantified the connections between annual FLCC frequencies, sea surface temperature (SST), North Pacific high-pressure fields, inland temperature gradients, and other factors for the purpose of incorporating stratocumulus-forming processes into a regional climate model (RCM) at a 10 km scale shows promise [O’Brien, 2011; O’Brien et al., 2013]. O’Brien’s [2011] was able to reproduce annual...
historical patterns from Johnstone and Dawson [2010] and historical reanalysis as well as forecast fog frequency into the future. A downward trend emerged for all climate futures modeled. Similar global drivers and long-term historical trends have been observed from other coastal fog regions [Garreau, 2011; Haensler et al., 2011; Cermak, 2012; Schulz et al., 2012; Sugimoto et al., 2013]. Forecasting future temporal and spatial variability and inland penetration patterns at resolutions comparable to those of this set of FLCC indices will require an analysis that links synoptic indices, subsidence strength, and SST at finer temporal scales while capturing the variability in topography and vegetation at relevant spatial scales. Certain key synoptic indices, pressure fields and surface winds in particular, can be derived from GCM output and can provide, at minimum, projections of the directional trend in FLCC frequency. Correlating the GOES-derived FLCC record to the full spectrum of meteorological observations could provide details about the synoptic mechanisms behind the observed spatiotemporal variability on shorter time scales. Improved quantification of FLCC formation, evolution, and dissolution processes could then be used as input to global climate models as they evolve to incorporate diurnal and shorter period intervals.

Application of the FLCC is just beginning, while improvement of the FLCC indices will be ongoing. An application question that has arisen is whether the interannual stability of the spatial patterns found through the CV analysis could be used to identify climate refugia. If FLCC continues to form over the ocean and the onshore/offshore breeze continues to advect FLCC, then places that are currently the foggiest will likely continue to be the foggiest in the future. How much does the stability of FLCC heterogeneity contribute to California’s status as a biodiversity hot spot? Geodiversity [Anderson et al., 2015] sets the stage for biodiversity, might areas that have stable and diverse FLCC values provide the bioclimatic variability to incubate species diversity?

Other questions that have arisen include the use of FLCC to pinpoint monitoring stations for indicators of climate change. This question has two conceptual branches. The first is the use of FLCC itself as an indicator. FLCC h/d contours at the “leading edge” of inland incursion might be good locations to monitor as these could be the most sensitive to climate change. Conversely, change in the areas with highest FLCC h/d may indicate larger synoptic influences. Atmospheric scientists would be needed to help weigh in on a monitoring design. The second conceptual branch is the use of FLCC patterns to identify locations for monitoring indicators of the factors that change the formation, evolution, and dissipation of FLCC. These would include additional monitoring buoys to increase the spatial resolution of ocean upwelling patterns, improved analysis and understanding of the onshore/offshore breezes across the SF Bay-Delta, additional wind/temperature profiler data in both horizontal and vertical dimensions along with improved mechanistic understanding of the interaction among layered air masses; and additional data on aerosol composition with improved understanding of sea spray, cloud condensation nuclei, and long-distance aerosol transport effect on FLCC. Dynamical downscaling of fog through RCMs is in its infancy; O’Brien [2011] was able to project a decrease in fog in 2061–2069 using the CCSM-A2 climate future, but it was necessary to statistically downscale SST using historical patterns to capture the California Current and upwelling that were not captured with the coarse-scale CCSM output.

5. Concluding Remarks

We were motivated to produce these data to satisfy the high demand from many different sectors for an easy to use data set that captures the influence of FLC and the complex topoclimatic patterns of the California coastal terrain [Terjung et al., 1969] for numerical analysis of coastal ecosystem processes. Unlike the current NOAA fog products that are based on absolute thresholds to differentiate low clouds from land and ocean, these data were derived using relative thresholds along both spatial and temporal dimensions, a more computationally demanding approach.

The digital data produced by this study will allow resource managers to ingest fog and low clouds into their spatial analyses and directly inform their management decisions. The nighttime component is a unique and strong point of this study. Daytime and nighttime maps of FLCC will help advance scientific research into FLCC impacts on managed and natural ecosystems. FLCC maps can be overlain directly into GIS to locate restoration areas for species that require the cool and moist conditions of persistent summertime low clouds. Viticulture managers can use the maps to identify new viticultural appellations such as the Petaluma Gap. Finally, researchers trying to understand the ecosystem service contribution of coastal fog will have indices to correlate FLCC with stream temperatures at landscape levels, urban energy use, and human health effects.
References

On Nov 18, 2019, at 10:00 AM, bonnie blackberry <bonnie@civilliberties.org> wrote:

John,

A few comments about the last Planning Commission Meeting regarding the Terra Gen Wind project.

I car-pooled with some friends. We came to observe, listen and speak. When we arrived a little before 4pm, the Board Chambers was guarded by 2-3 Sheriff deputies. We were directed down the hall (to a small room that was full with standing room only left) where there was a big screen with the Planning Commission proceedings. The sound and visuals were going in and out and then it was hard to hear what was being said because of the low volume and a loud buzz.

I walked back to the lobby to see if I’d be able to hear the proceedings from there. There were approximately 50 people standing around and sitting on benches and on the floor, crowded around one small loudspeaker on the wall trying to hear what was going on in the meeting. The volume was very low, making it very difficult to hear. It was very chaotic. I ended up standing, then sitting on the floor for approximately two hours before I was allowed inside.

We had each filled out one of the small pieces of paper with our names, and gave them to the deputies at the door. As the evening went on we were seeing people who came after us being called.

At the break around 8pm I asked the woman sitting in front of the Commission if we could see where we were in the stack of papers. She came back and said she found my name, which would be #5, but she could not find the names of the people I car-pooled with. Since we didn’t find their names, after hours of waiting, we left to spend another 2 hours driving home.

It’s obvious that there is a great public interest in this project. I assume that fast tracking is why there is no time to find an appropriate venue to accommodate the people who show up to participate. Standing around and sitting on the floor in the lobby for hours, trying to hear the proceedings after driving long distances to attend is very frustrating.

Suggestions:

1. Have a numbered sign up list with copies so that the commission as well as the people waiting to speak would be able to see where they are in the line.

2. If unable to find a larger location for a meeting when there is a great deal of public interest, then need to make accommodations so the people who make the effort to attend can actually at minimum hear the proceedings.

If people are forced to hang out in the lobby, how about some chairs and higher volume on the one wall speaker or multiple devices for listening.
I’ll probably be at the next meeting to try again,

Bonnie
Dear Humboldt Government,

I am opposed to the Wind Farm proposal on Bear and Monument Ridges. Reading some recent arguments both pro and con, this Scotia official, Mr Frank Basik speaks for what I believe. I’ve cut and pasted what he wrote and sign my name in support of his arguments.

“I’ve identified 24 plans, permits and programs that have been deferred,” he said referring to the Terra-Gen DEIR. “Everybody who submitted comments of a legal nature pointed out that this project defers too much of the environmental review.

“… Looking at the night-lighting of the windmills, we don’t know what the impacts will be. We don’t know how many lights will be required. We don’t know what the impacts are and how they should be mitigated. That’s because we didn’t do the Part 77 consultation with the FAA [Federal Aviation Administration] yet. … Why wasn’t that done before we get here?

“How about the incidental take permits that will be necessary for management in the way that we’ll take endangered species? It’s a federal crime to take endangered species unless you have an incidental take permit. Even if you believe the analysis that only seven marbled murrelets will be killed, you still need an incidental take permit. Why wasn’t that permitting done? We don’t know what the mitigations will be.

"...This commission and this staff is not competent to determine whether a take will occur or won’t occur, how many takes will occur and how to mitigate them. And you cannot give a permit. So why are we spending our time assessing this project when these key restrictions are not yet known?

“Another one would be timber harvest planning. This is a 21-mile clear-cut that will be undertaken for the right-of-way. There’s no conversion permit in the hopper. There’s no timber harvest plan for harvesting all the trees that it will be necessary to remove for the road construction. ... We don’t know what mitigations will be required by CalFire and we can’t make an informed assessment now as to what needs to be done.

“So I oppose the project. I think that the EIR cannot be certified in its current state and, if it is, it’s relatively easy to turn over.

Sincerely,

Jack Kinnear
Pine Hill, Humboldt, CA
707-888-5107
Dear Humboldt County Planning Commission,

I just signed a petition addressed to you titled *Humboldt Wind Farm*. So far, 410 people have signed the petition.

You can reach me directly by replying to this email. **Or, post a response for MoveOn.org to pass along to all petition signers by clicking here:** http://petitions.moveon.org/target_talkback.html?tt=tt-142445-custom-99640-20291118-edoXG5

The petition states:

"Citizens opposed to the industrialization of our wild and rural wilderness. Opponents to the massive scale of industrial wind turbines."

My additional comments are:

This decision needs much more time to study. The complete destruction of this beautiful and fragile land and death of so much important wildlife is at stake, and that should make the decision to shelve this project very easy. One step ahead to four steps behind? It doesn't make sense.

To download a PDF file of all of your constituents who have signed the petition, including their addresses, click this link: http://petitions.moveon.org/deliver_pdf.html?job_id=2508484&target_type=custom&target_id=99640

To download a CSV file of all of your constituents who have signed the petition, including their addresses, click this link: http://petitions.moveon.org/deliver_pdf.html?job_id=2508484&target_type=custom&target_id=99640&csv=1

Karen Steele
EUREKA, CA

*This email was sent through MoveOn's public petition website, a free service that allows anyone to set up their own online petition and share it with friends. MoveOn does not endorse the contents of petitions posted on our public petition website. If you have any questions, please email petitions@moveon.org. If you don't want to receive further emails updating you on how many people have signed this petition, click here:* http://petitions.moveon.org/delivery_unsub.html?e=rMQJWLo17qsyZ4OLyRaiVBSYW5uaW5nQnYpbGRpbmdAY28uaHVtYm9sZHQuY2EudXM-\&petition_id=142445.
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The petition states:

"Citizens opposed to the industrialization of our wild and rural wilderness. Opponents to the massive scale of industrial wind turbines."

My additional comments are:

These wind turbines are not green energy and are not sustainable. They do not benefit the people, only benefit corporations to make money

To download a PDF file of all of your constituents who have signed the petition, including their addresses, click this link: http://petitions.moveon.org/deliver_pdf.html?job_id=2508485&target_type=custom&target_id=99640

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Radley Davis
Bella Vista, CA

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The petition states:

"Citizens opposed to the industrialization of our wild and rural wilderness. Opponents to the massive scale of industrial wind turbines."

My additional comments are:

Wind Farms would not be built across our nation if they were not Federally subsidized. They only benefit those that build them.

To download a PDF file of all of your constituents who have signed the petition, including their addresses, click this link: http://petitions.moveon.org/deliver_pdf.html?job_id=2508486&target_type=custom&target_id=99640

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Jess Lattin
Oak Run, CA
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The petition states:

"Citizens opposed to the industrialization of our wild and rural wilderness. Opponents to the massive scale of industrial wind turbines."

My additional comments are:

I am totally opposed to Wind Turbine projects placed in timber lands because of high fire risk & because local communities receive no benefits from them.

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Joan M. DiMaio
Montgomery Creek, CA

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The petition states:

"Citizens opposed to the industrialization of our wild and rural wilderness. Opponents to the massive scale of industrial wind turbines."

My additional comments are:

There is nothing green or reliable about industrial wind turbines.

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Lisa MacDonald
Round Mountain, CA

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"Citizens opposed to the industrialization of our wild and rural wilderness. Opponents to the massive scale of industrial wind turbines."

My additional comments are:

When all the concrete, steel, roads, infrastructure, trucks, etc. are factored in, these huge wind farms are NOT green energy!

To download a PDF file of all of your constituents who have signed the petition, including their addresses, click this link: **http://petitions.moveon.org/deliver_pdf.html?job_id=2508483&target_type=custom&target_id=99640**

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Seabrook Leaf
BIG BEND, CA

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http://petitions.moveon.org/delivery_unsub.html?e=rMOJWLov17qsyZ4OLyRaiVBsYW5uaW5nOnVpbGRpbmdAY28uaHVtYm9sZHQuY2EudXM-\&petition_id=142445.
The Coast Guard and other military operations could be impacted....

Wind Farm Interference Shows Up on Doppler Radar
https://www.weather.gov/mkx/windfarm

S. E. A.
To whom it may concern,

I am a Eureka resident and voter and I am writing to voice my solidarity with the Wiyot tribe in opposition to the planned wind energy development. Surely another viable site can be found in the area that is not a sacred site with such sensitive plant and animal communities. I will continue to voice my opposition to this project and vote accordingly.

Thank you,

Michael Drucker
I wonder where 13 billion comes from???

...... and maintenance of over 2,000 MWs of renewable projects. The company primarily sells the output of the renewable energy projects to utilities and power cooperatives under long-term power purchase agreements. Terra-Gen continues to expand operations in renewable generation through a combination of acquisitions of operating projects, development of new projects and partnering on mid and late stage development opportunities. For more information, please visit www.terra-gen.com.

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Contacts:
Energy Capital Partners
Paul Parshley
(973) 671-6106

S. E. A.
From: Dennis Leonardi
To: Planning Clerk
Subject: wind generation
Date: Friday, November 15, 2019 5:06:15 PM

I am a strong proponent of the Teragen wind project. It is a non-fossil fuel energy source, wind is totally renewable, nobody own it just passes through and the scenic impact is minimal. Unless you are of the I see a microphone and need to complain to get attention personalities there is little cause to raise a legitimate objection over this project. The last 5 nights you couldn’t even see the hills above Scotia. Please don’t be intimidated by the few who can find time at 4 o’clock to attend a meeting to object. The rest of us are working and appreciate the lights on when we get home or during a PSPS outage. Dennis Leonardi
Dear Chairperson Bohn,

As the opposition to certification of the Humboldt Wind Energy Project FEIR grows, I have highlighted key sections in the CEQA Guidelines (below) to help the Planning Commission and Board of Supervisors address the comments I submitted on the DEIR (again attached), and fully disclose all adverse cumulative impacts of this project, as required.

In summary, Section 15130 of the CEQA Guidelines requires that the FEIR include a Cumulative Impact Analysis, fully disclosing all impacts created by a "combination of the project evaluated in the EIR together with other projects causing related impacts," (i.e. all Renewables & "related" Load Following Fossil Fuel Projects).

This Cumulative Impact Analysis must including a "summary of the expected environmental effects produced" by all of the "past, present, and probable future projects producing related or cumulative impacts, including, if necessary, those projects outside the control of the agency."

As always, let me know if I can help with the mandated disclosure of all impacts and benefits of this important project, before final action is taken to approve, or deny the project!

Kirk

Kirk Gothier
Senior Planning Advisor
(707) 786-9040

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15130. Discussion of Cumulative Impacts

(a) An EIR shall discuss cumulative impacts of a project when the project's incremental effect is cumulatively considerable, as defined in section 15065(a)(3). Where a lead agency is examining a project with an incremental effect that is not "cumulatively considerable," a lead agency need not consider that effect significant, but shall briefly describe its basis for concluding that the incremental effect is not cumulatively considerable.

(1) As defined in Section 15355, a cumulative impact consists of an impact which is created as a result of the combination of the project evaluated in the EIR together with other projects causing related impacts. An EIR should not discuss impacts which do not result in part from the project evaluated in the EIR.

(2) When the combined cumulative impact associated with the project's incremental effect and the effects of other projects is not significant, the EIR shall briefly indicate why the cumulative impact is not significant and is not discussed in further detail in the EIR. A lead agency shall identify facts and analysis supporting the lead agency's conclusion that the cumulative impact is less than significant.
(3) An EIR may determine that a project's contribution to a significant cumulative impact will be rendered less than cumulatively considerable and thus is not significant. A project's contribution is less than cumulatively considerable if the project is required to implement or fund its fair share of a mitigation measure or measures designed to alleviate the cumulative impact. The lead agency shall identify facts and analysis supporting its conclusion that the contribution will be rendered less than cumulatively considerable.

(b) The discussion of cumulative impacts shall reflect the severity of the impacts and their likelihood of occurrence, but the discussion need not provide as great detail as is provided for the effects attributable to the project alone. The discussion should be guided by standards of practicality and reasonableness, and should focus on the cumulative impact to which the identified other projects contribute rather than the attributes of other projects which do not contribute to the cumulative impact. The following elements are necessary to an adequate discussion of significant cumulative impacts:

(1) Either:

(A) A list of past, present, and probable future projects producing related or cumulative impacts, including, if necessary, those projects outside the control of the agency, or

(B) A summary of projections contained in an adopted general plan or related planning document, or in a prior environmental document which has been adopted or certified, which described or evaluated regional or areawide conditions contributing to the cumulative impact. Any such planning document shall be referenced and made available to the public at a location specified by the lead agency.

(2) When utilizing a list, as suggested in paragraph (1) of subdivision (b), factors to consider when determining whether to include a related project should include the nature of each environmental resource being examined, the location of the project and its type. Location may be important, for example, when water quality impacts are at issue since projects outside the watershed would probably not contribute to a cumulative effect. Project type may be important, for example, when the impact is specialized, such as a particular air pollutant or mode of traffic.

(3) Lead agencies should define the geographic scope of the area affected by the cumulative effect and provide a reasonable explanation for the geographic limitation used.

(4) A summary of the expected environmental effects to be produced by those projects with specific reference to additional information stating where that information is available; and

(5) A reasonable analysis of the cumulative impacts of the relevant projects. An EIR shall examine reasonable, feasible options for mitigating or avoiding the project's contribution to any significant cumulative effects.

(c) With some projects, the only feasible mitigation for cumulative impacts may involve the adoption of ordinances or regulations rather than the imposition of conditions on a project-by-project basis.

(d) Previously approved land use documents such as general plans, specific plans, and local coastal plans may be used in cumulative impact analysis. A pertinent discussion of cumulative impacts contained in one or more previously certified EIRs may be incorporated by reference pursuant to the provisions for tiering and program EIRs. No further cumulative impacts analysis is required when a project is consistent with a general, specific, master or comparable programmatic plan where the lead agency determines that the regional or areawide cumulative impacts of the proposed project have already been adequately addressed, as defined in section 15152(f), in a certified EIR for that plan.

(e) If a cumulative impact was adequately addressed in a prior EIR for a community plan, zoning action, or general plan, and the project is consistent with that plan or action, then an EIR for such a project should not further analyze that cumulative impact, as provided in Section 15183(j).

On Sat, Nov 2, 2019 at 11:46 AM Kirk Gothier <kirkgothier@gmail.com> wrote:
November 2, 2019

Chairperson Rex Bohn  
Humboldt County Board of Supervisors  
825 5th Street, Room 111  
Eureka, CA 95501

Subject: Humboldt Wind Energy Project Final EIR

Dear Chairperson Bohn,

Unfortunately, my June 6, 2019 comments on the Humboldt Wind Energy Project Draft EIR (attached) did not receive a response, as required by California Environmental Quality Act (CEQA), and were dismissed as:

“...opinions on the potential effects of the proposed project and links to several technical websites, but no data or other information to support these opinions. This comment is not directed at the adequacy of the DEIR, nor does it contain any questions regarding the CEQA analysis.”

Before the Humboldt County Planning Commission can make a decision on this project, the Final EIR must be revised to address my submitted comments, which are in summary:

“...Natural Gas/Renewables Industries are aggressively promoting misguided energy production projects, like the Humboldt Wind Energy Project, which will adversely impact our environment...

Absent a clear path towards clean air and water...(as outlined in my attached 2018 Comments to the California Energy Commission)... 10 million people die each year globally from air pollution and energy poverty…”

The “data or other information to support” my comments, were clearly included in these links:

http://www.who.int/airpollution/en/

The Humboldt Wind Energy Project continues Humboldt County’s reliance primarily on Fossil Fuels, which is clearly a Significant Adverse Energy Production Cumulative Impact. This Cumulative Impact must be fully disclosed, discussed and mitigated in the Final EIR, before the Planning Commission takes action to approve, or deny the project.

Incremental improvements to infrastructure and essential services that are projected to fail, including energy production improvements which do not clearly lead towards compliance with State GGE mandates, distract all of us from the important work of identifying a clear path, considering all risks and benefits, towards clean air and water, sustainable communities, and prosperity, for all our children...

Sincerely,
Kirk Gothier
Blissfully Retired Assistant Planning Director

kirkgothier@gmail.com
(707) 786-9040

Attachments:

June 6, 2019 Comments on Draft EIR
2018 Comments to the California Energy Commission

This email is confidential. If it is not intended for you please do not read, distribute or copy it or any attachments. Please notify the sender by return email and delete the original message and any attachments.

--
6/6/19 Draft EIR Comments

Unfortunately, the Natural Gas/Renewables Industries are aggressively promoting misguided energy production projects, like the Humboldt Wind Energy Project, which will adversely impact our environment, and rarely deliver essential energy production improvements!

While over 10 million people die each year globally from air pollution and energy poverty, our local, state and federal agencies continue to approve projects which benefit wealthy corporations, support unprecedented levels of income disparity, and distract all of us from the urgent conversation we need to have ASAP, based on standard EPA Risk Assessment and the consensus of our Scientific Community...

http://www.who.int/airpollution/en/
https://www.pewinternet.org/interactives/public-scientists-opinion-gap/

Absent a clear path towards clean air and water, sustainable communities and prosperity (as outlined in my attached 2018 Comments to the California Energy Commission), these adverse impacts will continue…

I have had the pleasure of working with several Physicists, Engineers and Ecomodernists over the past decade, who are developing emerging energy production technologies with the promise of finally realizing our dream of clean air and water, sustainable communities, and prosperity, for all our children!


Please let me know if I can provide any more additional links, or data from the numerous Physicists, Engineers, and Ecomodernists I work with daily, to help build a better world.

Kirk Gothier
Blissfully Retired (and following my passions)

http://www.ecomodernism.org
My goodness! I am so sorry about that and really appreciate your attention to our concerns. I will send the attachment again. This project is one that will be of such great significance and that I am so concerned about that I probably overlooked that one last step!

On Monday, 18 November 2019, 17:17:59 GMT-8, PlanningBuilding <planningbuilding@co.humboldt.ca.us> wrote:

Good Evening,

I did not see an attached letter. Have a great evening.

Thanks,

Tasheena Evenson
Planning and Building Department

I hereby respectfully submit another comment letter for your attention. I appreciate your serious consideration of our concerns. Thank you for your time.

Joan Tippetts
What does the term quality mean when used in the phrase “quality of life”, and how does it relate to what we have here in Humboldt County that has been lost in the name of “progress” in other places in California and elsewhere? To me, it means something that cannot necessarily be put into words but has to be experienced by being present in the moment and both knowing and feeling that it is something to be cherished and respected, that we can only be a part of if we do not disturb it. It is what makes us glad to be alive and a part of this place rather than imposers or who want to use or extract anything from it. It means letting nature take its course and not interfere or “improve” on it. It means letting predators be part of the whole; they only take what they need to survive. It means the color of the sky at different times of day, the sounds made by the birds and insects that strive to survive without human intervention. It means having a buffer against the noise and pollution that humans have managed to drum up to combat nature, as if nature were our foe instead of our source of being. Humans in large part have forgotten that they are born of the earth and shall return to it one day. That, I believe, is due to fear of death. Human beings have for some reason aligned in their minds that combatting nature will somehow put them in control of things and thereby make them immune to death. Instead of being able to be comfortable in the presence of nature, they want to overcome it and thus become immortal. Yes, humans also want to survive, but they need nature in order to have quality of life.

How do I know that the proposed wind turbine project would diminish quality of life for those of us who live here in Humboldt County and those who inhabit the rest of the planet as well? I know this because the wind project would create pollution, tear up forest and grasslands, desecrate a sacred Wiyot space, disturb the lives of countless creatures, kill many of them, and despoil a habitat that is home to both humans and many other lives. In addition, it would fail to make up for these losses by providing anything that we really need, unless we need electricity more than we need anything else in the world. This means that our quality of life is defined and constrained by our capacity to generate electricity. Do we really want a little more electricity so that we can live virtual lives rather than actual ones? Is this our future “quality of life”? From what I have researched regarding these wind turbines, they are not a benevolent addition to our communities but instead have unwholesome impacts to our health and presumably the health of our wildlife community as well. The lead agency failed to adequately answer these points in its statement of overwriting considerations. The FEIR is an adequate.

Joan Tippetts
Eureka, California
Suzanne: please see below. Thanks

**Kathy Hayes, Clerk of the Board**  
**County of Humboldt**  
(707) 476-2396  
khayes@co.humboldt.ca.us

From: ernieorjudy <ernieorjudy@suddenlink.net>  
Sent: Tuesday, November 19, 2019 2:39 PM  
To: Hayes, Kathy <KHayes@co.humboldt.ca.us>  
Subject: Factual blog on Climate Change

Kathy, you’ve been so helpful in sending information to the Planning Commissioners. I’d appreciate your sending them this blog, which I copied from the internet on either Lost Coast Outpost or Red Headed Blackbelt. Can’t remember which one, but it is the information I feel is important for the Commissioners to have. Thank you. Regards, Ernie DeGraff, Fortuna

_This is a Long 5 min read, but this guy knows about climate change and deals in FACTS! C C, as portrayed by the left, is the biggest hoax ever concocted in history (my opinion). The author knows what of he speaks! Ernie_

Perhaps President Trump is better than Neil Young at reading and understanding factual material like this:

The fact is, there has been global warming, but the contribution of human-generated carbon dioxide is necessarily so small as to be all but undetectable. Here’s why:

Carbon dioxide, considered the main vector for human-caused global warming, is some 0.04% of the atmosphere by volume, or some 400 parts per million (ppm)[1]. Water vapor varies from 0% to 4% by volume[2], and so should easily average above 1%[3] near the Earth’s surface, where the greenhouse effect would be most important, and is about three times more effective[4] a greenhouse gas than carbon dioxide. So water vapor is some 25 times more prevalent and three times more effective; that makes it some 75 times more important
to the greenhouse effect than carbon dioxide[5]. The TOTAL contribution of carbon dioxide to the greenhouse effect is therefore 0.013 or less.

Since the start of the industrial revolution, carbon dioxide is estimated to have risen from 280 ppm to the current approximately 400 ppm. Even if the entire increase were the result of human emissions - which is by no means certain, given uncertainty about how much CO2 is produced by natural sources such as decomposition of biomass and carbonate rock, volcanism and the little-understood ocean-atmosphere exchange - the total human contribution to atmospheric carbon dioxide would be about 0.3 of the total. Therefore human carbon dioxide adds at most only 0.0039 of the greenhouse effect, and may well be less.

Total warming of the Earth by the greenhouse effect is widely accepted as about 33 degrees Centigrade (which is equal to 59 degrees Fahrenheit), raising average temperature to 15 degrees Centigrade, or 59 degrees above zero Fahrenheit. So the contribution of anthropogenic carbon dioxide is at most 0.23 degrees Fahrenheit, or at most 0.13 degree Centigrade, and perhaps considerably less. Global warming since the beginning of the industrial revolution is thought by many to be perhaps 0.8 to 1.0 degree Centigrade.

But that's only the beginning. We've had global warming for more than 10,000 years, since the end of the last Ice Age, and there is evidence temperatures were actually somewhat warmer 9,000 years ago and again 4,500 to 8,000 years ago than they are today[6]. Whatever caused that, it was not human activity. It was not all those power plants and factories and SUVs being operated by Stone Age cavemen while chipping arrowheads out of bits of flint. Whatever the cause was, it melted the glaciers that in North America once extended south to Long Island and parts of New York City[7] into virtually complete disappearance (except for a few mountain remnants). That's one big greenhouse effect! If we are still having global warming - and I suppose we could presume we are, given this more than 10,000 year history - it seems highly likely that it is still the overwhelmingly primary cause of continued warming, rather than our piddling 0.0039 contribution to the greenhouse effect.

Yet even that trend-continuation today needs to be proved. Evidence is that the Medieval Warm Period centered on the 1200s was somewhat warmer than we are now[8], and the climate was clearly colder in the Little Ice Age in the 1600s than it is now[9]. (Whether the earlier Roman Warm Period around the time of Christ was as warm or was warmer than present is less clear.) So we are within the geologically recent range of normal up-and-down fluctuations without human greenhouse contributions that could be significant, or even measurable.

Principal scientists arguing for human-caused global warming have been demonstrably disingenuous[10], and now you can see why. They have proved they should not be trusted.
The idea that we should be spending trillions of dollars and hamstringing the economy of the entire world to reduce carbon dioxide emissions is beyond ludicrous in light of the facts above; it is insane. Furthermore, it sucks attention and resources from seeking the other sources of warming and from coping with climate change and its effects in realistic ways. The true motivation underlying the global warming movement is almost certainly ideological and political in nature, and I predict that Anthropogenic Global Warming, as currently presented, will go down as the greatest fraud of all time. It makes Ponzi and Madoff look like pikers by comparison.

[1] Mauna Loa Observatory [https://www.co2-earth/daily...]


by Micheal Pidwirney Concentration varies slightly with the growing season in the northern hemisphere. HYPERLINK [http://www.physicalgeograph...]

[3] The Earth’s tropics, the so-called “Torrid Zone,” where temperatures and therefore the capacity of the atmosphere to hold water vapor are at their highest, and where the 4% maximum is found, comprise a far greater portion of the Earth’s surface - 40% - than do the areas where water vapor content is at its lowest, the polar areas (8%), and the world’s deserts (10%). Moreover, the troposphere, which contains 99% of the world’s water vapor, is far deeper at the equator (10-12 miles) than near the poles (4 to 6 miles), enabling substantially more water vapor retention in the tropics even if other factors were equal rather than favoring more water retention rather than less. I have chosen an arbitrarily low working figure of 1% to give the AGW argument the benefit of any doubt. The higher the actual figure is above that, the lower must be the actual contribution of carbon dioxide, and therefore of anthropogenic carbon dioxide. If the true figure is 2%, the contribution of human-generated carbon dioxide is half that shown.


[5] Three quarters of the atmosphere and virtually all water vapor are in the troposphere. Including all the atmosphere would change the ratios to about 20 times more prevalent and 60 times more effective. However, the greenhouse effect of high-altitude carbon dioxide on lower-altitude weather and the earth’s surface seems likely to be extremely small if not nil, given that heat rises and high-altitude gases would also intercept relevant frequencies of solar radiation before they reach the earth.

[6] Encyclopedia Britannica - Holocene Environment and Biota, et al. [https://www.britannica.com/" for early holocene. See also History of Earth’s Climate, Ch. 7,
What initially troubled me, years ago, was the aberrant behavior of the climate research unit at East Anglia University, which had been the main data source for AGW arguments. They initially refused(!) to reveal their algorithms and data on the grounds that they were proprietary(!!). They responded to critics with ad hominem attacks and efforts to block their publication in scientific journals. Now, as I am sure you know, this is not how one does honest science, in which you PUBLISH your data and methodology and invite critical comment to ferret out error or oversights. It took the now-famous Wikileaks "Climategate" to pry loose the data and expose their machinations. Yet despite the devastating blow these revelations should have to their credibility, the AGW "cause" has taken on a life of its own.

Fundamentally, the argument seems to rest on a logical fallacy, post hoc ergo propter hoc - after this, therefore because of this. We see a rise in temperature and a rise in (principally) carbon dioxide, and therefore conclude one must have caused the other. It does not necessarily follow at all. There can be other causes entirely behind both phenomena, and as you see above, almost certainly there are. Beyond that, I have encountered numerous assertions of fact that cannot add up given the physical properties of water vapor and carbon
dioxide that go unchallenged. One-sided arguments proliferate and people arguing the other side are frequently denounced as being employed by business interests rather than rebutted on the merits.

In sum, I have not come lightly to the conclusion that the AGW argument as it applies to carbon dioxide is largely untrue and certainly does not account for more than a very small, nearly negligible part of the phenomena we are seeing. The implications of widespread assertions of and belief in such an untruth are staggering, and potentially enormously destructive. It is unwise indeed to let oneself be stampeded in this matter, and stampede is clearly what many have been and are trying to induce.

I can understand politicians behaving this way; a carbon tax or carbon trading regime would allow enormous revenues to fall into their hands. I can understand "Progressive" ideologues; it logically leads to enormous expansion of government power over industry, the economy, and the daily life of individuals, which they regard as a good thing. I understand the environmentalists; they want to shrink the size and impact on the environment of modern civilization. But responsible citizens need to put aside such considerations when drawing conclusions.

Please feel free to copy this essay and post it wherever you think it may do some good. The more people who understand this the better.
Hi,

My name is Roger. I'm the one with the beard & the wire rim glasses who is not Santa Claus.

I have been installing renewable energy systems for 42 years, including most of the past 4,665 days putting in solar systems in the greater Arcata-Eureka area. I'm briefly away installing a solar system on Coyote Tribal Housing.

Fifteen years ago a typical 4 kilowatt solar system cost around $18,000. Today it is about $8,000. Now it actually costs more not to have solar. Our next decade of installing solar systems and associated renewable energy will conservatively create more than 600 new full-time jobs in Humboldt County.

I have literally talked with thousands of families over the years and it is clear that simple conservation efforts would save more than 30% of our "demand for electricity." This would be a very safe financial investment. Establishing Eureka as a safe place to bicycle is a safe financial investment.

I believe erecting wind towers in the proposed sensitive areas is an abusive path to renewable energy.
It really does not matter how many solar panels I put up, if we do not have a renewable culture.

Thanks for your attentions & considerations. And thanks for listening to me, without having to look at me.

Roger

11/11/2019

P.S. On the popular present topic of power outages and the ability to have backup power:

As we head into the age of the electric car, you will have the backup battery of your dreams, that you can also use when the power is out!

[Roger called in the following revision on 11/14/2019:]

P.S. In this country we waste more than 30% of our food, which amounted to $161 billion in loss in 2010. Similarly, we waste about 30% of our electricity. We don't need to plow more fields to produce more food. Similarly, if we just use the electricity we have more righteously, local solar production will rise to meet our electricity needs.
Dear Humboldt County Planning Commission,

My name is Kristi Erlich. I was born and raised in California. I relocated to Oregon almost two decades ago from the Bay Area when I could no longer afford to live there. And, while I built a successful community and business there, it never truly, in my heart, felt like home. I always longed to be back in California among the people and landscapes where I feel a sense of belonging.

For the last ten of those years, I built my business, all the while plotting my return, which I finally actualized in August of this year. I purchased a 5.5 acre home and property on Monument Road in Rio Dell. One of the reasons I chose Rio Dell is that I saw an opportunity to a part of something that is beautiful, quiet and has potential for so much prosperity as a community…a community whose economy might benefit from my presence as a resident and small business developer. While I wouldn’t want to substantially change anything about Rio Dell, it is also clear to me that the community values invested residents who can contribute to its prosperity.

I write you today to express my deep concern over the windmill farm project being approved. As a citizen who is committed to environmental justice and former ecologist by profession, I am also a proponent of cleaner energy sources. However, they must be implemented at the right time and in the right place. I do not believe this project qualifies as either. I will enumerate my most critical concerns, though there are many.

I feel a grave concern for the first nations who are opposing this project. It’s imperative that we, as a society and community, listen and respond to those from whom we have taken so much, and embody the notion of reparation and value of those people.

I feel a grave concern for the animals and plants that will be negatively impacted by the project. This project does not, in my opinion, lend itself to long term and overarching benefit to the environment, given its projected impacts that seem not to be based on research of our local environment, but of largely dissimilar sites.

I feel grave concern in Terra-Gen’s response to requests for mitigation of impacts, which has been, by and large, “it’s not economically feasible” and seemingly lazy in their depth of analysis. This is a for-profit company and when those words are uttered, I am confident it actually means, “our profit margin is too slim for it to be possible.” In addition, their responses to solar energy sources as an option are inherently self-interested. Of course they would oppose a project that would result in less dependence on them as a utility supplier, given their for-profit agenda.

I have heard the phrase NIMBY used to refer to those of us who oppose the project. This term has historically critiqued affluent communities who reject similar projects. Rio Dell and neighboring concerned communities are not affluent. This is, in fact, another example of economically vulnerable communities bearing the brunt of the impacts of “progress.”

I humbly ask you to weigh the adjacent communities’ opposition for this project heavily as you move forward, including Rio Dell and the Wiyot Tribe, as we and our immediate environment will be most heavily impacted by the project.
Dear Commissioner Morris:

I am a resident of Arcata and am writing in support of the Terra-Gen Wind Energy Project.

We are already starting to see the effects of climate change. Recently over 11,000 scientists from around the world warned of untold suffering in the years ahead unless we immediately begin to reduce our carbon footprint in the atmosphere. This project promises to reduce greenhouse gasses, the equivalent of taking 82,000 cars off the road.

I was a young child at the beginning of WWII. Immediately after the shock of the Pearl Harbor attacks, the country came together and united behind the war effort. It was an existential crisis. Prior to Pearl Harbor, many were in denial about the looming crisis ahead.

Similarly, many now are in denial about the existential threat of climate change, despite a raft of scientific evidence to the contrary. It’s hard to think of the severe future changes that will affect our lifestyles. Yet, that’s what we’re facing unless drastic action is taken.

I respect the project concerns by many friends and neighbors. Yet the overriding imperative is to take action right now.

Please support the Terra-Gen Wind Energy Project.

Sincerely,

Lew Litzky
Dear Dr Golightly,

I listened to your testimony to the Humboldt County Planning Commission on 11/14/19 and was confused by your assertion that the successful Kure oil spill mitigation for MaMu was the “clean crumb” campaign that has been replicated in many parks.

You repeat the DEIR claims that “This particular kind of restoration effort (corvid control in parks) was the most consistent and coordinated action taken by the Trustee Councils overseeing the restoration funds to replace murrelets lost in the oil spills.” 3.5-78

However, Contrary to this assertion, the major effective action taken to address the Kure and Stuyvesant oil spills’ combined killing of an estimated 265 marbled murrelets was the acquisition of permanent conservation easements from Green Diamond Company:

"The responsible parties in the Kure settlement purchased a Conservation Easement for the Big Mynot and E.F. Hunter parcels, containing approximately 77 acres of old-growth forest and approximately 222 acres of surrounding buffer areas. For the Stuyvesant settlement, the responsible parties purchased an easement for the Miracle Mile complex of parcels containing approximately 135 acres of old-growth forest and approximately 489 acres of surrounding buffer areas.”


The oil spill funding from the Kure and Stuyvesant spills reported in the January 13 update (see above), entitled “Corvid Management for Marbled Murrelets,” provides no quantifiable data on the success or outcomes of their scavenger-proof trashcans, or public education efforts.

Of course, you are certainly aware of the fact that “saving” murrelet eggs or chicks from corvid predation cannot compensate for loss of breeding adults because of the high mortality of the former, often from non-aviary predators that also benefit from corvid reduction, such as reptiles and mammals (reptiles and mammals were responsible for over 50% of predation in the Luginbuhl et al 2001 and Marzluff and Neatherlin 2006 studies).
HRC protects over 2000 acres of murrelet habitat for 50 years from the 1999 HCP, after which they will be subject to “management.” This habitat could be permanently protected with conservation easements as mitigation for TerraGen HumWind inevitable take of murrelets.

Finally, you confidently assert that climate change will reduce redwood and other nesting habitat for the murrelet as an argument for the TerraGen wind facility, as if this project will in any way lessen the potentially lethal effects of climate change on the redwoods, or MaMu habitat.

Clearly, we know little of the eventual effects of climate change, including the adaptive evolution of species like the murrelet subjected to such changes. However, we do know from studies by Keith and Miller, et al, of the adverse downwind hydrometeorological effects of large WGTs, including dehydration, warming and turbulence on all habitat up to over 20 km downwind (see references below).

The Periodic Status Review for the Marbled Murrelet in Washington in 2016 warned that "For nesting habitat, a reduced moisture climate could also affect moss and epiphyte development and its role in providing and sustaining potential nesting platforms in tree branches, and possibly increase prevalence of tree insect and disease outbreaks.” (Effects of Climate on Forest Habitat, https://wdfw.wa.gov/sites/default/files/publications/01827/wdfw01827.pdf)

Have you considered these effects, and if not, why not? They are certainly no more speculative, nor less well quantified than the results of corvid management plans on murrelet breeding success.

Finally, it would have been helpful had you identified yourself as an employee of HT Harvey, a hired consultant and ardent advocate of the TerraGen project.

(Published: 29 April 2012)


“EXTRACTING ENERGY FROM WIND: Simulating impacts of wind farms on local hydrometeorology,” Somnath Baidya Roy, J. of Wind Engineering and Industrial
Aerodynamics journal homepage: www.elsevier.com/locate/jweia

Climatic Impacts of Wind Power

Wind beats fossil, but wind power does cause non-negligible climatic impacts. This study advances work on wind power’s climate impacts by: (1) providing a mechanistic explanation for wind turbines’ climate impacts by comparing numerical simulations with observations, (2) filling a current gap between small- and very-large-scale wind power simulation studies, (3) making the first quantitative comparison between wind power’s climatic impacts and benefits, and (4) using the same framework to make a quantitative comparison with solar power.

Lee M. Miller, David W. Keith
lmiller@seas.harvard.edu (L.M.M.)
david_keith@harvard.edu (D.W.K.)

HIGHLIGHTS
Wind power reduces emissions while causing climatic impacts such as warmer temperatures

Warming effect strongest at night when temperatures increase with height

Nighttime warming effect observed at 28 operational US wind farms

Wind’s warming can exceed avoided warming from reduced emissions for a century
Climatic Impacts of Wind Power

Lee M. Miller1,3,* and David W. Keith1,2,*

SUMMARY
We find that generating today’s US electricity demand (0.5 TWe) with wind power would warm Continental US surface temperatures by 0.24 °C. Warming arises, in part, from turbines redistributing heat by mixing the boundary layer. Modeled diurnal and seasonal temperature differences are roughly consistent with recent observations of warming at wind farms, reflecting a coherent mechanistic understanding for how wind turbines alter climate. The warming effect is: small compared with projections of 21st century warming, approximately equivalent to the reduced warming achieved by decarbonizing global electricity generation, and large compared with the reduced warming achieved by decarbonizing US electricity with wind. For the same generation rate, the climatic impacts from solar photovoltaic systems are about ten times smaller than wind systems. Wind’s overall environmental impacts are surely less than fossil energy. Yet, as the energy system is decarbonized, decisions between wind and solar should be informed by estimates of their climate impacts.

INTRODUCTION
To extract energy, all renewables must alter natural energy fluxes, so climate impacts are unavoidable, but the magnitude and character of climate impact varies widely. Wind turbines generate electricity by extracting kinetic energy, which slows winds and modifies the exchange of heat, moisture, and momentum between the surface and the atmosphere. Observations show that wind turbines alter local climate,1–10 and models show local- to global-scale climate changes from the large-scale extraction of wind power.11–15 Previous studies have assessed climate impacts of hydropower,16 biofuels,17 and solar photovoltaic systems (PVs).18 Rapid expansion of renewable energy generation is a cornerstone of efforts to limit climate change by decarbonizing the world’s energy system. In addition to climate benefits, wind and solar power also reduce emissions of criteria pollutants (NOx, SOx, and PM2.5) and toxic pollutants such as mercury that cause significant public health impacts.19,20 The climate impacts of wind and solar are small compared with the impacts of the fossil fuels they displace, but they are not necessarily negligible. Improved understanding of the environmental trade-offs between renewables would inform choices between low-carbon energy sources. With growth of wind and solar PVs far outstripping other renewables,21 we combine direct observations of onshore wind power’s impacts with a continental-scale model, and compare it to prior estimates of PVs’ impacts to assess the relative climate impacts of wind and solar energy per unit energy generation.

Climatic impacts due to wind power extraction were first studied using general circulation models (GCMs). These studies found statistically significant climatic impacts within the wind farm, as well as long-distance teleconnections, with impacts outside the wind farm sometimes as large in magnitude as impacts inside the wind farm.11–13,22 Note that such impacts are unlike greenhouse gas (GHG)-driven warming, as in some cases wind power’s climatic impacts might counteract such GHG
warming—at least four studies have found that mid-latitude wind power extraction can cool the Arctic.11,12,23,24 However, these studies often used idealized or unrealistic distributions of turbines installed at unrealistic scales. Model simulations of geometrically simple, isolated wind farms at smaller scales of 3,000–300,000 km² (10- to 1,000 times larger than today’s wind farms) in windy locations found substantial reductions in wind speed and changes in atmospheric boundary layer (ABL) thickness, as well as differences in temperature,11,13,14,24 precipitation,14,25 and vertical atmospheric exchange.15,26

We want to assess wind power’s climate impacts per unit of energy generation, yet wind’s climatic impacts depend on local meteorology and on non-local climate teleconnections. These twin dependencies mean that wind power’s impacts are strongly dependent on the amount and location of wind power extraction, frustrating the development of a simple impact metric.

As a step toward an improved policy-relevant understanding, we explore the climatic impacts of generating 0.46 TWe of wind-derived electricity over the Continental US. This scale fills a gap between the smaller isolated wind farms and global-scale GCM. We model a uniform turbine density within the windiest one-third of the Continental US, and vary the density parametrically.

Our 0.46 TWe benchmark scenario is ~18 times the 2016 US wind power generation rate.21 We intend it as a plausible scale of wind power generation if wind power plays a major role in decarbonizing the energy system in the latter half of this century. For perspective, the benchmark’s electricity generation rate is only 14% of current US primary energy consumption,25 about the same as US electricity consumption,27 and about 2.4 times larger than the projected 2050 US wind power generation rate of the Central Study in the Department of Energy’s (DOE) recent Wind Vision.28 Finally, it is less than one-sixth the technical wind power potential over about the same windy areas of the US as estimated by the DOE.28,29

Modeling Framework
We use the WRF v3.3.1 high-resolution regional model30 with a domain that encompasses the Continental US, forced by boundary conditions from the North American Regional Reanalysis.31 The wind farm region is more than 500 km from the model boundaries, and encompasses only 13% of the domain (shown in Figure 1A). The model configuration used dynamic soil moisture and 31 vertical levels with 3 levels intersecting the turbine’s rotor and 8 levels representing the lowermost kilometer. The model is run for a full year after a 1-month spin-up using horizontal resolutions of 10 and 30 km. The wind turbine parametrization was originally released with WRF v3.3,32 and represents wind turbines as both a momentum sink and turbulent kinetic energy (TKE) source. We updated the wind turbine parameterization to make use of the thrust, power, and TKE coefficients from a Vestas V112 3 MW. This treatment of wind power is very similar to previous modeling studies.14,15,24

The advantage of the regional model is that we can use a horizontal and vertical resolution substantially higher than previous global modeling studies,11–13,22,23,26,33,34 allowing better representation of the interactions of the wind turbines with the ABL. The disadvantage of using prescribed boundary conditions is that our simulations will underestimate the global-scale climatic response to wind power extraction compared with a global model with equivalent resolution, which would allow the global atmosphere to react to the increased surface drag over the US and would reveal climate teleconnections.
We tested horizontal resolution dependence by comparing the 10- and 30-km simulations with a turbine density of 3.0 MW km$^{-2}$ with the respective 2012 controls. Differences in the annual average 2-m air temperature were small, as shown in Figure S1. The following results use a 30-km resolution (about one-ninth of the computational expense) and 2012, 2013, and 2014 simulation periods to reduce the influence of interannual variability. We use four turbine densities (0.5, 1.0, 1.5, and 3.0 MW km$^{-2}$) within the wind farm region to explore how increased wind power extraction rates alter the climatic impacts.

**RESULTS AND DISCUSSION**

Figure 1 shows the climate impacts of the benchmark scenario (0.5 MW km$^{-2}$). The wind farm region experiences warmer average temperatures (Figure 1A), with about twice the warming effect at night compared with during the day (Figures 1B and 1C). Warming was generally stronger nearer to the center of the wind farm region, but...
perhaps because teleconnections are suppressed by the forced boundary conditions. The climate response is concentrated in the wind farm region, but there are regions well outside the wind farm region also experiencing a climate response. The clearest example here is along the East Coast during the daytime, where average daytime temperatures are 0.1°C–0.5°C cooler (Figure 1B).

To separate the local direct boundary layer impacts from the mesoscale climate changes, we ran a diagnostic simulation with a 250 × 250-km “hole” near the center of the wind farm region, finding that the “hole” experienced about half the warming of the original “no hole” benchmark scenario during 2014 (Table S1 and Figure S2). This suggests that about half the warming effect is attributed to localized changes in atmospheric mixing, with the other half attributed to mesoscale changes, but this requires further study.

Changes in precipitation are small and show no clear spatial correlation (Figure S3). The warming is greatest in an N-S corridor near the center of the wind turbine array, perhaps because of an interaction between wind turbines and the nocturnal low-level jet (LLJ). The LLJ is a fast nocturnal low-altitude wind (>12 m s⁻¹ at 0.5 km) common in the US Midwest, which occurs when the atmosphere decouples from surface friction, resulting in a steep vertical temperature gradient — meteorological conditions that might be sensitive to perturbations by wind turbines. We quantified the presence of the LLJ in our control simulation but did not find a strong spatial correlation between the probability of LLJ occurrence and the nighttime warming (Figure S4). To explore mechanisms, we examine the vertical temperature gradient, atmospheric dissipation, and wind speed (Figure S5), and then explore the relationship between warming and these variables using scatterplots (Figure S6). We find some consistency between the dissipation rate of the control and the warming effect of wind turbines, but the correlation is weak.

Figure 2 explores the relationship between changes in vertical temperature gradient, atmospheric dissipation, and the simulated warming. Wind turbines reduce vertical gradients by mixing. During the day, vertical temperature gradients near the surface are small due to solar-driven convection and are only slightly reduced by the turbines. Gradients are larger at night, particularly during summer, and the gradient reduction caused by turbine-induced mixing is larger. The largest warming occurs when the reduction in gradient is strongest and the proportional increase in TKE is largest.

Warming and power generation saturate with increasing turbine density (Figure 3). The temperature saturation is sharper, so the ratio of temperature change per unit energy generation decreases with increasing turbine density. This suggests that wind’s climate impacts per unit energy generation may be somewhat larger for lower values of total wind power production.

Power generation appears to approach the wind power generation limit at turbine densities somewhat above the maximum (3.0 MW km⁻²) we explored. A capacity density of 1.5 MW, km⁻² roughly matches that of US wind farms installed in 2016, and that simulation’s power density of 0.46 Wm⁻² is very close to the 0.50 Wm⁻² observed for US wind farms during 2016. The highest turbine density yields an areal (surface) power density of 0.70 Wm⁻², consistent with some previous studies, but half the 1.4 Wm⁻² assumed possible by 2050 from the same 3.0 MW km⁻² turbine density into windy regions by the DOE. While we did not compute a maximum wind power generation rate here, extrapolation of
Figure 3 suggests that it is about 2 TWe, significantly less than the 3.7 TWe of technical potential estimated by the DOE over less land area. Clearly, interactions of wind turbines with climate must be considered in estimates of technical wind power potential.

Interpretation

The climatic impacts of wind power may be unexpected, as wind turbines only redistribute heat within the atmosphere, and the 1.0 W m⁻² of heating resulting from kinetic energy dissipation in the lower atmosphere is only about 0.6% of the diurnally averaged radiative flux. But wind's climatic impacts are not caused by additional heating from the increased dissipation of kinetic energy. Impacts arise because turbine-atmosphere interactions alter surface-atmosphere fluxes, inducing climatic impacts that may be much larger than the direct impact of the dissipation alone.

As wind turbines extract kinetic energy from the atmospheric flow and slow wind speeds, the vertical gradient in wind speed steepens, and downward entrainment increases. These interactions increase the mixing between air from above and air near the surface. The strength of these interactions depends on the meteorology and, in particular, the diurnal cycle of the ABL.

During the daytime, solar-driven convection mixes the atmosphere to heights of 1–3 km.
Figure 3. Variation in Mean Response to Changes in Installed Capacity Density

(A–D) The shared x axis is the installed electrical generation capacity per unit area. All values are averages over the wind farm region. (A) Eighty-four-meter hub-height wind speed, (B) capacity factor, (C) generation rate (TW_e), and (D) Δ2-meter temp. (°C)
Wind turbines operating during the daytime are enveloped within this already well-mixed air, so climatic impacts such as daytime temperature differences are generally quite small. At night, radiative cooling results in more stable surface conditions, with about 100–300 m of stable air separating the influence of surface friction from the winds aloft.\(^3\)\(^5\) Wind turbines operating at night, with physical extents of 100–150 m and an influence height at night reaching 500 m or more,\(^1\)\(^5\) can entrain warmer (potential temperature) air from above down into the previously stable and cooler (potential temperature) air near the surface, warming surface temperatures. In addition to the direct mixing by the turbine wakes, turbines reduce the wind speed gradient below their rotors and thus sharpen the gradient aloft. This sharp gradient may then generate additional turbulence and vertical mixing.

This explanation is broadly consistent with the strong day-night contrast of our benchmark scenario (Figures 1B and 1C). Within the wind farm region during the day, most locations experience warmer air temperatures, although \(\sim 15\%\) of locations show a daytime cooling effect in July-September. At night during July-September, less than 5% of locations show a cooling effect, and the warming effect at night over all months is much larger than during the daytime. This daytime and nighttime warming effect is also larger with higher turbine densities (Figure S7). Finally, the temperature perturbation in the benchmark scenario shows a strong correlation to differences in TKE within the lowest model level from 0 to 56 m (Figure 2B), with these increases in TKE downwind of turbines previously observed in Iowa\(^4\) and offshore Germany,\(^3\) supporting our explanation that the temperature response is driven by increased vertical mixing (Figure 2).

**Observational Evidence of Climatic Impacts**

While numerous observational studies have linked wind power to reduced wind speeds and increased turbulence in the turbine wakes,\(^1\)\(^4\)\(^7\)\(^3\)\(^8\)\(^3\)\(^9\) ten studies have quantified the climatic impacts resulting from these changes (Table 1).

Three ground-based studies have measured differences in surface temperature\(^1\)\(^5\)\(^7\) and evaporation.\(^5\) Generally, these ground-based observations show minimal climatic impacts during the day, but increased temperatures and evaporation rates at night.

Seven satellite-based studies have quantified surface (skin) temperature differences. By either comparing time periods before and after turbine deployment, or by comparing areas upwind, inside, and downwind of turbines, the spatial extent and intensity of warming for 28 operational wind farms in California,\(^3\)\(^6\) Illinois,\(^6\) Iowa,\(^7\) and Texas\(^8\)\(^-\)\(^1\)\(^1\) has been observed. There is substantial consistency between these satellite observations despite the diversity of local meteorology and wind farm deployment scales. Daytime temperature differences were small and slightly warmer and cooler, while nighttime temperature differences were larger and almost always warmer (Table 1). Interpretation of the satellite data is frustrated by fixed overpass times and clouds that sometimes obscure the surface.
Joule density of 0.5 MW km

turbines with taller hub heights and larger rotor diameters. We also assumed

we modeled a specific 3.0-MW turbine, but future deployment may shift to wind

climate response is partly related to the choice and placement of wind turbine(s).

limitations of model framework

temperature observations upwind and downwind of a large turbine array were

being captured by our model. This mechanism could be tested more directly if

the physical mechanisms being modified by the deployment of wind turbines are

are strongly correlated (Figure 4). This agreement provides strong evidence that

warming is spatially consistent with the arrangement of wind turbines

Table 1. Overview of Observational Studies Linking Air Temperature Differences to Wind Farms

<table>
<thead>
<tr>
<th>Reference</th>
<th>SAT or GND</th>
<th>Period</th>
<th>State</th>
<th>Notes: Climatic Impacts within or Very near to the Operational Wind Farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baidya Roy and</td>
<td>GND</td>
<td>53 days</td>
<td>CA</td>
<td>summer, ~1°C increase in 5-m air temperature downwind at night through the early</td>
</tr>
<tr>
<td>Traiteur,(^1) 2010</td>
<td></td>
<td></td>
<td></td>
<td>morning; slight cooling effect during the day</td>
</tr>
<tr>
<td>Walsh-Thomas et al.(^4,6) 2012</td>
<td>SAT -</td>
<td>CA</td>
<td>~2°C warmer skin temperatures extending to about 2 km downwind, with visible</td>
<td></td>
</tr>
<tr>
<td>Zhou et al.(^7) 2012</td>
<td>SAT 9 years</td>
<td>TX</td>
<td>JJA night = +0.72°C, DJF night = +0.46°C, JJA day = −0.04°C, DJF day = +0.23°C;</td>
<td></td>
</tr>
<tr>
<td>Zhou et al.(^8,9) 2013</td>
<td>SAT 6 years</td>
<td>TX</td>
<td>Q1A values: DJF night = +0.22°C, MAM night = +0.29°C, JJA night = +0.35°C,</td>
<td></td>
</tr>
<tr>
<td>Zhou et al.(^10) 2013</td>
<td>SAT 2 years</td>
<td>TX</td>
<td>Q1A values: DJF night = −0.01°C, MAM night = +0.42°C, JJA night = +0.67°C,</td>
<td></td>
</tr>
<tr>
<td>Xia et al.(^5) 2016</td>
<td>SAT 7 years</td>
<td>TX</td>
<td>DJF night = +0.26°C, MAM night = +0.40°C, JJA night = +0.42°C, SON night = +0.27°C,</td>
<td></td>
</tr>
<tr>
<td>Harris et al.(^7) 2014</td>
<td>SAT 11 years</td>
<td>IA</td>
<td>along the edge of a large wind farm directly downwind of ~13 turbines; generally</td>
<td></td>
</tr>
<tr>
<td>Rajewski et al.(^1) 2013</td>
<td>GND 122 days</td>
<td>IA</td>
<td>cooler temperatures (0.07°C) with daytime periods that were 0.75°C cooler and</td>
<td></td>
</tr>
<tr>
<td>Rajewski et al.(^3) 2014</td>
<td>GND 122 days</td>
<td>IA</td>
<td>nighttime periods that were 1.0–1.5°C warmer</td>
<td></td>
</tr>
<tr>
<td>Slawsky et al.(^6) 2015</td>
<td>SAT 11 years</td>
<td>IL</td>
<td>DJF night = +0.39°C, MAM night = +0.27°C, JJA night = +0.18°C, SON night = +0.26°C,</td>
<td></td>
</tr>
<tr>
<td>Smith et al.(^7) 2013</td>
<td>GND 47 days</td>
<td>confidential</td>
<td>Spring; nighttime warming of 1.9°C downwind of a ~300 turbine wind farm</td>
<td></td>
</tr>
</tbody>
</table>

SAT, satellite-based observations; GND, ground-based observations. Note that measurements identified as the same state were completed over the same wind farms.

Although our benchmark scenario is very different in scale and turbine placement compared with operational wind power, it is nevertheless instructive to compare our simulation with observations. We compare results at a single Texas location (100.2°W, 32.3°N) where one of the world’s largest clusters of operational wind turbines (~200 km\(^2\), consisting of open space and patchy turbine densities of 3.8–4.7 MW km\(^{-2}\)) has been linked to differences in surface temperature in 3 of the observational studies in Table 1. Weighting the observations by the number of observed-years, the Texas location is 0.01°C warmer during the day and 0.29°C warmer at night (data in Table S2). Our benchmark scenario with a uniform turbine density of 0.5 MW km\(^{-2}\) at this location is 0.33°C warmer during the day and 0.66°C warmer at night. To explore the quantitative correlation between the seasonal and diurnal response, we take the 8 seasonal day and night values as independent pairs (Table S2), and find that the observations and the simulations are strongly correlated (Figure 4). This agreement provides strong evidence that the physical mechanisms being modified by the deployment of wind turbines are being captured by our model. This mechanism could be tested more directly if temperature observations upwind and downwind of a large turbine array were available at a high temporal resolution (<3 hr).

Limitations of Model Framework

Climate response is partly related to the choice and placement of wind turbine(s). We modeled a specific 3.0-MW turbine, but future deployment may shift to wind turbines with taller hub heights and larger rotor diameters. We also assumed
that turbines were evenly spaced over the wind farm region, but real turbine deployment is patchier, potentially also altering turbine-atmosphere-surface interactions.

The model’s boundary conditions are prescribed and do not respond to changes caused by wind turbines. Yet prior work has established that non-local climate responses to wind power may be significant, suggesting that simulating our benchmark scenario with a global model (no boundary conditions restoring results to climatology) would allow possible climatic impacts outside the US to be assessed. Removal of the boundary conditions might also increase the warming in the wind farm region. The 3-year simulation period was also completed in 1-year blocks, so we do not simulate the response of longer-term climate dynamics influenced by variables such as soil moisture. Finally, model resolution influenced the estimated climatic impacts. Simulations with a 10-km horizontal resolution and the highest turbine density of 3.0 MW km\(^{-2}\) caused 18\% less warming than the 30-km simulation (\(+0.80\)\(^{\circ}\)C and \(+0.98\)\(^{\circ}\)C). Simulations using a global model with an unequally spaced grid with high-resolution over the US could resolve some of these uncertainties.

### Comparing Climatic Impacts to Climatic Benefits

Environmental impacts of energy technologies are often compared per unit energy production. Because a central benefit of low-carbon energies like wind and solar is reduced climate change, dimensionless climate-to-climatic comparisons between the climate impacts and climate benefits of reduced emissions are relevant for public policy.

Climate impacts will, of course, depend on a range of climate variables that would need to be examined in a comprehensive impact assessment. In this analysis we nevertheless use 2-m air temperature as a single metric of climate change given (1) that there are important direct impacts of temperature, (2) that temperature...
change is strongly correlated with other important climate variables, and (3) that use of temperature as a proxy for other impacts is commonplace in climate impacts assessments. Limitations and caveats of our analysis are addressed in the following sub-section.

When wind (or solar) power replace fossil energy, they cut CO₂ emissions, reducing GHG-driven global climate change, while at the same time causing climatic impacts as described above and elsewhere. The climatic impacts differ in (at least) two important dimensions. First, the direct climatic impact of wind power is immediate but would disappear if the turbines were removed, while the climatic benefits of reducing emissions grows with the cumulative reduction in emissions and persists for millennia. Second, the direct climatic impacts of wind power are predominantly local to the wind farm region, while the benefits of reduced emissions are global. We revisit and elaborate these differences in a systematic list of caveats at the end of this subsection.

As a step toward a climate-impact to climate-benefit comparison for wind, we compare warming over the US. We begin by assuming that US wind power generation increases linearly from the current level to 0.46 TWₑ in 2080 and is constant thereafter. We estimate the associated warming by scaling our benchmark scenario’s temperature differences linearly with wind power generation. The amount of avoided emissions—and thus the climate benefit—depends on the emissions intensity of the electricity that wind displaces. We bracket uncertainties in the time evolution of the carbon-intensity of US electric power generation in the absence of wind power by using two pathways. One pathway assumes a static emissions intensity at the 2016 value (0.44 kgCO₂ kWh⁻¹), while the second pathway’s emissions intensity decreases linearly to zero at 2100, which is roughly consistent with the GCAM model that meets the IPCC RCP4.5 scenario. The two emissions pathways are then reduced by the (zero emission) wind power generation rate at that time (Figure 5C). The first pathway likely exaggerates wind power’s emission reductions, while the second reflects reduced climate-benefit for wind in a transition to a zero-carbon grid that might be powered by solar or nuclear.

It is implausible that the US would make deep emissions cuts while the rest of the world continues with business-as-usual, so we include a third pathway, which functions just like the first pathway, except that the global (rather than just US) electricity emissions intensity declines to zero (Figure S8).

We estimate wind’s reduction in global warming by applying the two US and one global emission pathways to an emissions-to-climate impulse response function. We convert these global results to a US warming estimate using the 1.34:1 ratio of US-to-global warming from IPCC RCP4.5 and RCP8.5 ensemble means (Figure S9).

The benchmark scenario’s warming of 0.24°C over the Continental US and 0.54°C over the wind farm region are small-to-large depending on the baseline. Climatic impacts are small if compared with US temperature projections—historical and ongoing global emissions are projected to cause the Continental US to be 0.24°C warmer than today by the year 2030 (Figure S8). Assuming emissions cuts are implemented globally, then the climatic impacts of wind power affecting the US in 2100 are approximately equivalent to the avoided warming from reduced global emissions (green region of Figure 5D). Climatic impacts are large if the US is the only country reducing emissions over this century (blue and gray shaded regions of...
Figure 5. Climate Warming Impacts Compared to Climate Benefits of Reduced Emissions
(A) Two US scenarios, static (black) and declining (blue) emissions intensity, $I$, from US electric power.
(B) A scenario in which power output, $P$, from wind or solar power increases to our benchmark scenario’s 0.46 TWe by 2080.
(C and D) Avoided emissions computed as $\Delta E = I \cdot P$ (C) and the resulting 2-m temperature differences within the wind farm region (dotted lines) and the Continental US (solid lines) (D). Values for wind power linearly scaled from our benchmark scenario, while values for solar power are derived from Nemet. 18 For comparison, the avoided warming of the Continental US from reduced emissions is shown for the static US scenario (gray) and the declining US scenario (blue). The green area shows the avoided warming of the Continental US if global electricity emissions were zero by 2080. The range of avoided warming for each pathway is estimated from the min and max values within the emissions-to-climate impulse response function.

Figure 5D). Timescale matters because climatic impacts are immediate, while climate benefits grow slowly with accumulated emission reductions. The longer the time horizon, the less important wind power’s impacts are compared with its benefits (Box 1).
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Box 1. Limitations of Using these Results to Compare the Climatic Impacts of Wind Power to Climate Change from Long-Lived Greenhouse Gases

The comparison above suggests that if US electricity demand was met with US-based wind power, the wind farm array would need to operate for more than a century before the warming effect over the Continental US caused by turbine-atmosphere interactions would be smaller than the reduced warming effect from lowering emissions. This conclusion is subject to a number of caveats including:

- Fundamentally different mechanisms cause warmer temperatures from climate change compared with wind power. Increased GHG concentrations reduce radiative heat losses to space, trapping more heat in the atmosphere and causing warmer surface temperatures. Wind power does not add more heat to the atmosphere—wind turbines redistribute heat by mixing and alter large-scale flows both which can change climate.
- Our comparison was based solely on surface air temperature differences. Wind turbines and GHGs both alter a host of interrelated climate variables. The use of surface temperature as the sole proxy for climate impacts may bias the resulting ratio of impacts-to-benefits in either direction.
- Climate impacts of the benchmark scenario will likely be larger and more widespread if we did not use forced boundary conditions, which prevents any feedbacks from the large-scale circulation.
- Results depend on the wind electricity generation rate, consistent with previous work. Our results (Figure 3) suggest the temperature response is roughly linear to the generation rate and power density. To the extent that we see deviations from linearity (Figure S7), climate impacts per unit generation are larger for lower turbine densities.
- Results depend on the spatial distribution and density of wind turbines. We assumed that the windiest areas would be exploited and that developers would use low turbine densities to maximize per-turbine generation. Based on simulated results with higher turbine densities (Figure 3), doubling the turbine density over an area half as large as the benchmark scenario might generate almost the same power as the benchmark scenario, while increasing warming over this smaller region by only about a third.
- Our comparison metric ignores many possible benefits and drawbacks of the climate impacts caused by wind power deployment, including:
  - Warmer minimum daily temperatures have been observed to reduce crop yield. The comparison depends on area-weighting. We used equal weighting but one could consider weighting by, for example, population or agricultural production.
  - The comparison depends very strongly on the time horizon. We examined the century timescale consistent with Global Warming Potentials, but there is no single right answer for time discounting.
  - Finally, results depend on the comparison of US and global-scale impacts and benefits: our model framework prevents global-scale analyses, but, assuming a substantial fraction of the warming effect occurred where US wind turbines were operating, global area-weighted benefits would offset the climatic impacts sooner than if impacts and benefits were quantified over just the US (as done here).

Implications for Energy System Decarbonization

Wind beats fossil fuels under any reasonable measure of long-term environmental impacts per unit of energy generated. Assessing the environmental impacts of wind power is relevant because, like all energy sources, wind power causes climatic impacts. As society decarbonizes energy systems to limit climate change, policy makers will confront trade-offs between various low-carbon energy technologies such as wind, solar, biofuels, nuclear, and fossil fuels with carbon capture. Each technology benefits the global climate by reducing carbon emissions, but each also causes local environmental impacts.

Our analysis allows a simple comparison of wind power’s climate benefits and impacts at the continental scale. As wind and solar are rapidly growing sources of low-carbon electricity, we compare the climate benefit-to-impact ratio of wind and solar power.

The climate impacts of solar PVs arise from changes in solar absorption (albedo). A prior study estimated that radiative forcing per unit generation increased at 0.9 mW/m²/TWₑₑ in a scenario in which module efficiency reaches 28% in 2100 with installations over 20% rooftops, 40% grasslands, and 40% deserts. Assuming that the climatic impact is localized to the deployment area and using a climate
sensitivity of 0.8K/W m$^{-2}$ generating 0.46 TW of solar PVs would warm the Continental US by 0.024°C. This warming effect is 10-times smaller than wind’s (0.24°C, Figure 5D) for the same energy generation rate. This contrast is linked to differences in power density and thus to the areal footprint per unit energy—US solar farms presently generate about 5.4 W m$^{-2}$, while US wind farms generate about 0.5 W m$^{-2}$.

We speculate that solar PVs’ climatic impacts might be reduced by choosing low albedo sites to reduce impacts or by altering the spectral reflectivity of panels. Reducing wind’s climatic impacts may be more difficult, but might be altered by increasing the height of the turbine rotor above the surface distance to reduce interactions between the turbulent wake and the ground, or switching the turbines on or off depending on meteorological conditions.

In agreement with observations and prior model-based analyses, US wind power will likely cause non-negligible climate impacts. While these impacts differ from the climate impacts of GHGs in many important respects, they should not be neglected. Wind’s climate impacts are large compared with solar PVs. Similar studies are needed for offshore wind power, for other countries, and for other renewable technologies. There is no simple answer regarding the best renewable technology, but choices between renewable energy sources should be informed by systematic analysis of their generation potential and their environmental impacts.

SUPPLEMENTAL INFORMATION
Supplemental Information includes nine figures and two tables and can be found with this article online at https://doi.org/10.1016/j.joule.2018.09.009.

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AUTHOR CONTRIBUTIONS

DECLARATION OF INTERESTS
D.W.K. is an employee, shareholder, and executive board member at Carbon Engineering (Squamish, BC). Carbon Engineering is developing renewable electricity to fuels projects and is developing procurement contracts for wind and solar power.

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Observation-based solar and wind power capacity factors and power densities

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Abstract

Power density is the rate of energy generation per unit of land surface area occupied by an energy system. The power density of low-carbon energy sources will play an important role in mediating the environmental consequences of energy system decarbonization as the world transitions away from high power-density fossil fuels. All else equal, lower power densities mean larger land and environmental footprints. The power density of solar and wind power remain surprisingly uncertain: estimates of realizable generation rates per unit area for wind and solar power span 0.3–47 W e m$^{-2}$ and 10–120 W e m$^{-2}$ respectively. We refine this range using US data from 1990–2016. We estimate wind power density from primary data, and solar power density from primary plant-level data and prior datasets on capacity density. The mean power density of 411 onshore wind power plants in 2016 was 0.50 W e m$^{-2}$. Wind plants with the largest areas have the lowest power densities. Wind power capacity factors are increasing, but that increase is associated with a decrease in capacity densities, so power densities are stable or declining. If wind power expands away from the best locations and the areas of wind power plants keep increasing, it seems likely that wind’s power density will decrease as total wind generation increases. The mean 2016 power density of 1150 solar power plants was 5.4 W e m$^{-2}$. Solar capacity factors and (likely) power densities are increasing with time driven, in part, by improved panel efficiencies. Wind power has a 10-fold lower power density than solar, but wind power installations directly occupy much less of the land within their boundaries. The environmental and social consequences of these divergent land occupancy patterns need further study.

Introduction

Wind and solar power generation have grown dramatically, yet they still generate only a small fraction of electricity or of primary energy. In 2017, for example, wind and solar generated 6.0% and 1.8% respectively of US electricity (BP 2018). Wind and solar, like all energy systems, occupy land, displacing natural systems, agriculture, and human communities. Power density, the energy generation rate per time per unit ground area (expressed here as W e m$^{-2}$), is one important measure of the land use of energy systems (Smil 1984, 2015, MacKay 2009, 2013a, 2013b). Use of low-carbon energy sources such as wind and solar may increase dramatically as the energy systems is decarbonized to limit climate risks. Quantitative estimates of power densities are therefore important in understanding the scope and impacts of low-carbon energy systems. Yet, as we describe below, existing power density estimates for wind and solar are inconsistent. Here we estimate the power density of wind and solar power using data that includes most grid-connected commercial-scale installations in the US. We also examine how power densities vary with power plant age and size.

For wind power, estimates of the power density vary by about a factor of 70. Technological innovations in turbine design and arrangement show that up to 47 W e m$^{-2}$ is achievable over very small areas...

Note that all the values in the preceding paragraph, and throughout this paper, refer to the average annual power density over the entire area extent of the wind farm, hereafter ‘wind power plant’. This power density of wind power plants is much smaller than the power density computed by counting only the area directly occupied by infrastructure, such as the turbine pads and access roads (MacKay 2013a, Smil 2015). Including the whole area of the wind power plant when calculating wind power density is critical to establishing the reproducibility of similar plants in adjacent locations, which informs wind power’s generation potential at larger scales. The land use considerations of wind power are complex. While the open space between turbines is critical to minimizing turbine–turbine and turbine–atmosphere interactions, that same open space is usually co-utilized for other purposes like agriculture. Note that we defer to the Methods section the real-but-tractable issues of quantifying that area given knowledge of the wind turbine locations.

For solar photovoltaics (PV), estimates of the power density differ by a factor of 12. The low-end estimates by MacKay and Smil are the 3–9 W/m² (MacKay 2013b, Smil 2015). Kammen and Sunter (2016) estimate that typical values are 10 W/m², while Hernandez et al (2015) suggest values of 47–66 W/m² for sunny regions like California, and Kammen and Sunter (2016) estimate a technical potential of 120 W/m² if such sunny flat regions were blanketed with today’s highest (~40%) efficiency PV panels. Underlying these estimates are different assumptions regarding panel efficiency, the ratio of fraction of the land surface area to PV panels area, and whether the angle of the panels is fixed or uses 1- or 2-axis solar tracking.

Here we estimate the power densities and capacity factors for wind and solar power plants with AC-capacities greater than 1 MW which generated electricity in the US during 1998–2016. For wind we make a direct plant-by-plant bottom-up estimate while for solar our estimates of power density depend on a correlation analysis that provides a single estimate for the solar installed capacity density.

Data sources and methods

We used four data sources:

- EIA Power Plants, hereafter Power Plants, published on 19 April 2018 and current through January 2018 (US Energy Information Administration EIA 2018a). This base dataset provides status (operating, on standby, or short- or long-term out of service), a 3- to 5-digit unique ‘Plant Code’, geographic location, name, and nameplate AC-capacity for 1043 wind power plants and 2227 solar PV power plants.
- EIA Bulk Data, hereafter Electricity Generation (US Energy Information Administration EIA, 2018b). This data set includes monthly electricity generation data for each power plant through December 2016 including geographic location, name, and a ‘series id’ that is the same as the Plant Code in Power Plants. Note that most data is missing for power plants first operational in 2016.
- EIA-860, hereafter Detailed Data, published April 2018 (US Energy Information Administration EIA 2018c). This data set provides AC- and DC-capacity of the power plant, month and year of first operation, referenced by Plant Code.
- United States Wind Turbine Database, hereafter USWTDB, published April 2018 (current through early 2018) (Hoen et al 2018). This data set provides locations of 57,636 wind turbines, name of the wind power plant, number of turbines in the wind power plant, turbine nameplate capacity, and rotor diameter. It does not provide a Plant Code.

Following our Wind and Solar Methods (below), we computed annual averages from monthly generation (MWh/month) when 7 or more months of data is reported rather than using the data’s annual averages (MWh yr−1) which would obscure pre-startup or offline periods. Only about half of all wind and solar power plants were used in our analysis for the year 2016, with this ratio varying by technology and year. These solar and wind power plants were excluded because: (a) Power Plants could not be linked to Electricity Generation based on Plant Code, or (b) capacity factors calculated from the Power Plants and Electricity Generation exceeded 100%, or (c) Electricity Generation was zero or unreported for more than 6 months in a given year, (d) AC-capacities between Power Plants and Detailed Data differed by more than ±10%, or finally in the case of wind power, (e) if the resulting installed capacity density was less estimated to be less than 0.1 MW km−2.

These exclusions and filtering result in discrepancies between our dataset and those of the US Energy Information Administration EIA (2018d). For 2016, the cumulative capacity of the wind power plants included in our data was 58% the EIA’s estimate for total wind capacity while for solar capacity that figure was 53% (US Energy Information Administration EIA 2018d). Our base Power Plants data collated power plants through early 2018, but does not specify
when the power plant came online, preventing capacity for 2016 from being quantified. Detailed Data provides nameplate capacity and month-year per power plant, but for 2016, total capacities are 109% and 150% the capacity for wind and solar respectively compared to (US Energy Information Administration EIA 2018d). To verify that no region was systematically excluded, we spatially compared the raw EIA Power Plant locations (US Energy Information Administration EIA 2018a) to those making it through our methodology, and found no obvious spatial gaps.

**Wind methods**

Our approach for quantifying the area of US wind power plants begins with the location of the 57 636 wind turbines in the USWTDB (Hoen et al 2018). Voronoi polygons were calculated for each wind turbine using QGIS Development Team (2018). Using spatial linking, the Voronoi polygons were linked to the Power Plants (US Energy Information Administration EIA 2018a) and then filtered for an equivalent AC-installed capacity. The Plant Code in the Power Plants data was then used as the unique identifier for linking to Electricity Generation (US Energy Information Administration EIA 2018a, 2018b) and Detailed Data (US Energy Information Administration EIA 2018c). Capacity factors (MW hr/MW) of wind power plants are calculated from Electricity Generation and Power Plants (US Energy Information Administration EIA 2018a, 2018c). Spatial and temporal curtailment by the grid operator was not included in this analysis, but will influence the results slightly (e.g. ERCOT region of Texas in 2009).

There is no well-established method to compute the area of each wind power plant. To do so, we compute a Voroni polygon (after Георгий Вороной) using QGIS Development Team (2018) for each wind turbine in the USWTDB which delineates the ground area that is closest to each individual turbine location compared to every other turbine. The Voronoi polygon areas for wind turbines on the edge of wind power plants are very large, but the interior Voronoi polygons are a useful quantification of the ground surface area per turbine. We compute the median Voronoi polygon area for each wind power plant and then estimate the area of the wind power plant by multiplying this median Voronoi polygon area by the number of wind turbines listed in the USWTDB (Hoen et al 2018).

These steps yield the wind power plant area (km²), power density (W m⁻²), installed capacity density (MW km⁻²), and capacity factor for 411 wind power plants operating in 2016 (43.7 GW).

The advantage of this approach is that it only depends on the turbine locations and is independent from any rules-of-thumb, such as the typical spacing of 6-to-8 rotor diameters, or proprietary turbine information used by the developer as part of the wind power plant’s design. This approach is also responsive to differences in arrangement (parallel rows, ridgetop or coastal alignment) and between-turbine spacing due to taller hub-heights or larger rotor diameters, without prescribing any details other than the geographic location.

To illustrate how our approach performs, we selected 2 dissimilar wind power plants from a prior study of wind power plant area (Denholm et al 2009) that are still in operation as of 2016. At Bull Creek (figure 1(A)), the smaller Voronoi polygon areas at the interior of the wind farm contrast with those larger areas of the edge turbines but are not a problem—wind farm area is estimated from the median Voronoi polygon area and the turbine count. An 8 rotor

![Figure 1. Illustrating Voroni-polygon and buffer-based approaches for estimating the area of wind power plants. Individual turbine locations shown as orange dots, with the thin black line around each wind turbine designating the Voroni polygon boundary. The thick black lines designate Voroni polygons surrounding each wind power plant. The colored buffer regions illustrate an 8-rotor diameter buffer around each turbine. (A) Bull Creek (orange, top left, −101.6°E, 32.9°N) has an area of 243 km² according to (Denholm et al 2009), 47.8 km² using the 8D buffer, and 54 km² based on the median Voroni polygon area (0.3 km² per turbine with 180 turbines). (B) Fenton Wind Farm (teal, −93.2°E, 42.6°N) has an area of 156 km² according to (Denholm et al 2009), 100 km² using the 8D buffer, and 137 km² based on the median Voroni polygon area (1.0 km² per turbine with 137 turbines).](image)
Solar methods

Our solar dataset begins with *Power Plants* (US Energy Information Administration EIA 2018a). Using the unique Plant Code, we linked this file to *Electricity Generation* (US Energy Information Administration EIA 2018b), resulting in 1311 solar PV power plants. To reduce errors, we compare the installed capacity (MW\text{ac}) values with the same Plant Code between *Power Plants* and *Detailed Data* (US Energy Information Administration EIA 2018a), excluding the solar power plants that differ by ±10%, leaving 1150 solar power plants for our 2016 analysis (7.9 GW\text{ac}, 9.8 GW\text{dc}).

Unlike the wind methodology, we do not estimate the area of individual solar power plants from a primary dataset. Instead, we estimate the area of each solar PV farm by dividing its DC capacity from the *Detailed Data* by a fixed capacity density value of 30 MW\text{dc} km\textsuperscript{-2}.

This capacity density value is derived from a study that assessed the area and DC capacity for 192 solar PV power plants in the US (Ong et al 2013). For area, we use Ong et al’s *total area*, which is based on environmental impact statements, project applications, and satellite imagery, and describes the area enclosing the solar arrays, roads, substations, and service buildings. A linear fit to the (Ong et al 2013) data yields a best-fit at 30.05 MW\text{dc} km\textsuperscript{-2} (figure 2). This agrees well with the installed capacity density of 25–35 MW\text{dc} km\textsuperscript{-2} observed in California (Hernandez et al 2014).

One might expect that higher panel efficiencies or tracking would produce higher generation rates per unit area. We tested this assumption by binning the (Ong et al 2013) data that included PV panel efficiency (109 of 192 total data points) into two sets. The first with efficiencies greater than the median (14%) and the second with efficiencies less than the median (figure S2), and then separately estimating the best-fit capacity density for the two sets. The two results differ by only 1.2% suggesting that capacity density varies little with module efficiency.

Power density (i.e. areal power generation rate, W\textsubscript{e} m\textsuperscript{-2}) was calculated as:

\[
PD = CD\text{ac} / (30 \text{ MW}\text{dc} \text{ km}^{-2}) \times CD\text{dc} / (30 \text{ MW}\text{dc} \text{ km}^{-2})
\]

where CD\text{ac} and CD\text{dc} are the capacity densities measured on an AC or DC basis, and PD is the power density. Capacity factor was calculated from *Electricity Generation* (US Energy Information Administration EIA 2018b) and installed maximum AC capacity (MW\text{ac}) from *Power Plants* (US Energy Information Administration EIA 2018a).

Results

Distributions of power densities and capacity factors are shown in figure 3. Considering capacity-weighted data for all power plants operational during 2016, the summary results are as follows. The mean and 90-percentile power densities for wind are 0.50 and 0.80 W\textsubscript{e} m\textsuperscript{-2}, while the corresponding values for solar are 5.4 and 7.1 W\textsubscript{e} m\textsuperscript{-2}. Note that systematic uncertainty in the distribution of power densities are significantly larger for solar than for wind because the...
solar power results are derived from a fixed estimate of capacity density, whereas the wind results are computed directly. Our mean and 90-percentile capacity factors are 32.9% and 43% for wind, while the corresponding values for solar are 22.1% and 27.5%. Note that the capacity factors from EIA for 2016 are 34.5% for wind and 25.1% for solar (US Energy Information Administration EIA 2018d), and we expect that the discrepancy arises from the data sampling issues discussed above. Solar and wind power installed capacities, power densities, and capacity factors from 2010 to 2016 are shown in table 1.

Table 1. Solar and wind power values for the various years, with average capacity factor and average power density weighted by the installed capacity.

<table>
<thead>
<tr>
<th>Year</th>
<th>Installed capacity</th>
<th>Capacity factor (%)</th>
<th>Power density (Wₑ m⁻²)</th>
<th>Installed capacity</th>
<th>Capacity factor (%)</th>
<th>Power density (Wₑ m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MWₑ, dc</td>
<td>MWₑ, ac</td>
<td></td>
<td>MWₑ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>133</td>
<td>116</td>
<td>21.82</td>
<td>18.665</td>
<td>30.02</td>
<td>0.52</td>
</tr>
<tr>
<td>2011</td>
<td>306</td>
<td>267</td>
<td>19.08</td>
<td>22.693</td>
<td>31.37</td>
<td>0.52</td>
</tr>
<tr>
<td>2012</td>
<td>1257</td>
<td>1052</td>
<td>20.00</td>
<td>26.506</td>
<td>31.29</td>
<td>0.51</td>
</tr>
<tr>
<td>2013</td>
<td>2467</td>
<td>2041</td>
<td>22.16</td>
<td>33.026</td>
<td>30.58</td>
<td>0.49</td>
</tr>
<tr>
<td>2014</td>
<td>3876</td>
<td>3154</td>
<td>22.26</td>
<td>34.019</td>
<td>31.96</td>
<td>0.50</td>
</tr>
<tr>
<td>2015</td>
<td>5729</td>
<td>4660</td>
<td>22.09</td>
<td>38.262</td>
<td>30.77</td>
<td>0.46</td>
</tr>
<tr>
<td>2016</td>
<td>9812</td>
<td>7922</td>
<td>22.07</td>
<td>43.737</td>
<td>33.00</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Solar power results are derived from a fixed estimate of capacity density, whereas the wind results are computed directly. Our mean and 90-percentile capacity factors are 32.9% and 43% for wind, while the corresponding values for solar are 22.1% and 27.5%. Note that the capacity factors from EIA for 2016 are 34.5% for wind and 25.1% for solar (US Energy Information Administration EIA 2018d), and we expect that the discrepancy arises from the data sampling issues discussed above. Solar and wind power installed capacities, power densities, and capacity factors from 2010 to 2016 are shown in table 1.

Time trends are computed by binning power plants by their first year of operation (US Energy Information Administration EIA 2018b, 2018c). For solar, capacity-weighted mean capacity factors have increased by 1% per year over the years 2009–2015 (figure 4(A)). There is no significant trend in our estimate of the power density of solar power plants, but it is possible that this is an artifact of our use of a fixed DC capacity density.

Capacity factors for wind power have increased by 0.7% per year over the years 1998–2015 (figure 4(B)). The increase in wind’s capacity factor is particularly evident this decade. Wind farms operating since 2010 have a mean capacity factor of 34.4% for 2010–2016, whereas the capacity factor from 1998 to 2009 is 30.9%.

There is no significant trend in the power density of wind power plants. This result is surprising given the increase in capacity factor. What underlies it? Wind power plants have three defining characteristics: the rated capacity of individual turbines, the installed capacity density of the wind farm, and the area of the wind farm. The capacity factor and power density of
the wind power plants show no relationship to the rated capacity of the individual wind turbines (figure 5(A)), whereas capacity factor and power density do vary with capacity density (figure 5(B)). Note that the highest power densities are achieved with the highest capacity densities, but the highest capacity factors are achieved with the lowest capacity densities. Treating all wind turbines and their associated Voroni polygon areas individually, a decrease in capacity density over time is apparent (figure 5(C)). The capacity density peaked at about 2.5 MWi km$^{-2}$ for turbines installed between 2002 and 2005, and has since decreased to about 1.5 MWi km$^{-2}$ (figure 5(D)). In summary, we find that while improved wind turbine design and siting have increased capacity factors (and greatly reduced costs) they have not altered power densities.

Figure 6 provides a map of the power densities and capacity factors for 2016. Solar capacity factors are lower on the East Coast and around the Great Lakes, and highest in the southwest where most solar power plants with capacity factors greater than 30% are located. Wind’s highest capacity factors and power densities are in the Great Plains.

Finally, we examined the relationship between power plant area and power density. For solar, there is no clear relationship between area and power density (figure 7(A)), whereas for wind, there is a strong
relationship (figure 7(B)). While many wind power plants with areas less than 15 km² generate more than 1.0 $W_e \, m^{-2}$, power density decreases with increasing power plant size. This result was previously observed for 0–20 km² wind power plants by (MacKay 2013a). We verify this early result, and extend it by showing that wind’s power density reaches an asymptote of about 0.25 $W_e \, m^{-2}$ when the wind farm area exceeds about 150 km².

**Discussion**

Solar’s mean power density in 2016 was 5.4 $W_e \, m^{-2}$. Our approach for estimating the area of solar farms is not fully bottom-up so this estimate is subject to systematic error. It is possible, for example, that capacity densities have changed significantly given that the data used in our analysis is about 5 years old. That said, the assumption by (Jacobson et al 2018) that urban rooftops can be retrofitted with a capacity density 4.5-times higher than the commercial-scale solar plants measured by (Ong et al 2013) seems highly unlikely, as does the resulting 24–27 $W_e \, m^{-2}$ power density (Jacobson et al 2018). It is also possible that capacity densities vary strongly with larger size installations (see figure 2(A)). However, given that our analysis finds only a very weak relationship between module efficiency or installation size and capacity density, we expect the errors are small, likely less than 20%.
Theoretically it is possible to attain high power densities with solar (120 W·m\(^{-2}\) in Kammen and Sunter 2016) over small areas like an individual rooftop, but within the limitations of our data and analysis, we see no obvious trend towards increased solar power densities. Suggestions that solar power densities could be high enough to enable self-powered urban landscapes (Kammen and Sunter 2016) therefore seem implausible given the primary energy demand of large cities, such as Phoenix with a primary energy demand of 8.1 W·m\(^{-2}\), Los Angeles with 21 W·m\(^{-2}\) or New York City with 69 W·m\(^{-2}\).

Wind’s mean power density in 2016 was 0.50 W·m\(^{-2}\). This observed mean is consistent with estimates based on atmospheric theory and modeling (Gustavson 1979, Keith et al 2004, Wang and Prinn 2010, Miller et al 2011, Gans et al 2012, Jacobson and Archer 2012, Marvel et al 2012, Adams and Keith 2013, Miller et al 2015, Miller and Kleidon 2016) which predicted that large-scale wind power densities would be under 1.0 W·m\(^{-2}\) and also that power densities will decrease with increasing size of the wind farm installation. This observed mean power density is much smaller than many common estimates (Archer and Jacobson 2005, Lu et al 2009, Sta. Maria and Jacobson 2009, Jacobson and Delucchi 2011, Lopez et al 2012, US Department of Energy 2015, World Bank Group and Technical University of
is about 1 W m\(^{-2}\) kinetic energy from the free troposphere, a value that large-scale wind power density is the downward and the atmospheric boundary layer. The limit to account the interactions between wind turbine arrays in wind power density. First, many estimates did not account the capacity density of 1.5 MW\(\cdot\)km\(^{-2}\). Second, many studies assume installed capacity densities which are too high. While we observed an average of 1.7 W\(\cdot\)m\(^{-2}\) over about 1/3 of the Continental US (Lopez et al. 2012), or 1.4 W\(\cdot\)m\(^{-2}\) over about 2% of the US with excellent wind resources (US Department of Energy 2015). These are also by no means the highest estimates in the literature. For example, (World Bank Group and Technical University of Denmark 2018) quantify a wind power density of 808 W\(\cdot\)m\(^{-2}\) over the windiest 10% of US land, and (Kammen and Sunter 2016) estimated an upper bound of 35 W\(\cdot\)m\(^{-2}\) for wind power at urban-scales based on study observing numerous vertical axis turbines which generated up to 47 W\(\cdot\)m\(^{-2}\) over an area of about 50 m\(^2\) (Dabiri 2011).

There are two main reasons for these discrepancies in wind power density. First, many estimates did not account the interactions between wind turbine arrays and the atmospheric boundary layer. The limit to large-scale wind power density is the downward flux of kinetic energy from the free troposphere, a value that is about 1 W\(\cdot\)m\(^{-2}\) (Lorenz 1955, Peixoto and Oort 1992, Kim and Kim 2013). The effect of this atmospheric limit is illustrated by the relationship between wind power plant's area and power density. Second, many studies assume installed capacity densities which are too high. While we observed an average capacity density of 1.5 MW\(\cdot\)km\(^{-2}\), (Rinne et al. 2018) assume 5.5–9.4 MW\(\cdot\)km\(^{-2}\), (Jacobson et al. 2018) assume 7.2 MW\(\cdot\)km\(^{-2}\), (Lopez et al. 2012) assumed 5.0 MW\(\cdot\)km\(^{-2}\), the US-DOE Wind Vision: A New Era for Wind Power in the United States (US Department of Energy 2015) assumed 3.0 MW\(\cdot\)km\(^{-2}\). By assuming 2- to 6-times the observed capacity density but ignoring the atmospheric limits, these estimates resulted in power densities that are 2- to 6-times higher than observations.

Note that some important prior estimates from energy systems experts such as Ausubel (2007), MacKay (2013a) and Smil (2015) are much closer to our data-driven estimate.

Given that larger wind power plants have smaller power densities and given that a major increase in total wind power generation will presumably require expanding wind power plants into less-than-ideal locations, it seems likely that wind power density will decrease with time. It therefore seems—contrary to many prior estimates—unlikely that the power densities of greater than 1 W\(\cdot\)m\(^{-2}\) will be realized over substantial areas, and likely that average power densities will fall below 0.5 W\(\cdot\)m\(^{-2}\).

As an example of the implications of these results, consider Germany and its ambitious energy transformation policy (Energiewende). Germany’s primary energy consumption rate is 1.28 W\(\cdot\)m\(^{-2}\) (BP 2018). If our US wind power density of 0.50 W\(\cdot\)m\(^{-2}\) was applicable to Germany, then devoting all German land to wind power would meet about 40% of Germany’s total primary energy consumption, while if German wind power performs like the best 10% of US wind (0.80 W\(\cdot\)m\(^{-2}\)), then generation would be 62% of Germany’s consumption. Finally, if Germany’s goal was to generate the most wind power without economic constraints, very high capacity densities (e.g. 10 MW\(\cdot\)km\(^{-2}\)) could be deployed, reducing capacity factors but possibly raising the power density to 1.0 W\(\cdot\)m\(^{-2}\) and meeting 80% of consumption. Whereas for solar at 5.4 W\(\cdot\)m\(^{-2}\), 24% of Germany’s land area would need to be devoted to commercial-scale solar to meet total primary energy consumption.

Of course, no such single-technology scenario is plausible. A mix of energy sources and storage is essential to addressing temporal and seasonal variability. Note that the amount of primary energy required to supply the same amount of final energy will fall with electrification and battery storage-reducing requirements, but using electricity to make gas or other
synthetic fuels has the opposing tendency. Yet, we hope this example illustrates the relevance of power density when planning for deep decarbonization.

Power densities clearly carry implications for land use. Meeting present-day US electricity consumption, for example, would require 12% of the Continental US land area for wind at 0.5 \(W_{c} \text{ m}^{-2}\), or 1% for solar at 5.4 \(W_{c} \text{ m}^{-2}\). US electricity consumption is just 1/6 total primary energy consumption (BP 2018), so meeting total consumption would therefore require 72% and 6% respectively for US wind and solar. Of course, like the Germany example, no single energy source is likely to ever supply all electric power. These comparisons nevertheless provide a benchmark for understanding the implications of power densities for land use, while recognizing that solar and wind power also occupy the area within the power plant boundary differently. These observation-based results should be considered in light of the fact that (a) decarbonizing the energy system will require considerably more primary power than current electricity demand, (b) demand may continue to grow, and finally, (c) that many areas of the world have higher energy demand per unit area than does the Continental US.

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Dear Planning Commissioners,

Please incorporate these comments into the Administrative Record regarding the Humboldt Wind Energy Project. As a 17-year resident of Humboldt County, I oppose the wind farm proposal on these points:

- Industrial energy installation that would disturb a large relatively pristine area of great cultural and scenic value
- Energy will be immediately exported to the PG&E grid, not stay within the county
- Humboldt’s clean energy goals could be met by more solar installation, increased use of electric cars, conservation, and developing a local offshore wind farm. An offshore wind project will have much less environmental impact.
- Wiyot Tribe sacred lands will be irreparably harmed by the project – this cannot be mitigated
- Yurok Tribe objects to the potential impacts to their California condor reintroduction program
- Wind farm blades will kill tens of thousands of birds over the life of the project including threatened murrelets and spotted owls, as well as hawks and songbirds; and threaten the largest known congregation of hoary bats in North America located 4 miles away
- Wildlife will be affected not only by the wind turbines but by habitat loss and disturbance to grasslands and forests to construct and operate the project
- Terra Gen (the project developer) has not committed to proper mitigation measures to offset harm to birds, bats, and other wildlife.
- The project is being rushed through the environmental review process, precipitated by Terra Gen’s desire to construct the project by 2020 to obtain tax credits.

Signed, Tina Dawson
November 19, 2019

Additional Comments on the Terra-Gen/Humboldt Wind Project Proposal

From: Ken Miller, Secretary, Siskiyou Land Conservancy

Dear Commissioners,

Following are additional comments on behalf of myself, Ken Miller, and Siskiyou Land Conservancy, on the Terra-Gen Humboldt Wind proposal for Monument and Bear River Ridges.

First, it’s worth noting that during last week’s Planning Commission hearing on the issue a significant majority of speakers opposed the project. Clearly the people of Humboldt County do not want destructive wind turbines placed along one of the region’s last large prairie-forest ecosystems. At the Planning Commissioners meeting of Nov. 14, 2019, 53 speakers spoke eloquently against the project. Only 11 spoke in favor. During the RCEA Climate Action meetings, the ration against was 2:1.

Regarding TerraGen HumWind, overriding considerations should be precluded by the demonstrably preferable alternative of solar. To avoid unnecessary repetition, please refer to prior submissions for the many references supporting this contention.

•Permitting this CUP would be a violation of “The General Welfare Standard:”

"The establishment, maintenance or conducting of the use for which a use permit is sought will not, under the particular case, be detrimental to the public welfare or injurious to property or improvements in the neighborhood" (Hawkins v. County of Marin (1976) 54 Cal.App.3d 586). Substantial evidence supports the conclusion that TerraGen poses prejudicial harm to multiple species, entities and parties, including the public, with respect to downwind effects, night and day flicker and lights, loss of biodiversity, cultural blight, property values, untreated waste water, and sedimentation of waterways including the Eel River.

•Downwind Effects: turbulence & dehydration
This entire region will be affected in many ways. The GPU requires consideration of the “effect on potential down-wind sites,” (12.4 Goals and Policies Goals, E-S3.).

E-S3. Wind Generating Facilities.
1. Findings necessary for project approval shall be:
   1. The proposed use is not detrimental to the public health, convenience, safety, and welfare.
   2. That the use of the property for such purposes will not result in material damage or prejudice to other property in the vicinity.
   3. Within the Coastal Zone, the project will not have a significant adverse effect on coastal resources, including wildlife qualities.
Yet, the FEIR dismisses the findings of Harvard researchers who found dramatic hydro-meteorological effects downwind (Keith & Miller), including turbulent airflow, warming and vegetation drying. What could be worse with 25 miles of high voltage transmission lines surrounded by vegetation? Nothing has broader ecosystem effects than dramatically altering microclimates. “Our results show a significant warming trend of up to 0.72 °C per decade, particularly at nighttime, over wind farms relative to nearby non-wind-farm regions.” Impacts of wind farms on land surface temperature (Nature Climate Change volume 2, pages 539–543, 2012)

The FEIR Dismisses Established Science of Downwind Effects
“Perfection is not required, but the EIR must be adequate, complete, and a good faith effort at full disclosure (CEQA Guidelines Section 15151).”

FEIR: O8-17 The commenter expresses the opinion that wind turbine blade rotation creates a different climatic regime downwind, which increases the risk of wildfires and affects species in the surrounding habitat. The commenter includes references to various studies to support this opinion. O8-18 The commenter discusses two studies that the commenter believes show that wind farms can affect near-surface air temperature and humidity up to 18–23 km downwind. “Please see the response to Comment O8-17.”

Widespread Distributed Solar
• We have submitted incontrovertible evidence that widespread distributed public and private solar microgrids, rooftop, and open space arrays can meet most of the goals of RCEA and the County, and exceed some of those of TerraGen’s proposed project, with none of the adverse impacts: (see prior submissions for references)

Solar:
Affordable, available and feasible evidenced by the many urban and rural municipalities implementing widespread distributed solar
Resilient when grid down & emergencies
Reduced Carbon Footprint
Reduced PGE/grid electricity use
Electricity produced without GHG emissions
100s of jobs not just 15
Shared energy wealth rather than concentrated
Negligible GHG emissions
Minimal new infrastructure
Minimal transmission upgrades over time
Negligible risk of fire
Minimal maintenance over the 25-year lifetime
Facilitates Electric Vehicles (EVs)

• We have submitted substantial evidence regarding the pairing of onsite solar with EVs

EVs (see below for a few of the many references supplied in prior comments):
Maintenance and petroleum free
Long life
Quiet
Clean air
Mobile storage and supply
School busses in summer as storage
Cars parked 90% of time, can feed grids
Batteries still good for static storage after EV life
Solar vs Onshore Wind in Vulnerable Sites is a Political Decision

The testimony by Michael Winkler and others from RCEA and Schatz Energy casting offshore as too speculative is hard to square with their usually ebullient predictions of a prototype around 2025 generating 130 MWs. In all other venues, offshore wind generated electricity has been characterized in more optimistic language.

For example, in RCEA’s Sept 2018 offshore lease request, they conclude their Executive Summary: “RCEA and Project Partners are committed to deliver the Redwood Coast Project on or prior to 2024. We believe we can leverage the world-class wind resource, the natural enabling infrastructure and strong ecosystem of relevant stakeholders to make the Redwood Coast Project the first project to unlock the extraordinary value of offshore wind energy for California.”

The projected closure of Diablo Canyon nuclear plant in 2025 is cited as motivation
https://redwoodenergy.org/community-choice-energy/about-community-choice/power-sources/power-procurement/#1560279257453-46875d30-7617

The expanded offshore version with a capacity exceeding 1100MWs is also well underway. On April 2, 2019 The Bureau of Ocean Energy Management – Pacific Region reviewed and accepted 14 applicants as legally, technically, and financially qualified to hold an OCS renewable energy commercial lease.

On August 31, 2018, RCEA and the Humboldt Fishermen’s Marketing Association have entered into a Memorandum Of Understanding regarding this industrial development.

However, in the service of their relationship with TerraGen, and their obsessive dedication to utility scale onshore wind, these energy leaders offer up a convenient rebuttal to the reasonable question of why we would lay waste to so much when offshore is imminent. Their disingenuousness provides insight into why we have so little resilient distributed solar, when solar microgrids and Vehicle 2 Grid technologies are rapidly supplementing the grid in so many other places (see our prior submissions). They are so focused on becoming a utility and fostering an electricity exporting economy, that they dismiss and misrepresent the affordability and feasibility of widespread distributed solar, and all its social, technical, environmental, cultural and economic advantages over on-shore wind.

Distributed solar satisfies the goals of the GPU and RCEA:

• Creates a “Programmatic EIR,”
Permitting the Terra-Gen wind power project would open the County to expanded and streamlined onshore wind facilities, and in reality, permit the birth of an entire industry based on the net export of electricity from onshore and later offshore wind.

• The GPU and California Emphasize Wholesale Distributed Onsite Solar
• According to an RCEA report by Schatz Energy, in order to meet future energy demands, “…the State of California has developed energy policies that favor energy efficiency and conservation first, renewable energy and distributed generation second.”
GPU: 12.4 Goals and Policies Goals

2. **E-G2. Increase Energy Efficiency and Conservation.** Decrease energy consumption through increased energy conservation and efficiency in building, transportation, business, industry, government, water and waste management.

3. **E-G3. Supply of Energy from Local Renewable Sources.** Increased local energy supply from a distributed and diverse array of renewable energy sources and providers available for local purchase and export.

**•Monument & Bear River Ridges have always been TerraGen’s preferred and only locations for their WTGs**

TerraGen relies on claims that they initially considered Shively, Long and Rainbow Ridges, but after careful consideration reduced impacts by choosing Bear River and Monument Ridges. However, they had full access to Shell Wind intelligence from 2004-2012, which proposed 25 2MW WGTs on Bear River Ridge, NW of the current proposed locations. TerraGen installed their meteorological tower on Bear River Ridge in 2016. Consequently, TerraGen has always understood that the current configuration is the only feasible one, yet uses these other possibilities as “straw men” to satisfy CEQA and to delude decision-makers. There never was any serious consideration of any other location, only a paper one to make Bear & Monument Ridges appear less impactful or more feasible.

**•MaMu mitigations are not based on substantial evidence and are baseless**

TerraGen’s preposterous claim that “this project is the best thing for the murrelet” should tell you all you need to know about TerraGen, and their dry-labbed EIR. Marbled Murrelet compensatory mitigation relies on corvid reduction by cleaning Van Duzen campground. There is no supportable basis for this.

**Inland Habitat is the Only Effective Mitigation: The EIR is Disingenuous (lies) on this Point**

The EIR claims that: “This particular kind of restoration effort (corvid control in parks) was the most consistent and coordinated action taken by the Trustee Councils overseeing the restoration funds to replace murrelets lost in the oil spills.” 3.5-78

Contrary to this assertion, the major effective action taken to address the Kure and Stuyvesant oil spills’ combined killing of an estimated 265 marbled murrelets was the acquisition of permanent conservation easements from Green Diamond Company:

“Preservation/Management of Marbled Murrelet Habitat”

“The responsible parties in the Kure settlement purchased a Conservation Easement for the Big Mynot and E.F. Hunter parcels, containing approximately 77 acres of old-growth forest and approximately 222 acres of surrounding buffer areas. For the Stuyvesant settlement, the responsible parties purchased an easement for the Miracle Mile complex of parcels containing approximately 135 acres of old-growth forest and approximately 489 acres of surrounding buffer areas.”


The oil spill funding from the Kure and Stuyvesant spills reported in the January 13 update (see above), entitled “Corvid Management for Marbled Murrelets,” provides no quantifiable data on the success or outcomes of their scavenger-proof trashcans, or public education efforts.

“The earliest possible recovery time for nesting habitat, once lost, is generally 100—200 years. Specific nesting habitat requirements and life-history strategy, a low reproductive rate, a low current breeding success and recruitment rate (based on juvenile:adult ratios) are likely to yield a decreasing population, which cannot easily recover should numbers be further depleted by additional catastrophic events.”
Preconstruction Surveys Meaningless:
In a hearing before the State Of New Hampshire Site Evaluation Committee, November 1, 2012, Adam Gravel, Managing Leader of Stantec's Topsham, Maine office testified, in pertinent part: “Because, having the experience that I have that you just so noted, you can't, and I've said this for the past three projects as well, that you can't correlate pre-construction surveys with post-construction mortality.” (pg 21, lines 17-21)
(https://www.nhsec.nh.gov/projects/2012-01/documents/121101minutes201201am.pdf)

A few solar-EV references:
• “All The Energy Storage The Grid Needs Will Soon Be Under Our Noses”

“How batteries in electric school buses could be used to feed the grid”
During the summer, idle school buses could be put to work in energy storage.”

“EVs can also be employed as grid assets when managed to charge and discharge during energy demand peaks and valleys. In this application, especially in response to remote grid operator signals, they may support and stabilize the grid, serving as a load balancer.”

“During idle times, EVs can be used for temporary power storage. Once parked at the end of a workday commute, it could be connected to the grid and used to meet peak power demand when renewable generation is at its lowest.”

Respectfully Submitted in Opposition to Overriding Considerations TerraGen’s HumWind.

/s/
Ken Miller
Secretary
Siskiyou Land Conservancy
Nov. 9 '19

I think that it is important to note that the Terra-Gen Wind project is not the only wind power project being considered in Humboldt County and likely not the best suited for our area.

An offshore wind generating project currently being researched would negate the need to destroy miles of our natural landscape.

Choices made now will be living with our descendants for multiple generations to come.

It is important to weigh the lasting results of today's decisions.

I grew up in a quiet Southern CA beach town. An outside developer took note of a building ordinance loophole written to allow the flagpole reaching high atop the landmark hotel. Once construction of their nine extremely tall condos began - there was no stopping, no going back! The town, its skyline and yes, even the wind and shade - forever changed.

Please SLOW DOWN
Know that you have options.
Consider the gravity of your choice.

Thank you so much for your consideration on this important matter. Hollis Kreb
The windmills are too disturbing and distracting to the bird migration
More research is needed
Please hold off on development
Thanks

Sent from my iPhone
Please find attached comments related to the 11/14 hearing on the Humboldt Wind Energy Project.

Thank you,

Peter Carlson
To: Humboldt County Planning Commission and
John Ford, Director of Planning and Building Department
3015 H Street
Eureka, CA 95501
planningbuilding@co.humboldt.ca.us

November 19, 2019

RE: Humboldt Wind Energy Project Conditional Use Permit

I am writing in response to a couple items raised at the November 14 hearing on the Humboldt Wind Energy Project, where I did not have an opportunity to speak.

One is specific to a mitigation measure as referenced in the staff report as follows:

Mitigation Measures 3.5-6: (Minimize Construction Disturbance to Northern Spotted Owl)

The project gen-tie alignment was refined following circulation of the DEIR to include a 1,000-foot construction buffer from all activity centers, with the exception of one (Goat Rock, see Figure C-5 in Appendix C of the FEIR) where work will be avoided during the spotted owl breeding season.

Note that 1) the noise disturbance buffers for northern spotted owls during the breeding season range from 100 to 400 meters (up to 1316 feet) not the 1000 feet referenced, and that 2) Figure C-5 in Appendix C relates to Marbled Murrelet stands and staff likely is referring to Figure C-2. However, as seen in Figure C-2, four activity centers, not one, are within 400 meters and may need to be avoided during the breeding season.

I bring up this detail because it is an indication of how complex the proposed project is and that it is unreasonable that the county staff could keep all the details straight and review such a complex project in the time allowed. Who knows how many other details have been overlooked.

Second, I was surprised to hear that the financial analysis indicates that the project is only feasible at the highest pricing level, which is barely above the target level for the project to be feasible. Given the number of proposed mitigations, many that are still uncertain, it seems relevant to consider whether Humboldt County should be a testing ground for such a large project with uncertain impacts in a novel situation for a large scale wind farm (e.g. within the range of the Marbled Murrelet and in center of the redwood region).

Given the above, I encourage you to reject a conditional use permit until the details of the project and its impacts on our environment and local culture can be adequately assessed.

Sincerely,

Peter Carlson
Arcata, CA
Dear commissioners,

Please see the attached file that includes 410 signatures.

Thank you,

David Grant
To the Commission

Because of another commitment I am unable to attend the meeting this Thursday.

I will cut to the chase. While I understand the opposition's objections to impacts on natural beauty, wind power is an essential component of restructuring our power systems to address climate change. Yes, there are impacts, but the impacts are low compared to other sources such as natural gas or coal.

Please approve the Terra-Gen project. We need to diversify our local economy. We need to decentralize the power grid.

Thank you,

Eric V. Kirk
3551 N Street
Eureka, CA 95503
Please consider my public comment regarding new material circulated for the first time at the last (Nov. 14) meeting.

This includes the Staff recommended resolutions, the recitation of Findings and Evidence purported to show General Plan Consistency, the CUP, FEIR certification, MMRP and Overriding Considerations and other permits, standards and requirements including Staff's responses or non-responses to public comments written or spoken.

* Responses to Comments Raised During the Public Hearing: Wind Energy Effects on Fog. This response cites no peer reviewed or expert opinion sufficient to rebut the peer reviewed expert opinion placed in the administrative record by the public. ("They will mix the air mass that is present. This mixing will not affect fog formation in the valleys outside of the project site.") The response misstates the issue raised. The prior Official response ignored the June 14th public comments that raised a broad range of specific impacts resulting from the project's physical changes to the environment.

* The proposed Conditional Use Permit, CUP, to allow for electrical generation and transmission facilities will prejudice the rights and impair the health and safety of neighbors and affected persons downwind or within sight or sound or at risk of fire or turbulence or vibration from the project. This the activity identified by the CUP will infringe the County Ordinance welfare standard, Ca. Civ. Code 3334, and deny other constitutional and inalienable rights.

The Lead Agency is knowingly and purposefully, deliberately, or intentionally acting to single out classes of people forcing them to bear disproportionate burdens that could have been avoided or mitigated. (see 28 attachments).

Industrial Wind Turbines
- Petition - Paul Swift: Stop all wind turbine developments until "infrasound" health issues have been investigated · Change.org
- Farmland Owner Encourages People Not to Sign up for Wind Turbines – Redheaded Blackbelt
- A Problem With Wind Power [AWED.org]
- Medical testimony of Dr Herb Coussons — Friends Against Wind
- The Power of Community - How Cuba Survived Peak Oil - YouTube
- Trump on Wind Power's Problems (cancer too) — Friends Against Wind
- Infrasound & Low Frequency Noise: A Public Health Nightmare - YouTube
- Heroes of Burbo Bank Extension - YouTube
- Outage-prone West Marin mulls microgrids to create an ‘island of power’ – Marin Independent Journal
- Ontario Unwilling Hosts
- Property value impacts: a rebuttal | Wind Energy Impacts and Issues
- This country isn't just carbon neutral — it's carbon negative | Tshering Tobgay - YouTube
- Best Wind Turbine CRASH/FAIL Compilation HD 2016 - YouTube
- Wind Energy And Birds | Windmills Kill
- AWED – More Technical Information
- Retired Cal Fire Battalion Chief warns of fire hazards posed by wind projects - YouTube
- Birdwatchers see rare swift killed by wind turbine - Telegraph
- Cutting through the Spin | Wind Energy Impacts and Issues
- Wind Turbine Shadow Flicker and Noise, Byron Wisconsin - YouTube
- Life Under a Windplant - Part 3 - YouTube
- Where does the problem stop? - Google Groups
- Wind Turbine Projects | Windmills Kill
- The Sound of Silence: Iowa Farmers Cherish Peace & Quiet After Judge Shuts Down Wind Turbines – STOP THESE THINGS
- DON QUIXOTE BATTLES WINDMILLS – AND SO DO THE FOLKS IN BOULEVARD | East County Magazine
- Community Wind Farm Opposition | Wind Concerns Ontario
- Infrasound caused by Industrial Wind Turbines - YouTube
- AWED – More Economic Information
- SpeakOut Ontario - Nikki - YouTube
- Peter Jelbart's submission to the senate inquiry — Friends Against Wind
- Ontario Wind Resistance
- AWED – Mission Statement
- DOWN WIND - Wind Farm documentary - FULL DOC in HD - YouTube
- About us | EPAW - European Platform Against Windfarms
- Winning
- Three Decades of Wind Industry Deception — Friends Against Wind
Retired Cal Fire Battalion Chief warns of hazards posed by wind projects
Preview YouTube video Wind Turbine Shadow Flicker and Noise, Byron Wisconsin
Infrasound caused by Industrial Wind Turbines
Preview YouTube video SpeakOut Ontario - Nikki
Is Wind Energy Actually Clean?
Preview YouTube video Wind farm illness: Waubra Disease
Life with Industrial Wind Turbines in Wisconsin Part 2
Preview YouTube video Tallest Wind Turbine in the U.S. installed at West Texas A&M University
Tallest Wind Turbine in the U.S. installed at West Texas A&M University
Preview YouTube video Living Next Door to a Wind Farm Australia
How to Enjoy the End of the World
Preview YouTube video INFRASOUND AND LOW FREQUENCY NOISE - Ljubljana 2018
Professor Mariana Alves-Pereira explains vibroacoustic disease.
Preview YouTube video: Cliff Speaks out on Terra-Gen.
EVIDENCE a) is a fraud.

Humboldt County can meet its SB100 goal immediately with existing PGE 100% Solar Choice and directly displace fossil fuel use for $0.27036 kwhr. There is an oversupply of solar now, and in the future. Existing %100 Solar Choice can displace emissions of more than 372,000 metric tons per year of carbon dioxide that would otherwise be required to generate the same amount of electricity as this 155-megawatt project. These specific economic and carbon footprint considerations render the Humboldt Wind project uncompetitive and therefore infeasible. These specific considerations also eliminate any and all need for overriding economic considerations. Humboldt Wind will have enormous unmitigated impacts, fuel emissions, cost more-- RCEApower+ costs $0.27544, requires 22 miles of additional incendiary transmission lines, and only partially displaces fossil fuel. Pursuant to law, wind energy is ordered dispatched first and ordered curtailed last, thus it is able to bid into the grid at a lower price and will directly displace fossil fuel generation. The proposed project will result in a net environmental detriment. The County has improperly evaluated the economic, legal, social, technological, or other benefits, including region wide or statewide environmental benefits, of the project against its unavoidable environmental risks in determining whether to approve the project, and has improperly determined that the specific economic, legal, social, technological, or other benefits,
including region wide or statewide environmental **detriment**, of the project outweigh its **avoidable**, adverse environmental impacts so that the identified significant unavoidable impact(s) may be considered acceptable. This project is not in accordance with Section 15093 of the CEQA Guidelines.

see EVIDENCE a) ENVIRONMENTAL BENEFITS

If the Commission finds 1) there are not compelling reasons to override the documented, Significant, adverse, unmitigated, "unavoidable" environmental effects, or 2) that Findings cannot be made:

the Commission can **elect not to approve the project** or to **select an Alternative** particularly the **No Project Alternative**. But a new Resolution will have to be prepared since Staff spent its time on the Approval Resolutions only.

Public Resources Code section 21081 provides: "[N]o public agency shall approve or carry out a project for which an environmental impact report has been certified which identifies one or more significant effects on the environment that would occur if the project is approved or carried out unless both of the following occur:(a) The public agency makes one or more of the following findings with respect to each significant effect:(1) Changes or alterations have been required in, or incorporated into, the project which mitigate or avoid the significant effects on the environment.(2) Those changes or alterations are within the responsibility and jurisdiction of another public agency and have been, or can and should be, adopted by that other agency.(3) Specific economic, legal, social, technological, or other considerations, including considerations for the provision of employment opportunities for highly trained workers, make infeasible the mitigation measures or alternatives identified in the environmental impact report.(b) With respect to significant effects which were subject to a finding under paragraph (3) of subdivision (a), the public agency finds that specific overriding economic, legal, social, technological, or other **benefits of the project outweigh the significant effects on the environment.**" (Pub. Resources Code, § 21081, italics added)