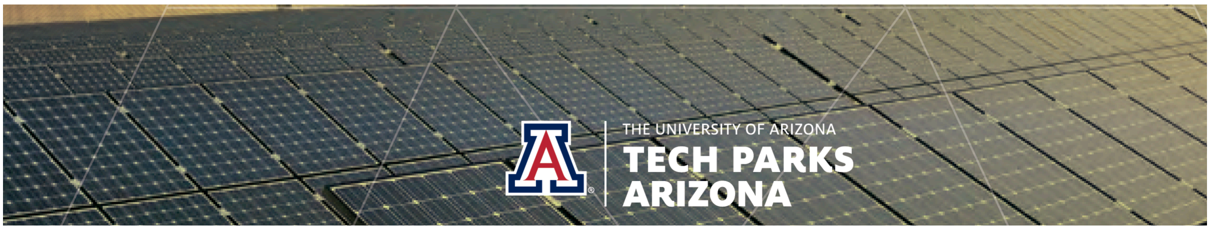
BARRON-GAFFORD RESEARCH GROUP
BIOGEOGRAPHY - ECOSYSTEM SCIENCE

Response to Technical Queries Associated with Permit NO: 2017-301
for the Proposed Solar Farm at:
1190 and 1220 Cosgrove-Lemnos Road,
260 Tank Corner East Road,
875 Boundary Road and
85 Crooked Lane LEMNOS VIC 3631



STATEMENT OF EVIDENCE BY GREG BARRON-GAFFORD ON SOLAR HEAT ISLANDING ISSUES

Prepared for Neoen Australia Pty Ltd

MAY 2018

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CONTENTS

1 INTRODUCTION: PRACTICE NOTE – EXPERT EVIDENCE

Name and Address of Expert

Greg Barron-Gafford, PhD
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B2 Earthscience, Biosphere 2, College of Science;
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Qualifications of Expert

PhD, Ecosystem Ecology, University of Arizona, 2010
MS, Natural Resources & Ecology, University of Georgia, 2001
BS, Environmental Science, Texas Christian University, 1998
Member, American Geophysical Union
Member, Ecological Society of America
Member, American Association of Geographers
Refer Curriculum Vitae at Attachment 1.

I have authored or co-authored 71 peer-reviewed publications that have been cited more than 1,900 times, and I have led research in ecosystem ecology and plant-atmosphere interactions for more than 17 years. I maintain an active research program in assessing the impacts of land use and climatic change in terms of plant function, ecosystem response, and local climate conditions. My team, under my supervision, produced the first experimental and empirical examination of the presence of a heat island effect associated with PV power plants.

Any Private or Business Relationship between the Expert Witness and the Party for Whom the Report is Prepared

None.

Instructions

Written instructions from White & Case Lawyers acting on behalf of Neoen Australia Pty Ltd dated 16 April as follows:

"*We would like you to prepare an expert witness statement for the panel in which you:*

(a) set out your background and expertise relevant to this issue;

(b) provide further information in relation to the Arizona study the subject of the paper that you co-authored titled The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures published in Nature Scientific Reports on 13 October 2016. In particular, we ask that you detail the following:

> *(i) brief description of study methodology;*
>
> *(ii) radius of the measured heat effects in that study, including those that were not outlined in the final paper. Explain the editing process that resulted in measured effects being excluded from study;*
>
> *(iii) analysis of your conclusions around the measured effects, including simple descriptions of energy pathways relevant to the 'heat island effect';*
>
> *(iv) outline contextual factors that may be relevant to the 'heat island effect', including environmental factors such as local landscape, humidity, cloud cover, fixed or rotating tilt panels, etc; and*
>
> *(v) briefly comment, if possible, on your understanding of the possible effect of wind on the heat island effect.*

(c) comment on your findings to date in other research work that you have been involved with relating to the PVHI effect and co-location of photovoltaics and agriculture;

(d) comment on the general implications of the above studies and literature for the Project and the interface between it and any established or future agricultural uses. Where possible, please include:

> *(i) comparative characteristics of the Arizona and Shepparton sites (e.g. presence of vegetation);*
>
> *(ii) your opinion as to whether the Project would change any onsite or offsite temperature;*
>
> *(iii) associated with that, your opinion as to how any change, if identified, would impact on bird and insect populations in the area;*
>
> *(iv) mitigating factors or measures that exist or could be implemented.*

We would also like you to consider the objections to the Project that are relevant to your area of expertise and respond to any relevant matters in your witness statement."

Facts, Matters and Assumptions

Facts, matters and assumptions on which opinions expressed in the report are based are set out in the report.

Documents and Materials Taken Into Account

The documents and any literature or other materials taken into account in preparing the report are identified in the report.

Methodology to prepare Witness Statement

In preparing this expert report I developed the following process:

(*i)* I reviewed the application and noted the submissions raising concerns about the potential negative impacts of the proposed solar farm on neighboring properties, environmental conditions, and birds, pollinators and other insects.

(*ii)* I reviewed the scientific literature on PVHI and collated the findings.

Examinations, Tests and Investigations

All examinations, tests, and investigations have been undertaken by me.

Summary of Opinion

A summary of opinion is included in the Conclusion.

Provisional Opinion

There are no provisional opinions.

Relevant Questions Outside of Expertise

There are no matters of relevance outside of my expertise.

Whether the report is incomplete or inaccurate in any respect

As far as I am aware the report is not incomplete or inaccurate in any respect.

Declaration

I have made all the inquiries that I believe are desirable and appropriate and no matters of significance, which I regard as relevant, have to my knowledge been withheld from the Panel.

2 MY WORK ON THE PHOTOVOLTAIC HEAT ISLAND (PVHI) EFFECT

2.1 BACKGROUND AND EXPERTISE RELEVANT TO SOLAR PROJECTS

I have led a team from January 2013 to present to assess the impacts of land use for renewable energy production in terms of plant function, ecosystem response, and local climate conditions. My colleagues in this work include faculty and students from the Department of Physics and Atmospheric Science and from the Department of Hydrology at the University of Arizona. We took continuous measurements (described below) for more than 18 months, and I then led a publication of the results in a co-authored, peer-reviewed manuscript entitled *The Photovoltaic Heat Island Effect (PVHI): Larger solar power plants increase local temperatures* published in ***Nature Scientific Reports*** on 13 October 2016. The paper details an objective look at the degree to which a PV power plant might alter local climate conditions. The paper is attached at Annexure 2. The study was conducted in response to requests from the Pima County (Arizona) Chief Building Official for Development Services for an assessment of the potential for a PVHI beyond the few studies previously presented in the literature.

2.2 FURTHER INFORMATION ON THE PUBLISHED STUDY OF THE PHOTOVOLTAIC HEAT ISLAND (PVHI) EFFECT IN ARIZONA

Brief description of methodology used to determine the presence of a PVHI within a solar farm

Early work on the detection of the presence of a PVHI in solar farms has been mostly theoretical or based upon simulated models. Furthermore, past empirical work had been limited in scope to a single biome. In order to determine whether or not a PV array elevated ambient air temperatures (°C) relative to native surroundings, we used shaded and aspirated temperature probes 2.5 m (manufacturer details can be found in *Barron-Gafford et al. (2016)*; Figure 1) at the following representative sites, all within a 1km^2 area:

- natural landscape (semiarid desert ecosystem);
- PV solar farm, where the probe was centrally located within the PV array; and
- within a traditional built environment (parking lot and commercial buildings).

Temperature probes were cross-validated for precision (closeness of temperature readings across all probes) at the onset and the conclusion of the experiment. We set the dataloggers to save the measurements of temperature at 30-minute intervals throughout a 24-hour day. We installed the weather stations in April 2014 and began simultaneously monitoring the three sites throughout an entire yearlong cycle to capture variations in temperatures across seasonal periods. We defined a PVHI effect as the difference in ambient air temperature between the PV solar farm and the natural landscape.

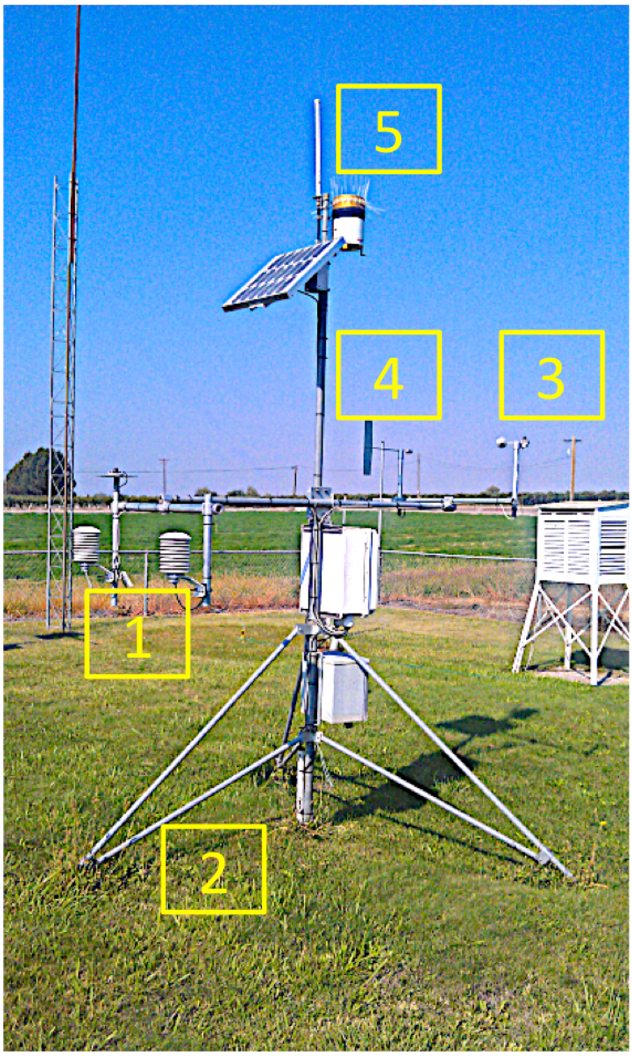

Figure 1. Weather stations were used to measure the local microclimate of an area. Each weather station used captured (1) ambient air temperature, (2) soil temperature, (3) wind speed, (4) wind direction, and (5) precipitation. All data were monitored every 30 minutes, and average conditions were saved by the datalogger. Cumulative precipitation was summed for each 30 minute period.

This type of weather station was installed at each of three sites: the photovoltaic array of a solar farm, the natural landscape, and a parking lot, to represent a typical built environment.

Photo credit: Campbell Scientific Instruments

Results illustrating the presence of a PVHI within a solar farm

Ultimately, we found that air temperatures within a PV solar farm are higher than those in nearby natural settings, and we referred to this as the PVHI effect (Figure 2). We found the PVHI effect to be much greater within the solar farm at night, with the greatest impacts being within the spring and summer months. Additionally, we found that presence of a PVHI effect to be much less significant during the day, and that the effects were least prominent in the winter and fall, regardless of time of day.

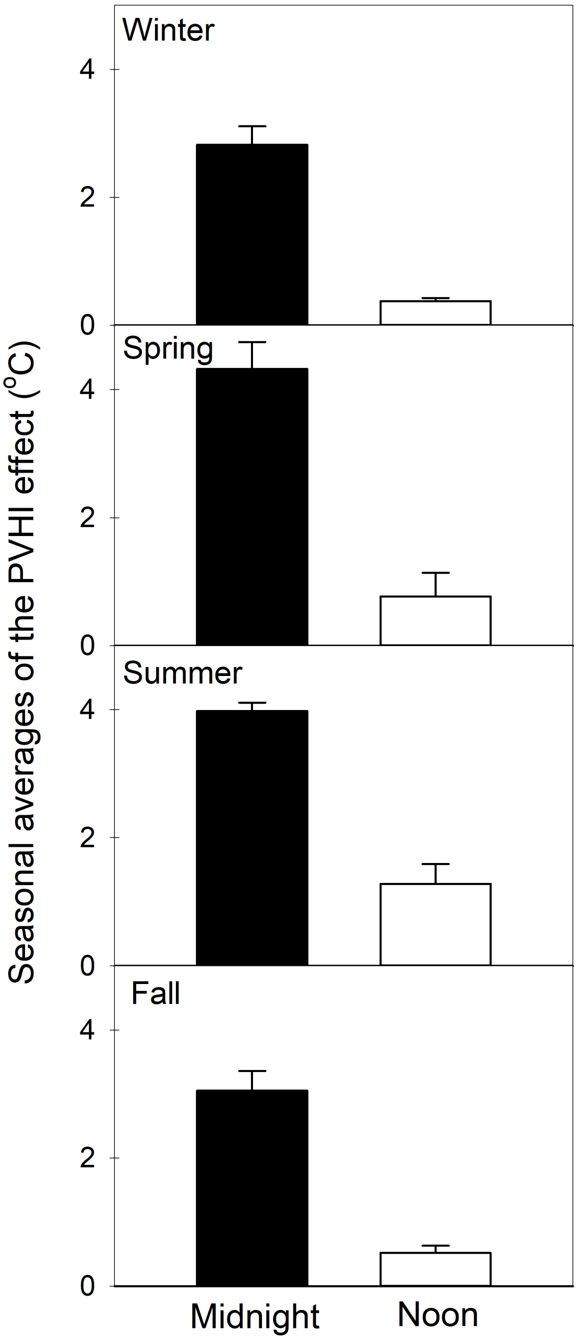

Figure 2. Through continuous monitoring of air temperatures within the center of a solar field for more than a year, we detected the presence of a PVHI effect. The effect was greatest in the nighttime hours (black bars indicate averages at midnight) and lowest during the day (white bars). The degree of the PVHI effect in the center of the solar farm was also seasonally variable with the warm season months experiencing greater impacts than the cool season months.

Figure recreated from Barron-Gafford et al. (2016).

Analysis of conclusions on the presence of a PVHI within a solar farm

As described in *Barron-Gafford et al. (2016*; in Annexure 2), incoming sun energy typically is either reflected back to the atmosphere or absorbed, stored, and later re-radiated in the form of latent or sensible heat. Within natural ecosystems, vegetation reduces heat gain and storage in soils by creating surface shading; this also occurs within PV arrays, but less so in the rows between the panels. Energy absorbed by vegetation and surface soils can be released as latent heat in the transition of liquid water to water vapor to the atmosphere through water loss from soils (evaporation) and vegetation (transpiration). This heat-dissipating latent energy exchange is dramatically reduced within a PV installation that does not have an “understory” of vegetation. PV panels convert ~20% of absorbed energy into usable electricity and also allow some light energy to pass, which, in unvegetated soils will lead to greater heat absorption. This greater sensible heat efflux from the soil becomes trapped under the PV panels, much like clouds trap the energy radiating from the Earth’s surface. On cloudy nights, air temperatures do not cool off as much as they do on clear nights. This is the same principle in the PVHI, and I believe the reason that the PVHI dissipates so quickly as one moves away from the edge of the panels. Under the panels, it is analogous to a cloudy night, and away from the array, where those panels are absent, conditions are analogous to a clear night sky.

2.3 DETERMINING THE SPATIAL EXTENT OF THE PVHI

Methods for measuring the radius of the measured heat effects in the study

In addition to measuring the degree of the photovoltaic heat island (PVHI) effect within the solar farm, we measured the extent to which the heat island effect extended outward from the PV array (Figure 3). We installed the weather stations with the same air temperature probe described in Section 2.2 to measure temperature:

- inside the array at 20m and 40m in from the edge of the array;
- at the edge of the array (0m); and
- outside the array at 10, 20, 30, 40, and 50m out from the edge of the array.

We installed these weather stations in April 2015, and we maintained them throughout a six-month period to capture variation in the relative differences in temperatures across seasonal periods. While this was a part of our original study design once we had identified the presence of the PVHI effect, this data and associated graphic were cut from our final manuscript by the *Nature Scientific Reports* editor due to space constraints. This is quite unfortunate because the distance of the PVHI effect is one of the primary questions I continue to receive since the publication of this manuscript.

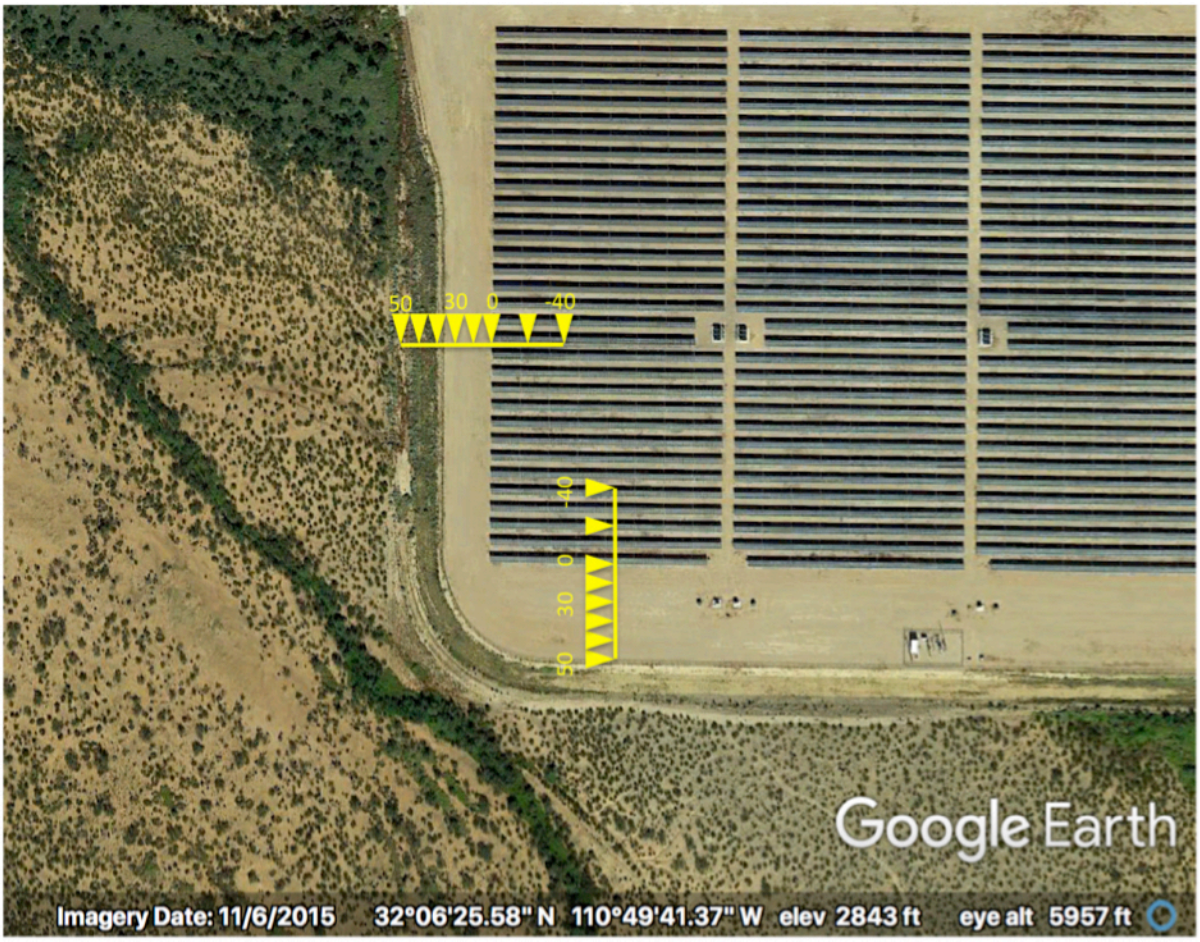

Figure 3. Locations of additional measures of air temperature are marked with yellow triangles. Stations were placed inside the array at 20m and 40m in from the edge of the array, at the edge of the array (0m), and outside the array at 10, 20, 30, 40, and 50m out from the edge of the array to quantify the spatial extent of the PVHI effect.

Results on the radius of the measured heat effects

We found that the PVHI was indistinguishable from air temperatures over native vegetation when measured at a distance of 30m from the edge of the PV array (Figure 4). This pattern held true for both daytime and nighttime conditions. Because the PV panels themselves trap the energy from diffuse sunlight that was able to reach the ground underneath them, air temperatures remain elevated within a PV array. As you leave this “overstory” of PV panels, energy is able to radiate back towards the atmosphere, as it does in a natural setting, and the PVHI quickly dissipates.

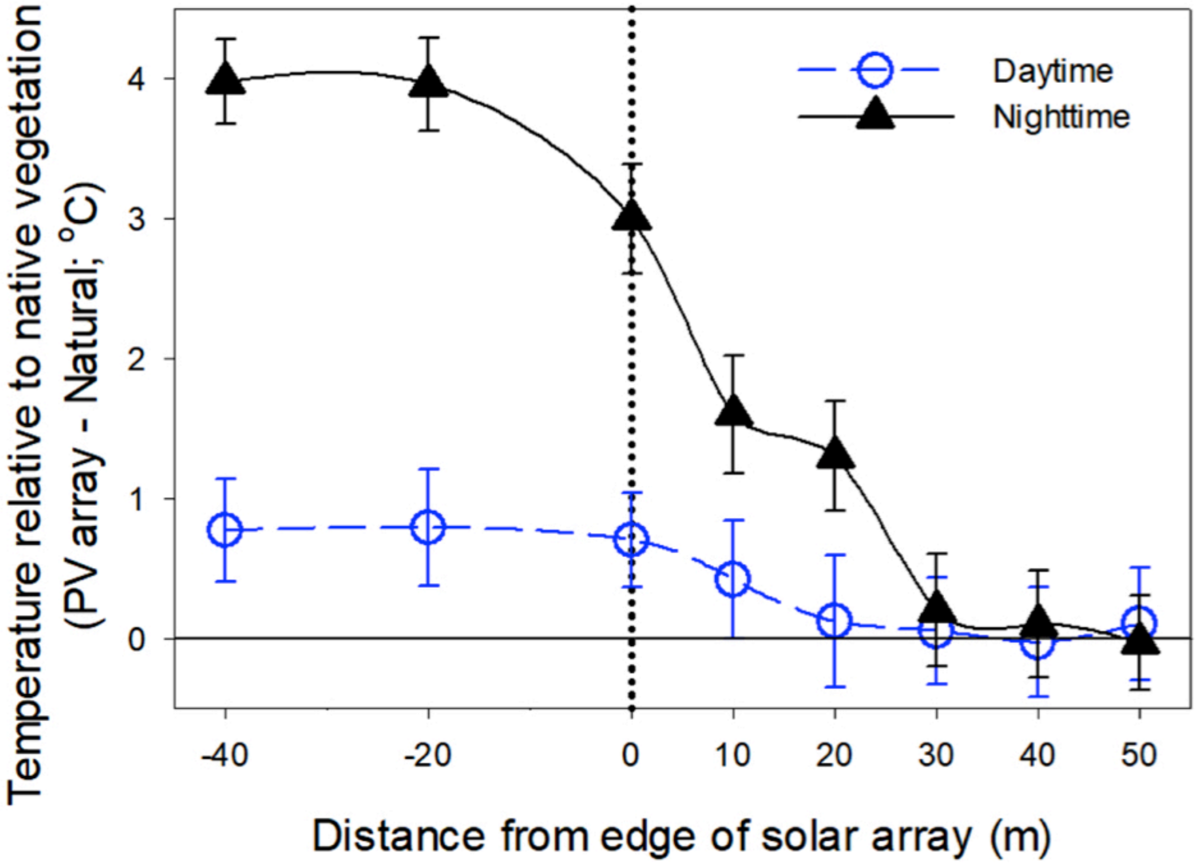

Figure 4. Measures of air temperature within (negative values on the X-axis) and outside of the PV array (positive values on the X-axis) were used to quantify the spatial extent of the PVHI effect. The dotted line represents the edge of the PV array.

The solid line at 0 on the Y-axis illustrates when there is no difference between a measurement along the transect and ambient air temperatures over native vegetation. At night, the PVHI effect of 3-4°C directly above the solar panels is reduced to 1.5 °C at 10m and to 0°C at 30m. There is a lesser PVHI effect by day. Error bars represent 1 standard error around the mean.

3 COMMENT ON THE GENERAL IMPLICATIONS OF THE ABOVE AND OTHER STUDIES IN THE LITERATURE

3.1 Consideration of Other Technical Papers Examining the PVHI Effect

One of the other primary research articles in the literature on the presence and extent of the PVHI comes from *Fthenakis and Yu (2013)*. This paper links both field data and computational fluid dynamics simulations. Ultimately, *Fthenakis and Yu* found that (*i*) ambient temperatures can be up to 1.9°C greater within a solar farm, and (*ii*) temperatures dissipate rapidly with increased distance from the solar farm, with no detectable effect by at about 300m (Figure 5). In my opinion, the approach and simulations appear sound. However, my critique is tied to the accuracy of the sensors used. For the paper published by *Fthenakis and Yu (2013)*, the accuracy of the Hawk weather station air temperature probe is only ± 0.5°C, but no data on the uncertainty or variation are presented. Please see: https://www.weatherhawk.com/wp-content/uploads/2016/06/Signature-Series-Comprehensive-Manual-V7.pdf

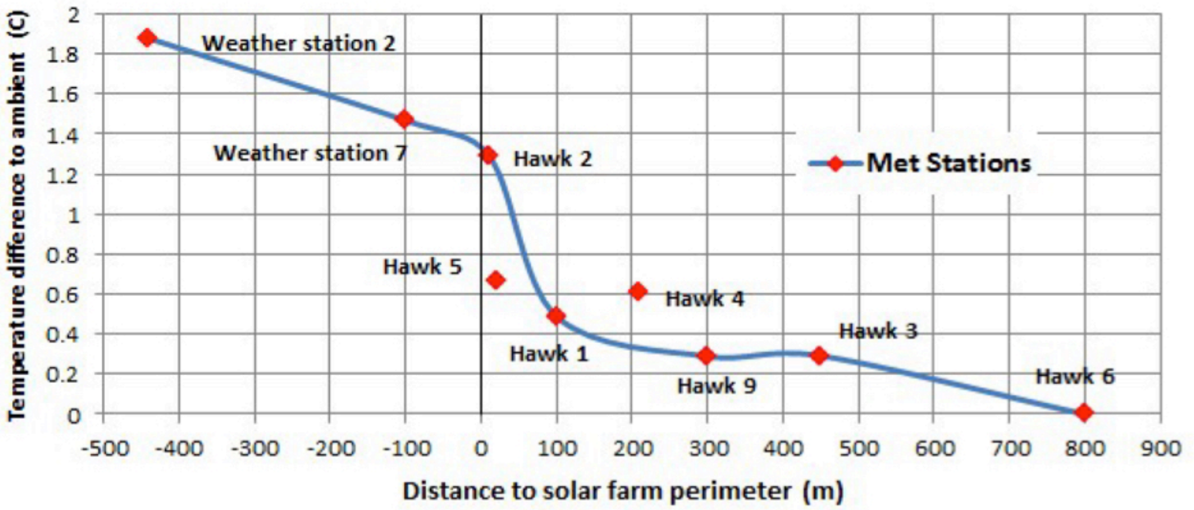

Figure 5. Measures of air temperature within (negative values on the X-axis) and outside of the PV array (positive values on the X-axis), as presented by *Fthenakis and Yu (2013)* to quantify the spatial extent of the PVHI effect. The solid line at 0 on the X-axis represents the edge of the PV array. The data illustrate that the PVHI dissipates rapidly with increasing distance away from the edge of the PV array.

In my opinion, then, if we added this uncertainty to their Figure 8 (shown here as Figure 5 within this report), all measures of air temperature beyond 200m may actually be indistinguishable from ambient air temperatures. Additionally, I do not consider "Hawk 4" to be evidence of a spike in the PVHI away from the PV array. *Fthenakis and Yu* suggest that the higher values at Hawk 4 might be due to the fact that they are on the downwind side of the solar farm. However, I interpret this more as a singular measure that is anonymously higher than those around it, which are on a downward trend as one moves away from the array. Finally, there are no measures of uncertainty on any of these measurements. From maintaining our research sites for more than a year, I know there are day-to-day variations in temperature. *Fthenakis and Yu* also dismiss another one of their sensors as showing "higher temperatures likely due to a calibration inaccuracy", which leads me to wonder if the same might be true for Hawk 4. Taken together, I wonder if this is anything more than an anomaly.

More recently, *Yang et al.* (*2017*) have added an additional manuscript to this body of literature through a detailed suite of measurements on air and soil temperatures at depth. Ultimately, *Yang et al.* found that the degree of PVHI in terms of daytime air temperatures was nearly absent during winter, but during the other seasons the daytime air temperature in the solar farm was higher than that in areas without PV. As in our study, the maximum PVHI effect was detected during their summer. *Yang et al.* found that the PVHI was present during nighttime hours during all four seasons; again this parallels our own research, which examined the seasonal variation in daytime and nighttime PVHI effect. *Yang et al.* did not mention any data on the spatial extent and dissipation of the PVHI effect in their paper.

3.2 CONTEXTUAL FACTORS THAT MAY BE RELEVANT TO THE PVHI EFFECT

To date, no empirical or experimental studies have explicitly examined correlations between environmental factors such as local landscape, humidity, cloud cover, fixed or rotating tilt panels, and either the degree or spatial extent of a PVHI. However, we can look to literature on the analogous Urban Heat Island (UHI) effect and on Human Thermal Comfort (HTC) for potential indicators. Increases in wind speed has been shown to reduce the UHI (*Rajagopalan et al. 2014*), including work conducted in Australia (*Santamouris et al. 2017*), however, there are less clear patterns in terms of the impacts of humidity on the UHI. Increased cloud cover is likely to exacerbate the PVHI because clouds trap any re-radiation of sun energy back towards the atmosphere, whether in a built or natural environment. Importantly, recent work has shown that the UHI effect is greater in locations with higher background temperatures (*Taha 2017).*

3.3 POSSIBLE EFFECT OF PV ANGLE TILT ON THE PVHI EFFECT

To date, no empirical or experimental studies have investigated the impacts of PV panel angle on the degree of PVHI within an array. A greater degree of tilt would allow for greater loss of heat trapped under the panels, but this should be considered in concert with potential reflection from panels at the end of the day, in which a more severe angle might lead to greater horizontal reflection. Our work (*Barron-Gafford et al. 2016*) was conducted within a PV array in which panels pivoted east-to-west tracking the sun, but maximum angles only approached 45°. The work of *Yang et al.* (*2017*), which found a similar contained PVHI effect within a PV array, was conducted within a PV array with panels at a fixed tilt angle of 36°, and the panels within the solar farm studied by *Fthenakis & Yu* (2013) had a tilt angle of 25°. I have been informed that the PV panels in the proposed Project will be single-axis tracking and could, therefore, be left at an angle to dissipate heat overnight. Together, the existing body of research suggests to me that further research on the linkage between PV angle tilt and the degree of the PVHI warrants more study, but I would predict that maintaining a PV panel angle overnight of 45-50° would aid in nighttime dissipation of any PVHI effect that is created within the array.

3.4 FINDINGS RELATING TO THE PVHI EFFECT AND CO-LOCATION OF PHOTOVOLTAICS AND RESTORATION OR AGRICULTURE (AGRIVOLTAICS)

Grass + Photovoltaics

The notion of “either-or” between green spaces and solar farms has been progressively more challenged in recent years as companies move towards either restoring solar farms with grasses after installation or leaving grasses in place instead of blading the soil during installation. Co-locating grasses under PV arrays can yield multiple ecosystem services (tangible and non-tangible amenities) including continued carbon dioxide sequestration from our atmosphere, localized cooling from the transpiration of the plants, grazing forage, and storm-water regulation. In my team's own preliminary work on the effects of revegetating PV solar farms with grasses, we found significant cooling of the local atmosphere (Figure 6). In addition to illustrating the positive effect of vegetation on PV solar farm temperatures, the fact that the plants did so well in such close proximity to the PV panels (around and under the panels) suggests to me a lack of a negative impact of PV installations on local vegetation.

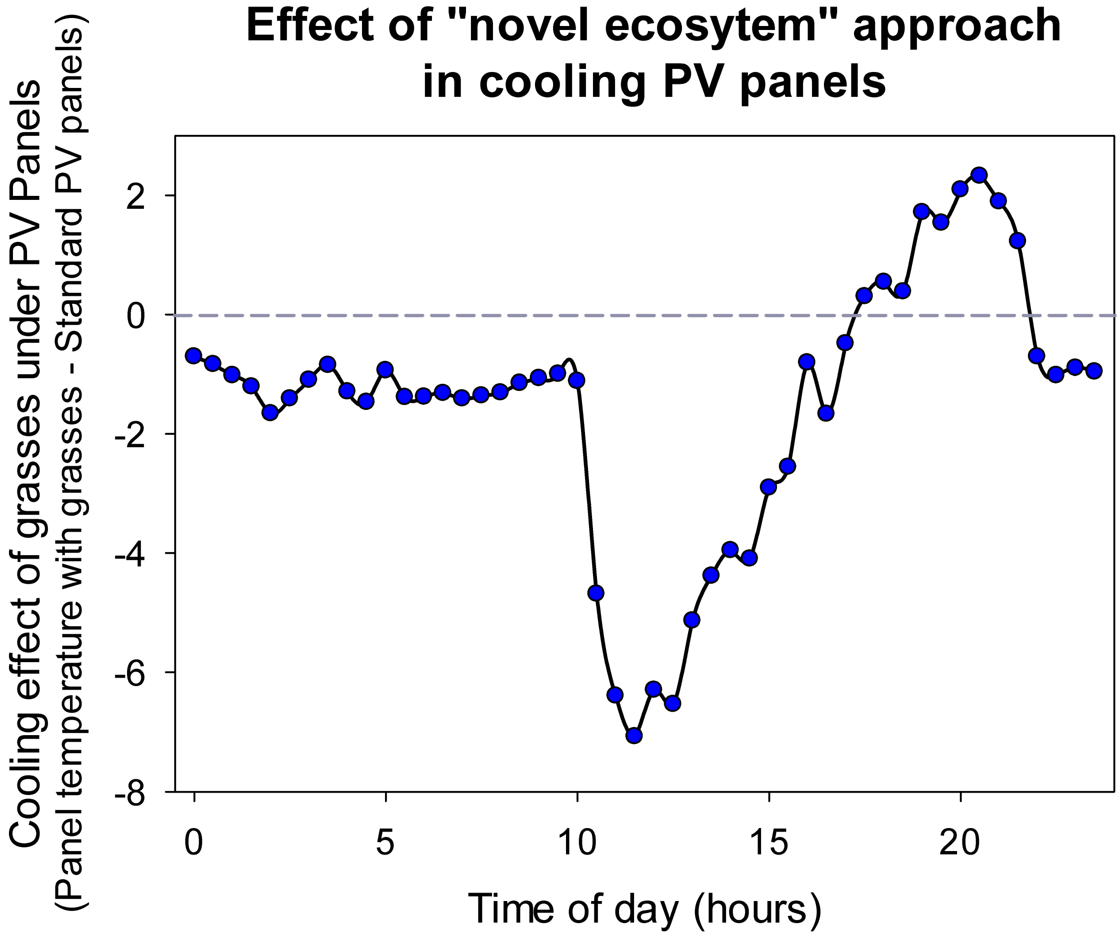

Figure 6. Measures of air temperature within a PV array restored with an understory of grasses versus a PV installation with only bare soil. The dotted line at 0 on the Y-axis illustrates when there is no difference between these measurements, and a negative value indicates the cooling effect of having a PV array restored with grasses. At night, the PVHI effect was cooled by about 1.5 °C, and the daytime PVHI effect was reduced by up to 7°C within the solar array. The reduced impacts in the early evening are likely due to the vegetation being 'shut down' for the day and, therefore, not providing any transpirational cooling.

Closer to the proposed Project site, co-location of grazing of sheep beneath an overstory of PV panels have illustrated a lack of quantifiable evidence of detrimental effects on livestock:
https://parkessolarfarm.com.au/Library/sheep-grazing-under-neoen-solar-farm/

I understand that grasses will be retained at the proposed Project site. While no published research to date measures the impacts at such a large spatial footprint, I believe that leaving the grasses under the panels should greatly reduce the PVHI effect within the solar farm, which will serve to only assist in any reductions in the spatial extent of the PVHI effect outside of the array.

Agriculture + Photovoltaics

Recently, my colleagues and I have been investigating a novel approach to co-located "green" agriculture and "grey" solar PV infrastructure, where crops are grown in the shade of the PV panels within a solar farm – a practice we call 'agrivoltaics'. We suggest that this novel energy and food generating ecosystem may become an important - but as yet under investigated - mechanism for maximizing crop yields, efficiently delivering water to plants, and generating renewable energy (Figure 7). Similar pilot studies in France and Germany have also suggested that this co-location can have beneficial effects on a balanced approach to food and renewable energy production. Beyond illustrating innovative applications in renewable energy systems, the co-location of an agriculture and PV arrays suggests that there are no ill effects of PV arrays on food production. Through our extensive measures of photosynthetic rates, transpirational water loss, and total fruit production, we have found no evidence to suggest that plants overheat or lose their potential to function by being in (extremely) close proximity to PV panels. In fact, in many cases production is increased, and water use efficiency becomes much higher because the solar panels reduced direct sunlight on the soils that drive the evaporation of irrigated waters.

Additionally, we have found that PV panels in a traditional ground-mounted array were significantly warmer in the day and experienced greater within-day variation than panels over an agrivoltaic understory, illustrating the cooling effect of vegetation. We attribute these lower daytime temperatures in PV panels in the agrivoltaic system to the greater balance of latent heat energy exchange from plant transpiration relative to sensible heat exchange from radiation off bare soil (the typical installation method). Across the core growing season, PV panels in an agrivoltaic system were ~ 8.9+0.2^{o}C cooler in the day. These data suggest that even a vegetative barrier can significantly cool panels and the local atmosphere below those caused by the PVHI effect.

Figure 7. The co-location of agricultural under an elevated ‘overstory’ of PV panels has demonstrated increased production of some crop species (tomatoes, carrots, cabbages, chiltepin peppers, and kale) and increased water savings in the irrigation needed for additional spring and summer crops including red and yellow chards, purple, tepary, and cow beans, cilantro, and Japanese eggplant.

3.5 GENERAL IMPLICATIONS OF THE ABOVE STUDIES AND LITERATURE FOR THE PROPOSED PROJECT

Comparative characteristics of the Arizona and Shepparton sites

Given recent work has shown that the Urban Heat Island effect is greater in locations with higher background temperatures (*Taha 2017*), it is important to consider comparative characteristics of the Arizona site, where much of my work has been conducted, and the Shepparton site under consideration here. Average climate data for Tucson (https://www.usclimatedata.com/climate/tucson/arizona/united-states/usaz0247) and Shepparton (http://www.bom.gov.au/climate/averages/tables/cw_081125.shtml) illustrate that Tucson is consistently warmer in terms of maximum and minimum temperatures in both the winter and summer seasons. Also noteworthy are vegetative differences in terms of understory vegetation. The installations in the Southwestern USA often are mechanically bladed to remove all vegetation, where as the proposed Project site will retain grasses in the understory. As noted above (Figure 6), this understory vegetation can provide significant cooling to mitigate the PVHI effect within a PV array. As such, we are working to adapt this type of practice more often here in the US installations.

Taken together with the results of *Taha 2017*, I would predict that the degree of PVHI within Shepparton might be lower than the values we measured in Tucson because of the differences in background temperatures and vegetation.

Table 1. A comparison of climatic differences between Tucson, Arizona, USA and Shepparton, Victoria, Australia, underscores the higher average temperatures of the Southwestern USA, which may lead to an elevated PVHI effect in the region.

	Summer		Winter	
	Maximum	Minimum	Maximum	Minimum
Tucson, Arizona, USA	38.1	24.7	18.9	5.5
Shepparton, Victoria, Australia	31.9	15.3	13.3	3.3

Potential for associated impact on bird and insect populations in the area

I have no experience in detecting ill effects on bird or insect populations in or around PV arrays, other than those that stem from a lack of vegetation. The fact that understory grass vegetation will be retained here should actually help to maintain local insect and bird abundances and biodiversity. Still, bolstering bird and insect populations could be achieved through either targeted revegetation efforts around the PV array or through co-location of PV and pollinator friendly vegetation, as has been carried out in multiple locations (Figure 8, for example). Multiple example stories are listed within the References section (5.2) of this report.

Beyond illustrating innovative applications in renewable energy systems, the co-location of pollinator habitat and grazing with PV arrays suggests that there are no ill effects of PV arrays on this vegetation or animals. Plants do not overheat or lose their potential to function by being in (extremely) close proximity to PV panels. Given that our research has shown that the increase in temperatures due to the PVHI effect do not extend past 30m, I do believe that off-site impacts on birds and insets are highly unlikely. Revegetating with native and locally adapted species will ensure that the solar farm does not contribute to any insect pest outbreaks that could negatively impact local agricultural areas.

Figure 8. The co-location of grasses and native or locally adapted pollinator species under an ‘overstory’ of PV panels has demonstrated increased abundance of bird populations and locally important pollinator species.
Photo of the Westmill Solar Park in Watchfield, England; Photo credit: Guy Parker

4 CONCLUSIONS

WILL THE PROJECT CHANGE ANY ONSITE OR OFFSITE TEMPERATURE?

In summary, both my own research and that of independent groups with which I am not affiliated have shown that solar farms can create PVHI effect, but the spatial extent of the effect is constrained. The PVHI effect is largely driven by the absence of vegetation and the vegetation's potential to cool the atmosphere through transpirational water loss. Bolstering the presence of vegetation through co-location (as described in Section 3.4) or having landscaping around the solar farm will mitigate the PVHI effect. My own research on adding grasses back into a solar farm showed the impacts of grasses on reducing the PVHI effect within a solar array. To-date, no study has published research on these patterns at such large scales, but I have no reason to believe that there will be a different outcome when extrapolated in scale. The increased practice of leaving or re-introducing vegetation within PV solar farms is acknowledging the multiple benefits that come from this practice.

Adding a vegetative buffer to the study site does not seem necessary to creating the dissipation of the PVHI effect as one moves outside of the PV array, as neither of the studies I have conducted or those described by *Fthenakis and Yu (2013)* monitored solar farms with a vegetative buffer.

I have made all of the enquiries that I believe are desirable and appropriate and that no matters of significance which I regard as relevant have to my knowledge, been withheld from the Panel.

Greg Barron-Gafford, PhD
University of Arizona
3 May 2018

5 REFERENCES

5.1 REFERENCES FOR PEER-REVIEWED MANUSCRIPTS CITED WITHIN THIS REPORT

Barron-Gafford, G. A. *et al.* The Solar Heat Island Effect: Larger solar power plants increase local temperatures. *Nature Scientific Reports* **6: 35070**, DOI: 10.1038/srep35070 (2016).

Fthenakis, V. & Yu, Y. Analysis of the potential for a heat island effect in large solar farms. *Analysis of the potential for a heat island effect in large solar farms; 2013 IEEE 39th Photovoltaic Specialists Conference*, 3362-3366 (2013).

Rajagopalan, P., Lim, K. C. & Jamei, E. Urban heat island and wind flow characteristics of a tropical city. Solar Energy 107, 159-170, doi:10.1016/j.solener.2014.05.042 (2014).

Santamouris, M. *et al.* Urban Heat Island and Overheating Characteristics in Sydney, Australia. An Analysis of Multiyear Measurements. *Sustainability* **9**, 21, doi:10.3390/su9050712 (2017).

Taha, H. Characterization of Urban Heat and Exacerbation: Development of a Heat Island Index for California. *Climate* **5**, doi:10.3390/cli5030059 (2017).

Yang, L. *et al.* Study on the local climatic effects of large photovoltaic solar farms in desert areas. *Solar Energy* **144**, 244-253, doi:10.1016/j.solener.2017.01.015 (2017).

5.2 REFERENCES FOR IMPACT ON BIRD AND INSECT POPULATIONS IN PV SOLAR FARMS

https://www.solarpowerworldonline.com/2017/05/pollinator-friendly-solar-vegetation/

http://eanvt.org/wp-content/uploads/2017/04/The-Effects-of-Solar-Farms-on-Local-Biodiversity-A-Comparative-Study-UK.pdf

https://www.greenbiz.com/article/pollinator-friendly-solar-sites

http://agriculture.vermont.gov/node/1507

Greg A. Barron-Gafford

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CHRONOLOGY OF EDUCATION

2005-2010 University of Arizona, Tucson, Arizona, USA
Ph.D. Ecology & Evolutionary Biology, 2010
Dissertation: *Temperature and precipitation controls over soil, leaf and ecosystem level CO_2 flux along a woody plant encroachment gradient*
Advisor: Travis Huxman

1998-2001 University of Georgia, Athens, Georgia, USA
M.S. Forest Ecology, 2001
Thesis: *The effects of increasing stand density on nutrient limitations to growth and nutrient budgets multi-species pine stands*
Advisors: Robert Teskey and Rodney Will

1994-1998 Texas Christian University, Ft. Worth, Texas, USA
B.S. Environmental Science, 1998
Thesis: *Analysis of forest structure and function at Huntsville State Park, Texas*
Advisors: Leo Newland and Glenn Kroh

CHRONOLOGY OF EMPLOYMENT

Aug 2017 – Present: **Tenure Track Associate Professor**, School of Geography & Development, University of Arizona, Tucson, AZ, 85721

Aug 2016 – Present: **Associate Director**, School of Geography & Development, University of Arizona, Tucson, AZ, 85721

Aug 2013 – Present: **Tenure Track Assistant Professor**, School of Geography & Development, University of Arizona, Tucson, AZ, 85721

Aug 2013 – Present: **Tenure Track Assistant Professor**, Biosphere 2, College of Science, University of Arizona, Tucson, AZ, 85721

Feb 2010 – Aug 2013: **Assistant Research Professor** and **Associate Research Scientist**, Biosphere 2, College of Science, University of Arizona, Tucson, AZ, 85721

Feb 2010 – Aug 2010: **Postdoctoral Research Associate**, Department of Botany, University of Wyoming, Laramie, WY, 82071

Dec 2003 – Feb 2010: **Research Specialist**, Department of Ecology & Evolutionary Biology, University of Arizona, Tucson, AZ, 85721

June 2001 – Dec 2003: **Senior Research Specialist**, Lamont-Doherty Earth Observatory ~ Biosphere 2, Columbia University, Palisades, NY, 10964

SERVICE / OUTREACH

Local / state outreach

2017	University of Arizona Museum of Art ~ *Art-Science Connections*
2017 – Present	Tucson Unified School District ~ *Rincon/University High Schools & Manzo Elementary School: Agrivoltaics installation and curriculum development*
2017	University of Arizona Biosphere 2 ~ *Earth Day: Agrivoltaics Hands-on Experiential learning station*
2017	University of Arizona Biosphere 2 ~ *Science Saturday: Agrivoltaics Presentations and Hands-on Experiential learning station*
2016	University of Arizona Museum of Art ~ *Fires of Change Panelist*
2013	Tumamoc Hill Public Lecture Series ~ *Lectures in the Libraries*
2013	The Santa Rita Experimental Range ~ *Discovery Saturday Public Series*
2008 – 2014	Science Saturdays (Hands-on Science activities) at Biosphere 2
2008 – Present	Informal presentations with Biosphere 2 visitors as we conduct experiments along the tour route

National / Professional

2017 – Present	Onsite Reviewer ~ U.S. National Science Foundation Environmental Biology
2017 – Present	Virtual Panel Reviewer ~ Swiss National Science Foundation, Swiss National Science Foundation Professorship
2017 – Present	Virtual Panel Reviewer ~ Israeli Science Foundation, China-Israel Research Program (CIRP) Review Panel
2017 – Present	International External Reviewer ~ University of Adelaide (Australia), External reviewer for doctoral dissertation
2017 – Present	International External Reviewer ~ Edith Cowan University (Australia), External reviewer for doctoral dissertation
2016 – Present	Onsite Reviewer ~ U.S. National Science Foundation Ecosystem Science Cluster program Doctoral Dissertation Improvement Grants (DDIG)
2013 – Present	Onsite Reviewer ~ U.S. Environmental Protection Agency (EPA) Science to Achieve Results (STAR) Graduate Fellowship

National / Professional (continued)

2013 – Present	Section Editor ~ *Annual Reviews in Plant Biology*
2013 – Present	Session Organizer for the Annual Meeting of the American Geophysical Union
2012 – Present	Section Editor ~ *Physiological Ecology of Photosynthesis* within *Oxford Bibliographies in Ecology*
2010 – Present	Oral presentation and poster judge for graduate student awards at the Annual Meeting of the American Geophysical Union
2010 – Present	Oral presentation and poster judge for Ecological Society of America's Plant Physiological Ecology section awards

2002 – Present	Journal Reviewer. (2012– 11; 2013- 12; 2014- 8; 2015- 9; 2016 – 8 so far): Representative Journals: *Journal of Biogeography, Agricultural and Forest Meteorology, Global Change Biology, Journal of Arid Environments, Nature, Nature Scientific Reports, Nature Energy, Journal of Geophysical Research-Atmospheres, Journal of Geophysical Research-Biogeosciences, New Phytologist, Methods in Ecology & Evolution, Oecologia*

University

2016 – 2017	Ecosystem Genomics Cluster Hire, Earth Sciences executive hiring committee
2015 – Present	UA Arid lands Steering Committee
2015 – Present	Art-Environment Network Governance Committee Member, Institute of the Environment
2014	University of Arizona Foundation Expo of Excellence, representing the School of Geography& Development and Biosphere 2's partnership in STEAM education programming with Manzo Elementary
2014	Water, Environmental, and Energy Solutions (WEES) Faculty Proposal Review Board
2013 – Present	National Ecological Observatory Network Regional Site Selection Committee
2013 – Present	UofA Sky School, Mt. Lemmon Sky Center – Project Organizer
2012 – Present	Institute of the Environment Faculty Exploratory Grant Referee
2011 – Present	University Representative for the Consortium of Universities Allied for Water Research (NSF sponsored program)
2011 – Present	Institute of the Environment Graduate Award Reviewer

Department

2016 – Present	SGD Associate Director
2014 – Present	SGD Undergraduate Committee
2014 – Present	SGD Curriculum and Assessment Committee

Department (continued)

2013 – 2015	SGD Graduate Committee
2013 – Present	Physical Geography Curriculum Sub-committee
2013 – Present	UC-San Diego Academic Connections, in partnership with Biosphere 2 – Project Organizer & student mentor
2013 – 2014	Association of Pacific Coast Geographers Conference Planning Committee
2013 – 2015	Biosphere 2 Earth Month Programming
2013 – 2015	Arizona Center for STEM Teachers – Presenter for weeklong program
2013 – 2014	Physical Geographer Position Hiring Committee
2010 – 2014	Advisor for Biosphere 2 Research Technicians
2011 – Present	Critical Zone Observatory – Ecohydrological Partitioning Sub-committee
2010 – Present	Specialty Tour Guide for Biosphere 2 VIP visitors

Societies

2014 – Present	Association of Pacific Coast Geographers (APCG)
2013 – Present	American Association of Geographers (AAG)
2007 – Present	American Geophysical Union (AGU)
2003 – Present	Ecological Society of America (ESA)

PUBLICATIONS / CREATIVE ACITIVITY

H-index (ISI)	22
Citations (ISI, October, 2017)	1635
Articles published in peer review journals	63
Articles in review	6
Other peer reviewed articles and book chapters	3

Chapters in scholarly books

2. Moore GW, McGuire K, Troch PA, **Barron-Gafford GA**. (2015). Ecohydrology and the Critical Zone: Processes and Patterns across Scales. *In* Principles and Dynamics of the Critical Zone, Giardino and Houser (Eds.). Elsevier.

1. Sengupta A, Pangle LA, Volkmann THM, Dontsova K, Troch PA, Meira AA, Neilson JW, Hunt EA, Chorover J, van Haren J, **Barron-Gafford GA**, Bugaj A, Abramson N, Sibayan M. (2016, *In press*). Advancing understanding of hydrological and biogeochemical interactions in evolving landscapes through controlled experimentation and monitoring at the Landscape Evolution Observatory. In Terrestrial Ecosystem Research Infrastructures: Challenges, New Developments and Perspectives. Abbad Chabbi & Hank Loescher (Eds.). Taylor and Francis Group.

Electronic publication (peer reviewed)

1. **Barron-Gafford GA (2015).** *Physiological Ecology of Photosynthesis*. Oxford Bibliographies Online Resource Library. DOI: 10.1093/OBO/9780199830060-0093

Conference Proceedings

3. **Barron-Gafford GA**, Osmond CB, Grieve KA, Lipson D, and Murthy R. (2005) Elevated CO_2 differentially effects photosynthesis and carbon balance in poplar stands, a four year study. In: van der Est, A. and Bruce, D. (eds). *Photosynthesis: Fundamental Aspects to Global Perspectives: Proceedings 13th International Congress on Photosynthesis*. ACG Publishing (Photosynthesis and Global Change, 973-976).

2. Armstrong AF, Hartley IP, Ineson P, **Barron-Gafford GA**, Murthy R and Atkin OK. (2005). Can climate driven changes in photosynthesis be used to predict changes in the rate and temperature sensitivity of ecosystem respiration? In: van der Est, A. and Bruce, D. (eds). *Photosynthesis: Fundamental Aspects to Global Perspectives: Proceedings 13th International Congress on Photosynthesis*. ACG Publishing (Photosynthesis and Global Change, 958-959).

1. Will RE, **Barron GA**, Teskey RO, and Shiver B. (2005). Within and between canopy variability of foliar nitrogen concentrations for loblolly and slash pine stands planted at different densities. *Biennial Southern Silviculture Conference Proceedings*.

Refereed journal articles

63. **Barron-Gafford GA**, Sanchez-Cañete EP, Hendryx S, Minor RL, Colella T, Murphy P, Lee E, Scott RL, Kumar P. (2017). Impacts of hydraulic redistribution on grass-tree competition versus facilitation in a semiarid savanna. *New Phytologist*, **215**: 1451-1461.
62. Potts DL, Minor RL, Braun Z, **Barron-Gafford GA**. (2017). Photosynthetic phenological variation may promote coexistence among co-dominant tree species in a Madrean sky island mixed conifer forest. *Tree Physiology*, **37**: 1229-1238.
61. Minor J, Falk DA, **Barron-Gafford GA**. (2017). Fire severity and regeneration strategy influence shrub patch size and structure following disturbance. *Forests*, **8**: DOI: 10.3390/f8070221.
60. Sanchez-Canete EP, Scott RL, van Haren J, **Barron-Gafford GA**. (2017). Improving the accuracy of the gradient method for determining soil carbon dioxide efflux. *Journal of Geophysical Research-Biogeosciences*, **122**: 50-64.
59. van Haren J, Dontsova K, **Barron-Gafford GA**, Troch PA, Chorover J, Delong SB, Breshears DD, Huxman TE, Pelletier JD, Saleska SR, et al. (2017). CO_2 diffusion into pore spaces limits weathering rate of an experimental basalt landscape. *Geology*, **45**: 203-206.
58. Villegas JC, Law DJ, Stark SC, Minor DM, Breshears DD, Saleska SR, Swann ALS, Garcia ES, Bella EM, Morton JM, Cobb NS, **Barron-Gafford GA**, Litvak ME, Kolb TE. (2017). Prototype campaign assessment of disturbance-induced tree loss effects on surface properties for atmospheric modeling. *Ecosphere*, **8**:3.
57. **Barron-Gafford GA**, Minor RL, Allen NA, Cronin AD, Brooks AE, Pavao-Zuckerman MA. (2016). The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures. *Nature Scientific Reports* **6**.
56. Scott RL, Biederman JA, Hamerlynck EP, **Barron-Gafford GA**. (2015). The carbon balance pivot point of southwestern U.S. semiarid ecosystems: Insights from the 21st century drought. *Journal of Geophysical Research-Biogeosciences*, **120**: 2612-2624, doi: 10.1002/2015JG003181.
55. Villegas JC, Dominguez F, **Barron-Gafford GA**, Adams HD, Guardiola-Claramonte M, Sommer ED, Selvey AW, Espeleta JF, Zou CB, Breshears DD, Huxman TE. (2015). Sensitivity of regional evapotranspiration partitioning to variation in woody plant cover: insights from experimental dryland tree mosaics. *Global Ecology and Biogeography,* **24**: 1040-1048.
54. Stielstra CM, Lohse KA, Chorover J, McIntosh JC, **Barron-Gafford GA**, Perdrial JN, Litvak M, Barnard HR, Brooks PD. (2015). Climatic and landscape influences on soil moisture are primary determinants of soil carbon fluxes in seasonally snow-covered forest ecosystems. *Biogeochemistry*, **123**: 447-465.

53. Pangle LA, DeLong SB, Abramson N, Adams J, **Barron-Gafford GA**, Breshears DD, Brooks PD, Chorover J, Dietrich WE, Dontsova K, Durcik M, Espeleta J, Ferre TPA, Ferriere R, Henderson W, Hunt EA, Huxman TE, Millar D, Murphy B, Niu G-Y, Pavao-Zuckerman M, Pelletier JD, Rasmussen C, Ruiz J, Saleska S, Schaap M, Sibayan M, Troch PA, Tuller M, van Haren J, Zeng X. (2015). The Landscape Evolution Observatory: A large-scale controllable infrastructure to study coupled Earth-surface processes. *Geomorphology*, **244**: 190-203.

52. Field JP, Breshears DD, Law DJ, Villegas JC, Lopez-Hoffman L, Brooks PD, Chorover J, **Barron-Gafford GA**, Gallery RE, Litvak ME, Lybrand RA, McIntosh JC, Meixner T, Niu G-Y, Papuga SA, Pelletier JD, Rasmussen CR, Troch PA. (2015). Critical Zone Services: Expanding context, constraints, and currency beyond Ecosystem Services. *Vadose Zone Journal,* **14,** doi: 10.2136/vzj2014.10.0142.

51. Ogle K, Barber JJ, **Barron-Gafford GA**, Bentley LP, Young JM, Huxman TE, Loik ME, Tissue DT. (2015). Quantifying ecological memory in plant and ecosystem processes. *Ecology Letters*, **18**: 221-235.

50. Zhang X, Niu G-Y, Elshall AS, Ye M, **Barron-Gafford GA**, Pavao-Zuckerman M. (2014). Assessing five evolving microbial enzyme models against field measurements from a semiarid savannah - What are the mechanisms of soil respiration pulses? *Geophysical Research Letters*, **41**: 6428-6434.

49. **Barron-Gafford GA**, Cable JM, Bentley LP, Scott RL, Huxman TE, Jenerette GD, Ogle K. (2014). Quantifying the timescales over which exogenous and endogenous conditions affect soil respiration. *New Phytologist*, **202**: 442–454, doi: 10.1111/nph.12675.

48. Potts DL, **Barron-Gafford GA**, Jenerette GD (2014). Metabolic acceleration quantifies biological systems' ability to up-regulate metabolism in response to episodic resource availability. *Journal of Arid Environments*, **104**: 9-16.

47. Scott RL, Huxman TE, **Barron-Gafford GA**, Jenerette GD, Young JM, Hamerlynck EP. (2014). When vegetation change alters ecosystem water availability. *Global Change Biology,* **20**: 2198-2210, doi: 10.1111/gcb.12511.

46. Nelson K, Kurc SA, John G, Minor RL, **Barron-Gafford GA**. (2014). Influence of snow cover duration on soil evaporation and respiration efflux in mixed- conifer ecosystems. *Ecohydrology*, **7**: 869-880.

45. Kimball S, Gremer JR, **Barron-Gafford GA**, Angert AL, Huxman TE, Venable DL. (2014). High water-use efficiency and growth contribute to success of non-native *Erodium cicutarium* in a Sonoran Desert winter annual community. *Conservation Physiology*, **2**: cou006, doi:10.1093/conphys/cou006.

44. Hamerlynck EP, Scott RL, Sánchez-Cañete EP, **Barron-Gafford GA**. (2013). Nocturnal soil CO_2 uptake and its relationship to subsurface soil and ecosystem carbon fluxes in a Chihuahuan Desert shrubland. *Journal of Geophysical Research-Biogeosciences*, **118**, 1593–1603, doi: 10.1002/2013JG002495.

43. **Barron-Gafford GA**, Scott RL, Jenerette GD, Hamerlynck EP, Huxman TE. (2013). Landscape and environmental controls over leaf and ecosystem carbon dioxide fluxes under woody plant expansion. *Journal of Ecology*, **101**: 1471–1483, doi: 10.1111/1365-2745.12161.

42. Hamerlynck EP, Scott RL, Cavanaugh ML, **Barron-Gafford GA**. (2013). Water use efficiency of annual- and bunchgrass-dominated savanna intercanopy space. *Ecohydrology*, **7**: 1208-1215, doi: 10.1002/eco.1452

41. Cable JM, Ogle K, **Barron-Gafford GA**, Bentley LP, Cable WL, Scott RL, Williams DG, Huxman TE. (2013). Antecedent conditions influence soil respiration differences in shrub and grass patches. *Ecosystems*, **16**: 1230-1247, doi: 10.1007/s10021-013-9679-7.

40. **Barron-Gafford GA**, Angert AL, Venable DL, Tyler AP, Gerst KL, Huxman TE. (2013). Photosynthetic temperature responses of co-occurring desert winter annuals with contrasting resource-use efficiencies and different temporal patterns of resource utilization may allow for species coexistence. *Journal of Arid Environments,* **91:** 95-103.

39. Hamerlynck EP, Scott RL, **Barron-Gafford GA**. (2013). Consequences of cool-season drought-induced plant mortality to Chihuahuan Desert grassland ecosystem and soil respiration dynamics. *Ecosystems*, **16**: 1178-1191, doi: 10.1007/s10021-013-9675-y.

38. Huxman TE, Kimball S, Angert AL, Gremer JR, **Barron-Gafford GA**, Venable DL. (2013). Understanding past, contemporary, and future dynamics of plants, populations, and communities using Sonoran Desert winter annuals. *American Journal of Botany*, **100**: 1369-80.

37. Pelletier JD, **Barron-Gafford GA**, Breshears DD, Brooks PD, Chorover J, Durcik M, Harman CJ, Huxman TE, Lohse KA, Lybrand R, Meixner T, McIntosh JC, Papuga SA, Rasmussen C, Schaap M, Swetnam TL, Troch PA. (2013). Coevolution of nonlinear trends in vegetation, soils, and topography with elevation and slope aspect: A case study in the sky islands of southern Arizona. *Journal of Geophysical Research: Earth Surface*, **118**: 741-758.

36. Adams HD, Germino MJ, Breshears DD, **Barron-Gafford GA,** Guardiola-Claramonte M, Zou CB, Huxman TE (2013). Nonstructural leaf carbohydrates dynamics during drought-induced tree mortality support role for carbon metabolism in mortality mechanism of *Pinus edulis*. *New Phytologist,* **197**: 1142-1151.

35. **Barron-Gafford GA**, Rascher U, Bronstein JL, Davidowitz G, Chaszar B, Huxman TE. (2012). Herbivory of wild *Manduca sexta* causes fast down-regulation of photosynthetic efficiency in *Datura wrightii*: an early signaling cascade visualized by chlorophyll fluorescence. *Photosynthesis Research*, **113**: 249-260, doi: 10.1007/s11120-012-9741-x

34. Jardine K, **Barron-Gafford GA**, Norman JP, Abrell L, Monson RK, Meyers KT, Pavao-Zuckerman M, Dontsova K, Kleist E, Werner C, Huxman TE. (2012). Green leaf volatiles and oxygenated metabolite emission bursts from mesquite branches following light-dark transitions. *Photosynthesis Research*, **113**: 321-333.

33. Ogle K, Lucas RW, Bentley LP, Cable JM, **Barron-Gafford GA**, Griffith A, Ignace D, Jenerette GD, Tyler A, Huxman TE, Loik ME, Smith SD, Tissue DT. (2012). Differential daytime and night-time stomatal behavior in plants from North American deserts. *New Phytologist*, **213**: 1229-1239, doi: 10.1007/s11258-012-0081-x

32. Hamerlynck EP, Scott RL, **Barron-Gafford, GA**, Cavannaugh M, Moran S, Huxman TE. (2012). Cool-season whole-plant gas exchange of exotic and native semiarid bunchgrasses. *Plant Ecology*, **213:** 1229-1239, doi: 10.1007/s11258-012-0081-x

31. Resco V, Goulden ML, Ogle K, Richardson AD, Hollinger DY, Davidson EA, Alday JG, **Barron-Gafford GA**, Carrara A, Kowalski AS, Oechel WC, Reverter BR, Scott RL, Varner RK, Moreno JM. (2012). Endogenous circadian regulation of carbon dioxide exchange in terrestrial ecosystems. *Global Change Biology*, **18**: 1956-1970.

30. **Barron-Gafford GA**, Scott RL, Jenerette GD, Hamerlynck EP, Huxman TE. (2012). *Temperature and precipitation controls over leaf- and ecosystem-level CO_2 flux of grass and woody species along a woody plant encroachment gradient. *Global Change Biology*, **18**: 1389-1400, doi:10.1111/j.1365-2486.2011.02599.x

29. Jenerette GD, **Barron-Gafford GA**, Guswa A, McDonnel J, Camilo Villegas, J. (2012). Organization of complexity in water limited ecohydrology. *Ecohydrology*, **5**: 184-189.

28. Cable JM, **Barron-Gafford GA**, Ogle K, Huxman TE, Pavao-Zuckerman MA, Scot RL, Williams DG. (2012). Shrub encroachment alters sensitivity of soil respiration to variation in temperature and moisture. *Journal of Geophysical Research-Biogeosciences*, **117**: G01001, doi: 10.1029/2011JG001757

27. **Barron-Gafford GA**, Scott RL, Jenerette GD, Huxman TE. (2011). *The relative controls of temperature, soil moisture, and plant functional group on soil CO_2 efflux at diel, seasonal, and annual scales. *Journal of Geophysical Research-Biogeosciences*, **116**: G01023, doi: 10.1029/2010JG001442.

26. Bobich EG, **Barron-Gafford GA**, Rascher KG, Murthy R. (2010). Effects of drought and changes in vapour pressure deficit on water relations of Populus deltoides growing in ambient and elevated CO_2. *Tree Physiology*, **30**: 886-875.

25. Scott, RL, Hamerlynck EP, Jenerette GD, Moran MS, **Barron-Gafford GA**. (2010). Carbon dioxide exchange in a semidesert grassland through drought-induced vegetation change. *Journal of Geophysical Research-Biogeosciences*, **115**: G03026, doi:10.1029/2010JG001348.

24. Wang L, Caylor KK, Villegas JC, **Barron-Gafford GA**, Breshears DD, Huxman TE. (2010). Partitioning evapotranspiration across gradients of woody plant cover: Assessment of a stable isotope technique, *Geophysical Research Letters*, **37**: L09401.

23. Jenerette GD, Scott RL, **Barron-Gafford GA**, Huxman TE. (2009). Gross primary production variability associated with meteorology, physiology, leaf area, and water supply in contrasting woodland and grassland semiarid riparian ecosystems. *Journal of Geophysical Research-Biogeosciences*, **114**: G04010, doi:10.1029/2009JG001074

22. Adams HD, Guardiola-Claramontea M, **Barron-Gafford GA**, Camilo-Villegas J, Breshears DD, Zou CB, Troch PA, Huxman TE. (2009). Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. *Proceedings of the National Academy of Sciences USA*, **106**: 7063–7066.

21. Adams HD, Guardiola-Claramonte M, **Barron-Gafford GA**, Camilo Villegas JC, Breshears DD, Zou CB, Troch PA, Huxman TE. (2009). Reply to Leuzinger et al.: Drought-induced tree mortality temperature sensitivity requires pressing forward with best available science. *Proceedings of the National Academy of Science*, **106**: E69-E69.

20. Adams HD, Guardiola-Claramonte M, **Barron-Gafford GA**, Camilo Villegas JC, Breshears DD, Zou CB, Troch PA, Huxman TE. (2009). Reply to Sala: Temperature sensitivity in drought-induced tree mortality hastens the need to further resolve a physiological model of death. *Proceedings of the National Academy of Science*, **106**: E107-107.

19. Huxman TE, **Barron-Gafford GA**, Gerst KL, Angert AL, Tyler AP, Venable DL. (2008). Photosynthetic resource-use efficiency and demographic variability in desert winter annual plants. *Ecology*, **89**: 1554-1563.

18. Venable DL, Flores-Martinez A, Muller-Landau HC, **Barron-Gafford GA**, Becerra JX. (2008). Seed dispersal of desert annuals. *Ecology*, **89**: 2218-2227.

17. Zou CB, **Barron-Gafford GA**, Breshears DD. (2007). Effects of topography and woody plant canopy cover on near-ground solar radiation: Relevant energy inputs for ecohydrology and hydropedology. *Geophysical Research Letters,* **34**: L24S21.

16. Pegoraro E, Potosnak MJ, Monson RK, Rey A, **Barron-Gafford GA,** Osmond CB. (2007). The effect of elevated CO_2, soil and atmospheric water deficit and seasonal phenology on leaf and ecosystem isoprene emission. *Functional Plant Biology,* **34**: 774-784.

15. **Barron-Gafford GA**, KA Grieve, Murthy R. (2007). Leaf- and stand-level responses of a forested mesocosm to independent manipulations of temperature and vapor pressure deficit. *New Phytologist*, **174**: 614-625.

14. Patrick L, Cable J, Potts D, Ignace D, **Barron-Gafford GA**, Griffith A, Alpert H, Van Gestel N, Robertson T, Huxman TE, Zak J, Loik ME, Tissue D. (2007). Effects of an increase in summer precipitation on leaf, soil, and ecosystem fluxes of CO_2 and H_2O in a sotol grassland in Big Bend National Park, Texas. *Oecologia*, **151**: 704-718.

13. Angert AL, Huxman TE, **Barron-Gafford GA**, Gerst KL, Venable DL. (2007). Linking growth strategies to long-term population dynamics in a guild of desert annuals. *Journal of Ecology,* **95**: 321–331.

12. Hartley IP, Armstrong AF, Murthy R, **Barron-Gafford GA**, Ineson P, Atkin AK. (2006). The dependence of respiration on photosynthetic substrate supply and temperature: integrating leaf, soil and ecosystem measurements. *Global Change Biology,* **12**: 1954–1968.

11. Lipson DA, Blair M, **Barron-Gafford GA**, Grieve K, Murthy R (2006). Relationships between microbial community structure and soil processes under elevated atmospheric carbon dioxide. *Microbial Ecology*, **51**: 302–314.

10. Druart N, Rodríguez-Buey M, **Barron-Gafford GA**, Sjödin A, Bhalerao R, Osmond CB, Hurry V (2006). Molecular targets of elevated [CO_2] in leaves and stems of *Populus deltoides*: implications for future tree growth and carbon sequestration. *Functional Plant Biology* **33**: 121–131.

9. **Barron-Gafford GA**, Martens D, McLain JET, Grieve KA, Murthy R. (2005). Growth of eastern cottonwoods (*Populus deltoides*) in elevated CO_2 stimulates stand-level respiration and rhizodeposition of carbohydrates, accelerates soil nutrient depletion, yet stimulates above and belowground biomass production. *Global Change Biology*, **11**: 1220-1233.

8. Pegoraro E, Abrell L, van Haren J, **Barron-Gafford GA**, Grieve K, Malhi Y, Murthy R, Lin G. (2005). The effect of elevated atmospheric CO_2 and drought on sources and sinks of isoprene in a temperate and tropical rainforest mesocosm. *Global Change Biology*, **11**: 1234-1246.
7. Murthy R, **Barron-Gafford GA**, Dougherty PM , Engel VC , Grieve K, Handley L, Klimas C, Potosnak MJ, Zarnoch SJ , Zhang J. (2005). Increased leaf area dominates carbon flux response to elevated CO_2 in stands of *Populus deltoides* (Bartr.) and underlies a switch from canopy light-limited CO_2 influx in well-watered treatments to individual leaf, stomatally-limited influx under water stress. *Global Change Biology*, **11**: 716-731.
6. Pegoraro E, Rey A, **Barron-Gafford GA**, Monson R, Malhi Y, Murthy R. (2005). The interacting effects of elevated atmospheric CO_2 concentration, drought and leaf-to-air vapour pressure deficit on ecosystem isoprene fluxes. *Oecologia*, **146**: 120-129.
5. Walter A, Christ MM, **Barron-Gafford GA**, Grieve K, Paige T, Murthy R, Rascher U. (2005). The effect of elevated CO_2 on diel leaf growth cycle, leaf carbohydrate content and canopy growth performance of *Populus deltoids. Global Change Biology*, **11**: 1207-1219.
4. Pegoraro E, Rey A, Murthy R, Bobich EG, **Barron-Gafford GA,** Grieve K, Malhi YC. (2004). Effect of elevated CO_2 concentration and vapor pressure deficit on isoprene emission from leaves of *Populus deltoides* during drought. *Functional Plant Biology*, **31**: 1137-1147.
3. **Barron-Gafford GA**, RE Will, EC Burkes, B Shiver, Teskey RO. (2003). *Nutrient concentrations and contents, and their relation to stem growth, of intensively managed *Pinus taeda* and *Pinus elliottii* stands of different planting densities. *Forest Science*, **49**: 291-300.
2. Burkes, EC, Will RE, **Barron-Gafford GA**, Teskey RO, Shiver BD. (2003). Biomass partitioning and growth efficiency of intensively managed *Pinus taeda* and *Pinus elliottii* stands of different planting densities. *Forest Science*, **49**: 224-234.
1. Will, RE, **Barron GA**, Burkes EC, Shiver BD, Teskey RO. (2001). *Relationship between intercepted radiation, net photosynthesis, respiration, and rate of stem volume growth of *Pinus taeda* and *Pinus elliottii* stands of different densities. *Forest Ecology and Management*, **154**: 155-163.

WORK IN PROGRESS

Articles in peer review, final preparation, or revision

6. Adams HA, **Barron-Gafford GA**, Minor RL, Gardea AA, Bentley LP, Breshears DD, Dowell NG, Huxman TE. (*In Re-review post-revision*). Ever increasing drought-induced mortality risk for tree species with ever rising temperatures. *Environmental Research Letters.*
5. Elshall AS, Ye M, Niu G-Y, **Barron-Gafford GA**. (*In Re-review post-revision*). Impacts of Residual Models on Bayesian Inference and Predictive Performance of Soil Respiration Models. *Journal of Geophysical Research – Biogeosciences*.
4. Elshall AS, Ye M, Niu G-Y, **Barron-Gafford GA**. (*In Re-review post-revision*). Relative Model Score: A Multi-Criteria Metric for Measuring Relative Predictive Performance of Multiple Models. *Water Resources Research*.

3. Lee E, Kumar P, **Barron-Gafford GA**, Hendryx S, Sanchez-Cañete EP, Minor RL, Colella T, Scott RL. (*In Review*). Impact of hydraulic redistribution on multispecies vegetation water use in a semi-arid savanna ecosystem: An experimental and modeling synthesis. *Water Resources Research*.

2. Froend RH, Breshears DD, Law DJ, **Barron-Gafford GA**. (*In Review*). Phreatophytes in the Anthropocene: State and Transition Models for Climate Change and Land Use Pressures. *Earth's Future*.

1. Minor J, Colella TR, Barnes M, Mann S, Murphy P, Pearl J, **Barron-Gafford GA**. (*In Review*). Critical Zone Science in the Anthropocene: Opportunities for Biogeographic Theory and Praxis to Drive Earth Science Integration. *Global Ecology and Biogeography*.

MEDIA OUTREACH

2017	UA News. *UA Researchers Plant Seeds to Make Renewable Energy More Efficient.* Interviewee discussing Agrivoltaics as an experiment in combining agriculture with energy efficiency, involves growing plants beneath solar panels, community outreach with Manzo Elementary and University High School, and the linkage between School of Geography & Development and Biosphere 2. Full online version: https://uanews.arizona.edu/story/ua-researchers-plant-seeds-make-renewable-energy-more-efficient?utm_source=uanow&utm_medium=email&utm_campaign
2016	ResearchGate. *Solar energy is hot right now, in more ways than one.* Interviewee discussing unintended impacts of large-scale renewable energy through photovoltaics. Full online version: https://www.researchgate.net/blog/post/solar-energy-is-hot-right-now-in-more-ways-than-one
2016	Arizona Daily Star. *Critical Zone Observatory gets grant to extend research.* Interviewee discussing the inter- and cross-disciplinary research within the context of the Critical Zone Observatory, and the linkage between School of Geography & Development and Biosphere 2. Full online version: http://tucson.com/news/science/environment/critical-zone-observatory-gets-grant-to-extend-research/article_aa4df9dc-a7a1-11e6-9f60-b341da1029a7.html
2014	Bill Buckmaster Show. *Superstars of Science.* Interviewee discussing the Manzo Elementary project, STEAM learning (including Art in STEM education), and the linkage between School of Geography & Development and Biosphere 2. Full online version: http://www.buckmastershow.com/2014/04/24/buckmaster-show-4242014-tusd-struggles-to-keep-students/
2013	Tucson Weekly (cover story). *Learning through Landscapes*. Interviewee on the partnership between School of Geography & Development and Biosphere

	2 with Manzo Elementary to introduce a new STEM learning program. Full online version: http://www.tucsonweekly.com/tucson/learning-through-landscapes/Content?oid=3918303
2013	Arizona Public Media. Interviewee on the biogeography of woody plant expansion and the linkage between School of Geography & Development and Biosphere 2. https://ondemand.azpm.org/videoshorts/watch/2013/9/16/26865-grassland-faces-threats-from-mesquite-trees-woody-plants/

CONFERENCES AND SCHOLARLY PRESENTATIONS *(limited to period in rank)*

Invited Symposia (limited to period in rank)

Barron-Gafford GA (*Invited speaker*). Biogeography in the Critical Zone: Insights from the Mountain Tops and Valley Floor. UCLA Department of Geography Tod Spieker Colloquium Series. Tucson, Arizona. November, 2015.

Barron-Gafford GA (*Invited speaker*). Ecohydrology in our Critical Zone: Insights from Semiarid Mountain Tops to the Valley Floor. School of Natural Resources & the Environment (SNRE) Colloquium. Tucson, Arizona. October, 2015.

Barron-Gafford GA (*Invited speaker*). Sensor Technologies and Unmanned Aerial Vehicles (drones) to Measure Ecosystem Processes in Semi-arid Environments. Research Insights in Semiarid Ecosystems (RISE) Symposium. Tucson, Arizona. October, 2015.

Barron-Gafford GA (*Invited speaker*). Examining ecosystem function in space and time within the critical zone through the lenses of ecology and biogeography. Department of Ecology & Evolutionary Biology Colloquium. Tucson, Arizona. September, 2015.

Barron-Gafford GA (*Invited speaker*). Woody plant encroachment: Influence of landscape change on aboveground-belowground linkages, pulse dynamics, and ecosystem function. Soil, Water, & Environmental Science (SWES) Colloquium. Tucson, Arizona. November, 2013.

Barron-Gafford GA (*Invited speaker*). Exploring the ecology of semiarid land-cover and land-use change in anticipation of a changing climate. Department of Ecology & Evolutionary Biology Colloquium. Tucson, Arizona. March, 2013.

Invited conferences (limited to period in rank)

Barron-Gafford GA. Lags and Legacies in Ecosystem Processes: Challenges and Opportunities for Biogeographers and Ecologists. Frontiers in Experimental Ecosystem Science. Paris, France. July, 2015.

Scott RL, Huxman TE, **Barron-Gafford GA**, Jenerette GD, Young JM. The ecohydrological consequences of woody plant encroachment: How accessibility to deep soil water Resources affects ecosystem carbon and water exchange (*Invited*). American Geophysical Union's Annual Fall Meeting, Dec. 9-13, 2013, San Francisco, CA.

Submitted presentations (limited to period in rank)

Barron-Gafford GA, Allen N, Minor RL, Pavao-Zuckerman M. The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures. American Geophysical Union's Annual Fall Meeting, Dec. 12-16, 2016, San Francisco, CA.

Scott RL, **Barron-Gafford GA**, Biederman JA. Insights from a network of long-term measurements of biosphere-atmospheric exchanges of water vapor and carbon dioxide in southern Arizona. American Geophysical Union's Annual Fall Meeting, Dec. 12-16, 2016, San Francisco, CA.

Barron-Gafford GA, Minor RL, Hendryx, S, Lee E, Sutter L, Colella T, Murphy P, Sanchez-Cañete EP, Hamerlynck EP, Kumar P, Scott RL. Impacts of hydraulic redistribution on overstory-understory interactions in a semiarid savanna. American Geophysical Union's Annual Fall Meeting, Dec. 12-16, 2016, San Francisco, CA.

Sanchez-Cañete EP, Scott RL, Van Haren JLM, **Barron-Gafford GA**. The Necessity of Determining the Gas Transfer Coefficient In-situ to Obtain More Accurate Soil Carbon Dioxide Effluxes Through the Gradient Method. American Geophysical Union's Annual Fall Meeting, Dec. 12-16, 2016, San Francisco, CA.

Elshall AS, Ye M, Niu G-Y, **Barron-Gafford GA**. Numerical Demons in Monte Carlo Estimation of Bayesian Model Evidence with Application to Soil Respiration Models. American Geophysical Union's Annual Fall Meeting, Dec. 12-16, 2016, San Francisco, CA.

Murphy P, Minor RL, Sanchez-Cañete EP, Potts DL, **Barron-Gafford GA**. Seasonal and Topographic Variation in Net Primary Productivity and Water Use Efficiency in a Southwest Sky Island Forest. American Geophysical Union's Annual Fall Meeting, Dec. 12-16, 2016, San Francisco, CA.

Lee E, Kumar P, , **Barron-Gafford GA**, Scott RL. An Experimental and Modeling Synthesis to Determine Seasonality of Hydraulic Redistribution in Semi-arid Region with Multispecies Vegetation Interaction. American Geophysical Union's Annual Fall Meeting, Dec. 12-16, 2016, San Francisco, CA.

Sutter L, Sanchez-Cañete EP, **Barron-Gafford GA**. Aspect as a Driver of Soil Carbon and Water Fluxes in Desert Environments. American Geophysical Union's Annual Fall Meeting, Dec. 12-16, 2016, San Francisco, CA.

Hingley R, Juarez S, Dontsova K, Hunt E, Le Galliard J-F, Chollet S, Cros A, Llavata M, Massol F, Barré P, Gelabert A, Daval D, Troch PA, **Barron-Gafford GA**, Van Haren JLM, Ferrière R. Effects of Climate Change and Vegetation Type on Carbon and Nitrogen Accumulation during Incipient Soil Formation. American Geophysical Union's Annual Fall Meeting, Dec. 12-16, 2016, San Francisco, CA.

Sanchez-Cañete EP, **Barron-Gafford GA**, van Haren J, Scott RL. Accurate long-term soil respiration fluxes based on the gradient method in a semiarid ecosystem. University of Arizona Arid Lands Poster Session, April, 2016, Tucson, AZ.

Murphy P, Minor RL, Potts DL, **Barron-Gafford GA**. Studying Topographic Controls on Primary Productivity. University of Arizona Arid Lands Poster Session, April, 2016, Tucson, AZ.

Sutter L, Sanchez-Cañete EP, **Barron-Gafford GA**. An important aspect of soil carbon and water fluxes in desert environments. University of Arizona Arid Lands Poster Session, April, 2016, Tucson, AZ.

Hendryx S, Minor RL, Colella T, Murphy P, Lee E, Scott RL, Kumar P, **Barron-Gafford GA**. Impacts of hydraulic redistribution on plant and soil carbon and water fluxes in a dryland savanna. University of Arizona Arid Lands Poster Session, April, 2016, Tucson, AZ.

Colella T, Mann SN, Murphy P, Minor J, Pearl J, Barnes M, Gallery R, Swetnam T, **Barron-Gafford GA**. Critical Zone Science in the Anthropocene. Association of American Geographers Annual Meeting, April, 2016, San Francisco, CA.

Elshall AS Ye M, Niu G-Y, **Barron-Gafford GA**. Bayesian multimodel inference of soil microbial respiration models: Theory, application and future prospective. American Geophysical Union's Annual Fall Meeting, Dec. 14-18, 2014, San Francisco, CA.

Scott RL, Biederman J, **Barron-Gafford GA**, Hamerlynck EP. The Carbon Balance Pivot Point of Southwestern U.S. Semiarid Ecosystems: Insights From the 21st Century Drought. American Geophysical Union's Annual Fall Meeting, Dec. 14-18, 2014, San Francisco, CA.

Barron-Gafford GA, Minor RL, Heard MM, Sutter LF, Yang J, Potts DL. Complex terrain in the Critical Zone: How topography drives ecohydrological patterns of soil and plant carbon exchange in a semiarid mountainous system. American Geophysical Union's Annual Fall Meeting, Dec. 14-18, 2014, San Francisco, CA.

Lee E, Kumar P, **Barron-Gafford GA**, Scott RL, Hendryx S, Sanchez-Cañete EP. Determining the Role of Hydraulic Redistribution Regimes in the Critical Zone. American Geophysical Union's Annual Fall Meeting, Dec. 14-18, 2014, San Francisco, CA.

Sanchez-Cañete EP, **Barron-Gafford GA**, van Haren JLM, Scott RL. Improving soil CO2 efflux estimates from in-situ soil CO2 sensors with gas transport measurements. American Geophysical Union's Annual Fall Meeting, Dec. 14-18, 2014, San Francisco, CA.

Parra EA, McFarland E, Minor RL, Heard MM, **Barron-Gafford GA**. Effects of isoprene production on the photosynthetic performance of Poplars (*Populus* sp.) under thermal and moisture stress. American Geophysical Union's Annual Fall Meeting, Dec. 14-18, 2014, San Francisco, CA.

Barron-Gafford GA. Examining ecosystem function in space and time within the critical zone through the lenses of ecology and biogeography. Ecological Society of America's Annual Meeting, August, 2015, Baltimore, MD.

Barron-Gafford GA. Capturing heterogeneity in carbon fluxes in space and time across a semiarid montane forest. Association of American Geographers Annual Meeting, April, 2015, Chicago, IL.

Elshall AS, Ye M, **Barron-Gafford GA**. Quantification of Model Uncertainty in Modeling Mechanisms of Soil Microbial Respiration Pulses to Simulate Birch Effect. American Geophysical Union's Annual Fall Meeting, Dec. 15-19, 2014, San Francisco, CA.

Pfeiffer AW, Minor RL, Heard MM, **Barron-Gafford GA**. Photosynthetic response of Poplars (*Populus*) to climatic stressors: Investigating isoprene's role in increasing tolerance to temperature and atmospheric water stress in Arizona. American Geophysical Union's Annual Fall Meeting, Dec. 15-19, 2014, San Francisco, CA.

Ibsen P, Van Leeuwn WJD McCorkel J, **Barron-Gafford GA**, Moore DJ. Physiology and thermal imaging of Poplar hybrids with varying temperature tolerance. American Geophysical Union's Annual Fall Meeting, Dec. 15-19, 2014, San Francisco, CA.

Troch PA, **Barron-Gafford GA**, Dontsova K, Fang Y, Niu G-Y, Pangle LA, Tuller M, Van Haren JLM. Monitoring and modeling water, energy and carbon fluxes at the hillslope scale in the Landscape Evolution Observatory. American Geophysical Union's Annual Fall Meeting, Dec. 15-19, 2014, San Francisco, CA.

Scott RL, Biederman JA, **Barron-Gafford GA**. The coupling of ecosystem productivity and water availability in dryland regions. American Geophysical Union's Annual Fall Meeting, Dec. 15-19, 2014, San Francisco, CA.

Ruiz J, Van Haren JLM, Dontsova K, **Barron-Gafford GA**, Troch PA, Chorover J. Rapid CO_2 consumption during incipient weathering of a granular basaltic hillslope in the Landscape Evolution Observatory, Biosphere 2. American Geophysical Union's Annual Fall Meeting, Dec. 15-19, 2014, San Francisco, CA.

Pavao-Zuckerman M, Knerl A, **Barron-Gafford GA**. Ecohydrology frameworks for green infrastructure design and ecosystem service provision. American Geophysical Union's Annual Fall Meeting, Dec. 15-19, 2014, San Francisco, CA.

Pfeiffer AW, Minor RL, Heard MM, **Barron-Gafford GA**. Photosynthetic response of Poplars (*Populus*) to climatic stressors. American Geophysical Union's Annual Fall Meeting, Dec. 15-19, 2014, San Francisco, CA.

Barron-Gafford GA, Minor RL, Heard M, Barrows J, Allen N. Using Water Smart Design and an Ecosystem Services Approach to Fight Solar Heat Islanding and Enhance Renewable Energy Production. Association of Pacific Coast Geographers Annual Meeting, Sept. 24-27, 2014, Tucson, AZ.

Barron-Gafford GA, Minor RL, Heard M, Yang J, Wright C, Potts DL. Aspect as a source of heterogeneity in carbon & water fluxes in space and time. National Critical Zone Observatory All-Hands Meeting, Sept. 21-24, 2014, Yosemite, CA.

Chorover J, Pelletier J, Breshears DD, McIntosh J, Rasmussen C, Brooks P, **Barron-Gafford GA**, Gallery R, Ferré T, Litvak M, Meixner T, Niu G-Y, Papuga S, Rich V, Schaap M, Troch P. The Catalina-Jemez CZO: Transformative Behavior of Energy, Water and Carbon in the Critical Zone II. Interactions between Long and Short Term Processes that Control Delivery of Critical Zone Services. National Critical Zone Observatory All-Hands Meeting, Sept. 21-24, 2014, Yosemite, CA.

Barron-Gafford GA. Heat islanding around solar energy installations ~ Valid concern or unnecessary worry about renewable energy production. Association of American Geographers Annual Meeting, April 8-12, 2014, Tampa, FL.

Barron-Gafford GA, Minor RL, van Haren J, Dontsova K, Troch PA. Precipitation pulse dynamics of carbon sequestration and efflux in highly weatherable soils. American Geophysical Union's Annual Fall Meeting, Dec. 9-13, 2013, San Francisco, CA.

Niu G, Zhang X, **Barron-Gafford GA**, Pavao-Zuckerman M. Modeling the "Birch Effect" using a microbial enzyme based soil organic carbon decomposition and gas transport model. American Geophysical Union's Annual Fall Meeting, Dec. 9-13, 2013, San Francisco, CA.

Yang J, **Barron-Gafford GA**, Minor RL, Heard M. Examining the physical drivers of photosynthetic temperature sensitivity within a sub-alpine mixed conifer forest. American Geophysical Union's Annual Fall Meeting, Dec. 9-13, 2013, San Francisco, CA.

van Haren J, **Barron-Gafford GA**, Dontsova K. CO_2 sequestration through weathering of basalt tephra in the Landscape Evolution Observatory (LEO). American Geophysical Union's Annual Fall Meeting, Dec. 9-13, 2013, San Francisco, CA.

DeMets CM, Pavao-Zuckerman M, **Barron-Gafford GA**, Jenerette GD, Young JM. Strategies for cooler cities? Ecophysiological responses of semi-arid street trees to storm water harvesting. American Geophysical Union's Annual Fall Meeting, Dec. 9-13, 2013, San Francisco, CA.

Law DJ, Ravi S, **Barron-Gafford GA**, Breshears DD, and Huxman TE. Evapotranspiration Partitioning: Competition between abiotic and biotic components of the water budget. AGU Chapman Conference on Soil-mediated Drivers of Coupled Biogeochemical and Hydrological Processes Across Scales. Tucson, AZ. October, 2013.

Niu GY, Zhang X, and **Barron-Gafford GA**. A microbial enzyme based Soil Organic Carbon (SOC) decomposition model for use in climate models. AGU Chapman Conference on Soil-mediated Drivers of Coupled Biogeochemical and Hydrological Processes Across Scales. Tucson, AZ. October, 2013.

Yang J and **Barron-Gafford GA**. Examining the physical drivers of photosynthetic temperature sensitivity within a sub-alpine conifer forest. Undergraduate Research Opportunities Consortium, Tucson, AZ. August, 2013.

Community Presentations (limited to period in rank)

Barron-Gafford GA. "Mesquites in the Grasslands ~ Environmental and Human Drivers of Landscape Change". Living Gently on the Land Educational Series, Appleton-Whittell Research Ranch of the National Audubon Society, Elgin, AZ. November, 2014.

Barron-Gafford GA. "Experiential Ecological Learning as a Transformative Gateway in Elementary Learning". Arizona Center for STEM Teachers (ACST) Residential Teacher Training Workshop at Biosphere 2, Tucson, AZ. July, 2013.

SCIENTIFIC REPORTS

OPEN

The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures

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While photovoltaic (PV) renewable energy production has surged, concerns remain about whether or not PV power plants induce a "heat island" (PVHI) effect, much like the increase in ambient temperatures relative to wildlands generates an Urban Heat Island effect in cities. Transitions to PV plants alter the way that incoming energy is reflected back to the atmosphere or absorbed, stored, and reradiated because PV plants change the albedo, vegetation, and structure of the terrain. Prior work on the PVHI has been mostly theoretical or based upon simulated models. Furthermore, past empirical work has been limited in scope to a single biome. Because there are still large uncertainties surrounding the potential for a PHVI effect, we examined the PVHI empirically with experiments that spanned three biomes. We found temperatures over a PV plant were regularly 3–4 °C warmer than wildlands at night, which is in direct contrast to other studies based on models that suggested that PV systems should decrease ambient temperatures. Deducing the underlying cause and scale of the PVHI effect and identifying mitigation strategies are key in supporting decision-making regarding PV development, particularly in semiarid landscapes, which are among the most likely for large-scale PV installations.

Electricity production from large-scale photovoltaic (PV) installations has increased exponentially in recent decades[1–3]. This proliferation in renewable energy portfolios and PV powerplants demonstrate an increase in the acceptance and cost-effectiveness of this technology[4,5]. Corresponding with this upsurge in installation has been an increase in the assessment of the impacts of utility-scale PV[4,6–8], including those on the efficacy of PV to offset energy needs[9,10]. A growing concern that remains understudied is whether or not PV installations cause a "heat island" (PVHI) effect that warms surrounding areas, thereby potentially influencing wildlife habitat, ecosystem function in wildlands, and human health and even home values in residential areas[11]. As with the Urban Heat Island (UHI) effect, large PV power plants induce a landscape change that reduces albedo so that the modified landscape is darker and, therefore, less reflective. Lowering the terrestrial albedo from ~20% in natural deserts[12] to ~5% over PV panels[13] alters the energy balance of absorption, storage, and release of short- and longwave radiation[14,15]. However, several differences between the UHI and potential PVHI effects confound a simple comparison and produce competing hypotheses about whether or not large-scale PV installations will create a heat island effect. These include: (*i*) PV installations shade a portion of the ground and therefore could reduce heat absorption in surface soils[16], (*ii*) PV panels are thin and have little heat capacity per unit area but PV modules emit thermal radiation both up and down, and this is particularly significant during the day when PV modules are often 20 °C warmer than ambient temperatures, (*iii*) vegetation is usually removed from PV power plants, reducing the amount of cooling due to transpiration[14], (*iv*) electric power removes energy from PV power plants, and (*v*) PV panels reflect and absorb upwelling longwave radiation, and thus can prevent the soil from cooling as much as it might under a dark sky at night.

Public concerns over a PVHI effect have, in some cases, led to resistance to large-scale solar development. By some estimates, nearly half of recently proposed energy projects have been delayed or abandoned due to local opposition[11]. Yet, there is a remarkable lack of data as to whether or not the PVHI effect is real or simply an issue

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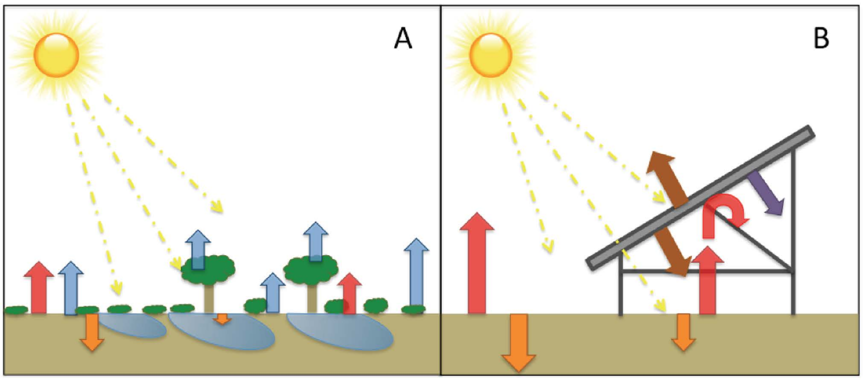

Figure 1. Illustration of midday energy exchange. Assuming equal rates of incoming energy from the sun, a transition from (**A**) a vegetated ecosystem to (**B**) a photovoltaic (PV) power plant installation will significantly alter the energy flux dynamics of the area. Within natural ecosystems, vegetation reduces heat capture and storage in soils (orange arrows), and infiltrated water and vegetation release heat-dissipating latent energy fluxes in the transition of water-to-water vapor to the atmosphere through evapotranspiration (blue arrows). These latent heat fluxes are dramatically reduced in typical PV installations, leading to greater sensible heat fluxes (red arrows). Energy re-radiation from PV panels (brown arrow) and energy transferred to electricity (purple arrow) are also shown.

associated with perceptions of environmental change caused by the installations that lead to "not in my backyard" (NIMBY) thinking. Some models have suggested that PV systems can actually cause a cooling effect on the local environment, depending on the efficiency and placement of the PV panels[17,18]. But these studies are limited in their applicability when evaluating large-scale PV installations because they consider changes in albedo and energy exchange within an urban environment (rather than a natural ecosystem) or in European locations that are not representative of semiarid energy dynamics where large-scale PV installations are concentrated[10,19]. Most previous research, then, is based on untested theory and numerical modeling. Therefore, the potential for a PHVI effect must be examined with empirical data obtained through rigorous experimental terms.

The significance of a PVHI effect depends on energy balance. Incoming solar energy typically is either reflected back to the atmosphere or absorbed, stored, and later re-radiated in the form of latent or sensible heat (Fig. 1)[20,21]. Within natural ecosystems, vegetation reduces heat gain and storage in soils by creating surface shading, though the degree of shading varies among plant types[22]. Energy absorbed by vegetation and surface soils can be released as latent heat in the transition of liquid water to water vapor to the atmosphere through evapotranspiration – the combined water loss from soils (evaporation) and vegetation (transpiration). This heat-dissipating latent energy exchange is dramatically reduced in a typical PV installation (Fig. 1 transition from A-to-B), potentially leading to greater heat absorption by soils in PV installations. This increased absorption, in turn, could increase soil temperatures and lead to greater sensible heat efflux from the soil in the form of radiation and convection. Additionally, PV panel surfaces absorb more solar insolation due to a decreased albedo[13,23,24]. PV panels will re-radiate most of this energy as longwave sensible heat and convert a lesser amount (~20%) of this energy into usable electricity. PV panels also allow some light energy to pass, which, again, in unvegetated soils will lead to greater heat absorption. This increased absorption could lead to greater sensible heat efflux from the soil that may be trapped under the PV panels. A PVHI effect would be the result of a detectable increase in sensible heat flux (atmospheric warming) resulting from an alteration in the balance of incoming and outgoing energy fluxes due to landscape transformation. Developing a full thermal model is challenging[17,18,25], and there are large uncertainties surrounding multiple terms including variations in albedo, cloud cover, seasonality in advection, and panel efficiency, which itself is dynamic and impacted by the local environment. These uncertainties are compounded by the lack of empirical data.

We addressed the paucity of direct quantification of a PVHI effect by simultaneously monitoring three sites that represent a natural desert ecosystem, the traditional built environment (parking lot surrounded by commercial buildings), and a PV power plant. We define a PVHI effect as the difference in ambient air temperature between the PV power plant and the desert landscape. Similarly, UHI is defined as the difference in temperature between the built environment and the desert. We reduced confounding effects of variability in local incoming energy, temperature, and precipitation by utilizing sites contained within a 1 km area.

At each site, we monitored air temperature continuously for over one year using aspirated temperature probes 2.5 m above the soil surface. Average annual temperature was 22.7 + 0.5 °C in the PV installation, while the nearby desert ecosystem was only 20.3 + 0.5 °C, indicating a PVHI effect. Temperature differences between areas varied significantly depending on time of day and month of the year (Fig. 2), but the PV installation was always greater than or equal in temperature to other sites. As is the case with the UHI effect in dryland regions, the PVHI effect delayed the cooling of ambient temperatures in the evening, yielding the most significant difference in overnight temperatures across all seasons. Annual average midnight temperatures were 19.3 + 0.6 °C in the PV installation, while the nearby desert ecosystem was only 15.8 + 0.6 °C. This PVHI effect was more significant in terms of actual degrees of warming (+3.5 °C) in warm months (Spring and Summer; Fig. 3, right).

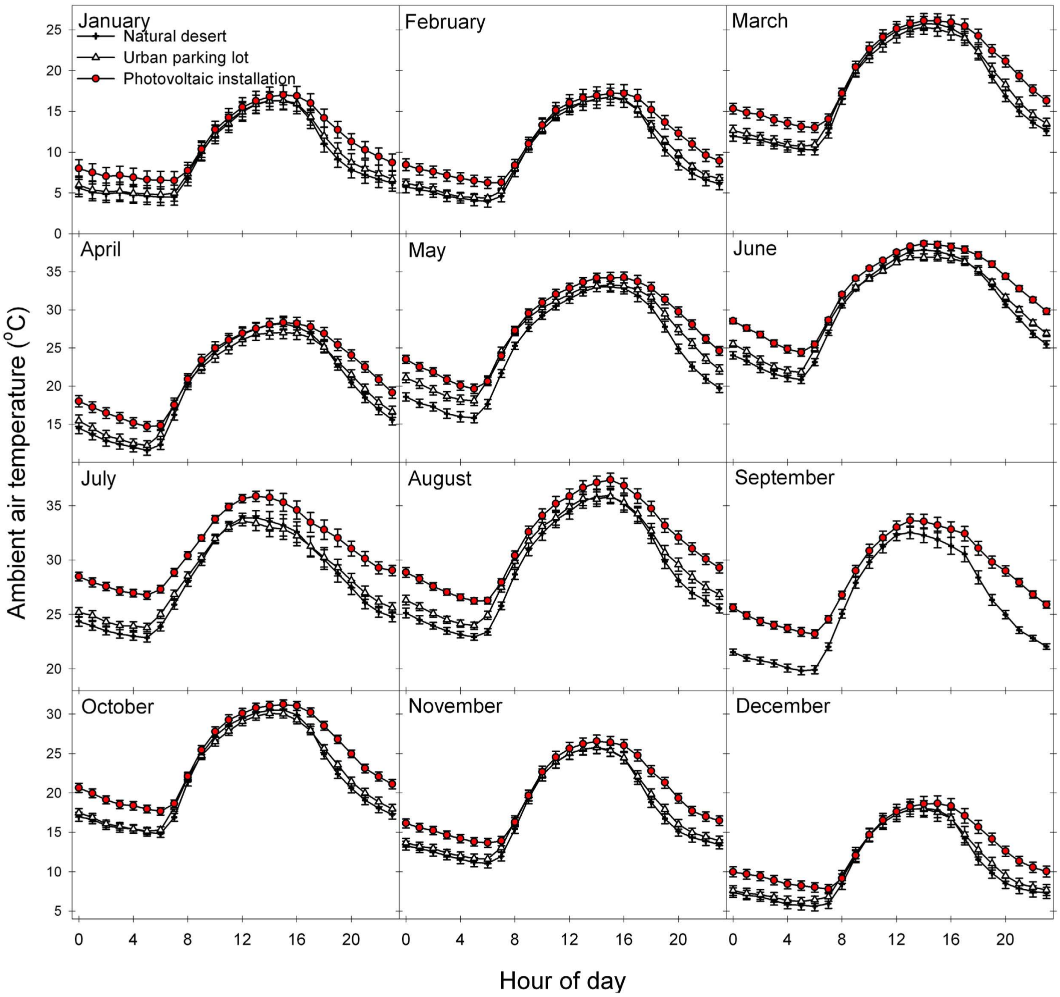

Figure 2. Average monthly ambient temperatures throughout a 24-hour period provide evidence of a photovoltaic heat island (PVHI) effect.

In both PVHI and UHI scenarios, the greater amount of exposed ground surfaces compared to natural systems absorbs a larger proportion of high-energy, shortwave solar radiation during the day. Combined with minimal rates of heat-dissipating transpiration from vegetation, a proportionally higher amount of stored energy is reradiated as longwave radiation during the night in the form of sensible heat (Fig. 1)[15]. Because PV installations introduce shading with a material that, itself, should not store much incoming radiation, one might hypothesize that the effect of a PVHI effect would be lesser than that of a UHI. Here, we found that the difference in evening ambient air temperature was consistently greater between the PV installation and the desert site than between the parking lot (UHI) and the desert site (Fig. 3). The PVHI effect caused ambient temperature to regularly approach or be in excess of 4 °C warmer than the natural desert in the evenings, essentially doubling the temperature increase due to UHI measured here. This more significant warming under the PVHI than the UHI may be due to heat trapping of re-radiated sensible heat flux under PV arrays at night. Daytime differences from the natural ecosystem were similar between the PV installation and urban parking lot areas, with the exception of the Spring and Summer months, when the PVHI effect was significantly greater than UHI in the day. During these warm seasons, average midnight temperatures were 25.5 + 0.5 °C in the PV installation and 23.2 + 0.5 °C in the parking lot, while the nearby desert ecosystem was only 21.4 + 0.5 °C.

The results presented here demonstrate that the PVHI effect is real and can significantly increase temperatures over PV power plant installations relative to nearby wildlands. More detailed measurements of the underlying causes of the PVHI effect, potential mitigation strategies, and the relative influence of PVHI in the context of the intrinsic carbon offsets from the use of this renewable energy are needed. Thus, we raise several new questions and highlight critical unknowns requiring future research.

What is the physical basis of land transformations that might cause a PVHI?

We hypothesize that the PVHI effect results from the effective transition in how energy moves in and out of a PV installation versus a natural ecosystem. However, measuring the individual components of an energy flux model remains a necessary task. These measurements are difficult and expensive but, nevertheless, are indispensable in identifying the relative influence of multiple potential drivers of the PVHI effect found here. Environmental

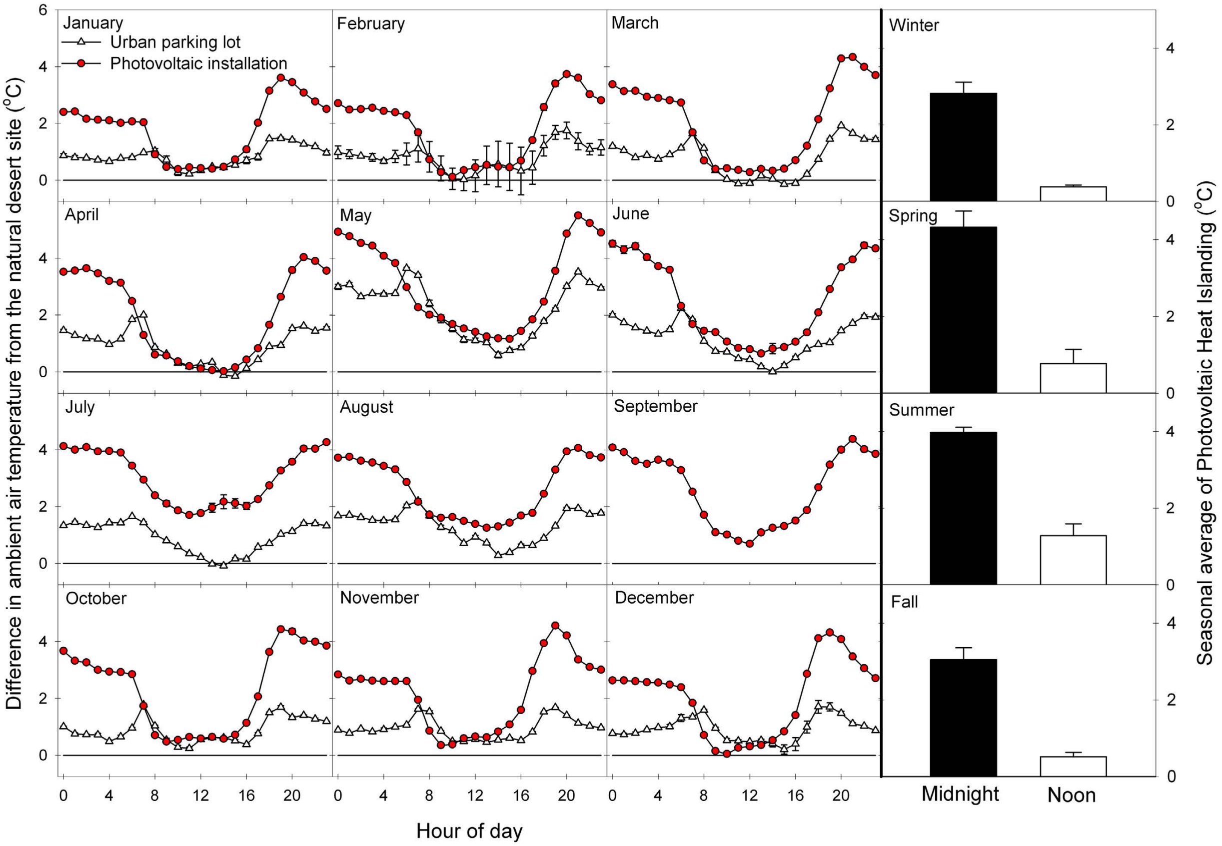

Figure 3. (Left) Average monthly levels of Photovoltaic Heat Islanding (ambient temperature difference between PV installation and desert) and Urban Heat Islanding (ambient temperature difference between the urban parking lot and the desert). (Right) Average night and day temperatures for four seasonal periods, illustrating a significant PVHI effect across all seasons, with the greatest influence on ambient temperatures at night.

conditions that determine patterns of ecosystem carbon, energy, and water dynamics are driven by the means through which incoming energy is reflected or absorbed. Because we lack fundamental knowledge of the changes in surface energy fluxes and microclimates of ecosystems undergoing this land use change, we have little ability to predict the implications in terms of carbon or water cycling[4,8].

What are the physical implications of a PVHI, and how do they vary by region?

The size of an UHI is determined by properties of the city, including total population[26–28], spatial extent, and the geographic location of that city[29–31]. We should, similarly, consider the spatial scale and geographic position of a PV installation when considering the presence and importance of the PVHI effect. Remote sensing could be coupled with ground-based measurements to determine the lateral and vertical extent of the PVHI effect. We could then determine if the size of the PVHI effect scales with some measure of the power plant (for example, panel density or spatial footprint) and whether or not a PVHI effect reaches surrounding areas like wildlands and neighborhoods. Given that different regions around the globe each have distinct background levels of vegetative ground cover and thermodynamic patterns of latent and sensible heat exchange, it is possible that a transition from a natural wildland to a typical PV power plant will have different outcomes than demonstrated here. The paucity in data on the physical effects of this important and growing land use and land cover change warrants more studies from representative ecosystems.

What are the human implications of a PVHI, and how might we mitigate these effects?

With the growing popularity of renewable energy production, the boundaries between residential areas and larger-scale PV installations are decreasing. In fact, closer proximity with residential areas is leading to increased calls for zoning and city planning codes for larger PV installations[32,33], and PVHI-based concerns over potential reductions in real estate value or health issues tied to Human Thermal Comfort (HTC)[34]. Mitigation of a PVHI effect through targeted revegetation could have synergistic effects in easing ecosystem degradation associated with development of a utility scale PV site and increasing the collective ecosystem services associated with an area[4]. But what are the best mitigation measures? What tradeoffs exist in terms of various means of revegetating degraded PV installations? Can other albedo modifications be used to moderate the severity of the PVHI?

Figure 4. Experimental sites. Monitoring a (1) natural semiarid desert ecosystem, (2) solar (PV) photovoltaic installation, and (3) an "urban" parking lot – the typical source of urban heat islanding – within a 1 km^2 area enabled relative control for the incoming solar energy, allowing us to quantify variation in the localized temperature of these three environments over a year-long time period. The Google Earth image shows the University of Arizona's Science and Technology Park's Solar Zone.

To fully contextualize these findings in terms of global warming, one needs to consider the relative significance of the (globally averaged) decrease in albedo due to PV power plants and their associated warming from the PVHI against the carbon dioxide emission reductions associated with PV power plants. The data presented here represents the first experimental and empirical examination of the presence of a heat island effect associated with PV power plants. An integrated approach to the physical and social dimensions of the PVHI is key in supporting decision-making regarding PV development.

Methods

Site Description. We simultaneously monitored a suite of sites that represent the traditional built urban environment (a parking lot) and the transformation from a natural system (undeveloped desert) to a 1 MW PV power plant (Fig. 4; Map data: Google). To minimize confounding effects of variability in local incoming energy, temperature, and precipitation, we identified sites within a 1 km area. All sites were within the boundaries of the University of Arizona Science and Technology Park Solar Zone (32.092150°N, 110.808764°W; elevation: 888 m ASL). Within a 200 m diameter of the semiarid desert site's environmental monitoring station, the area is composed of a sparse mix of semiarid grasses (*Sporobolus wrightii, Eragrostis lehmanniana*, and *Muhlenbergia porteri*), cacti (*Opuntia* spp. and *Ferocactus* spp.), and occasional woody shrubs including creosote bush (*Larrea tridentata*), whitethorn acacia (*Acacia constricta*), and velvet mesquite (*Prosopis velutina*). The remaining area is bare soil. These species commonly co-occur on low elevation desert bajadas, creosote bush flats, and semiarid grasslands. The photovoltaic installation was put in place in early 2011, three full years prior when we initiated monitoring at the site. We maintained the measurement installations for one full year to capture seasonal variation due to sun angle and extremes associated with hot and cold periods. Panels rest on a single-axis tracker system that pivot east-to-west throughout the day. A parking lot with associated building served as our "urban" site and is of comparable spatial scale as our PV site.

Monitoring Equipment & Variables Monitored. Ambient air temperature (°C) was measured with a shaded, aspirated temperature probe 2.5 m above the soil surface (Vaisala HMP60, Vaisala, Helsinki, Finland in the desert and Microdaq U23, Onset, Bourne, MA in the parking lot). Temperature probes were cross-validated for precision (closeness of temperature readings across all probes) at the onset of the experiment. Measurements of temperature were recorded at 30-minute intervals throughout a 24-hour day. Data were recorded on a data-logger (CR1000, Campbell Scientific, Logan, Utah or Microstation, Onset, Bourne, MA). Data from this instrument array is shown for a yearlong period from April 2014 through March 2015. Data from the parking lot was lost for September 2014 because of power supply issues with the datalogger.

Statistical analysis. Monthly averages of hourly (on-the-hour) data were used to compare across the natural semiarid desert, urban, and PV sites. A Photovoltaic Heat Island (PVHI) effect was calculated as differences in these hourly averages between the PV site and the natural desert site, and estimates of Urban Heat Island (UHI) effect was calculated as differences in hourly averages between the urban parking lot site and the natural desert site. We used midnight and noon values to examine maximum and minimum, respectively, differences in temperatures among the three measurement sites and to test for significance of heat islanding at these times. Comparisons among the sites were made using Tukey's honestly significant difference (HSD) test[35]. Standard errors to calculate HSD were made using pooled midnight and noon values across seasonal periods of winter (January-March), spring (April-June), summer (July-September), and fall (October-December). Seasonal analyses allowed us to identify variation throughout a yearlong period and relate patterns of PVHI or UHI effects with seasons of high or low average temperature to examine correlations between background environmental parameters and localized heat islanding.

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Author Contributions

G.A.B.-G., R.L.M. and N.A.A. established research sites and installed monitoring equipment. G.A.B.-G. directed research and R.L.M. conducted most site maintenance. G.A.B.-G., N.A.A., A.D.C. and M.A.P.-Z. led efforts to secure funding for the research. All authors discussed the results and contributed to the manuscript.

Additional Information

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