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TITLE:

Construction of a Compact Low-Cost Radiation Shield for Air-Temperature Sensors in Ecological Field Studies

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KEYWORDS:

Air temperature, climate change, data logger, thermochron, radiation shield, field studies

SUMMARY:

With the advent of small, low-cost environmental sensors, it is now possible to deploy high-density networks of sensors to measure hyper localized temperature variation. Here, we provide a detailed methodology for constructing a compact version of a previously described custom-fabricated radiation shield for use with inexpensive thermochrons.

ABSTRACT:

Low cost temperature sensors are increasingly used by ecologists to assess climatic variation and change on ecologically relevant scales. Although cost-effective, if not deployed with proper solar radiation shielding, the observations recorded from these sensors will be biased and inaccurate. Manufactured radiation shields are effective at minimizing this bias, but are expensive compared to the cost of these sensors. Here, we provide a detailed methodology for constructing a compact version of a previously described custom fabricated radiation shield, which is more accurate than other published shielding methods that attempt to minimize shield size or construction costs. The method requires very little material: corrugated plastic sheets, aluminum foil duct tape, and cable ties. One 15 cm and two 10 cm squares of corrugated plastic are used for each shield. After cutting, scoring, taping and stapling of the sheets, the 10 cm squares form the bottom two layers of the solar radiation shield, while the 15 cm square forms the top layer. The three sheets are held together with cable ties. This compact solar radiation shield can be suspended, or placed against any flat surface. Care must be taken to ensure that the shield is completely parallel to the ground to prevent direct solar radiation from reaching the sensor, possibly causing increased warm biases in sun-exposed sites in the morning and afternoon relative to the original, larger

design. Even so, differences in recorded temperatures between the smaller, compact shield design and the original design were small (mean daytime bias = 0.06 °C). Construction costs are less than half of the original shield design, and the new design results in a less conspicuous instrument that may be advantageous in many field ecology settings.

INTRODUCTION:

In light of anthropogenic global warming, there has been a growing interest in recording air temperature in a variety of settings to understand and predict ecological responses to climate change[1–3]. With the advent of small, low-cost environmental data recorders (also referred to as data loggers, thermochrons, or hygrochrons), it is now possible to deploy high-density networks of sensors to measure hyper localized temperature variation, increasing ecologists' ability to more directly observe the ambient environmental conditions experienced by organisms and ecosystems under study. Compared to existing, well-calibrated and rigorously tested—but sparsely distributed—permanent weather stations, such networks present opportunities to assess climatic variation on ecologically relevant scales but may reduce accuracy or comparability among studies if inconsistently or inappropriately deployed.

Near-surface air temperature sensors typically require some type of solar radiation shielding to prevent direct heating of the sensor element, which would result in erroneously warm measurements. Common ways to limit sensor bias include: 1) using existing environmental features such as trees for shading[4], 2) bias correction and sensor calibration[5] that derived corrections based on the thermal properties of sensors, and 3) the use of manufactured or custom fabricated shields[6, 7]. Many researchers choose to use custom fabricated shields because of the low-cost and easy deployment, and necessity in situations where environmental conditions do not provide natural shading. However, a review of the ecological literature indicated that the design of custom fabricated shields varies widely among studies, and individual designs are rarely tested for accuracy. Untested shields can be susceptible to poor choice of materials and design that cause additional heating of the air molecules immediately surrounding the sensor, direct absorption of solar radiation by the sensor itself, or both—leading to average biases of up to 3 °C[7]. On the other hand, simple and cost-effective designs[6, 7] are quite effective at shielding sensors (biases of 1 °C or less) and are comparable to commercially manufactured radiation shields.

Here, we provide a detailed methodology for constructing a previously evaluated custom fabricated radiation shield[7] for use with inexpensive thermochron temperature sensors. The shield design is a modification of one previously described and tested in an open Ponderosa Pine forest setting[6]. In recent tests of several custom-fabricated shield designs, this montane-tested shield resulted in the lowest biases when paired with small thermochrons[7], but we found it cumbersome and too conspicuous to deploy in the field. The design protocol proposed here reduces the dimensions of the radiation shield by 50%. Such a reduction in size has several benefits: 1) it is less conspicuous and therefore less susceptible to tampering, 2) it can be more feasibly used in a wider variety of ecological settings where space is limited (*e.g.,* on smaller urban street trees), 3) it is more accurate than other published shielding methods that attempt to minimize shield size or construction costs[7], and 4) it is less expensive than the original, larger design due to the reduced quantity of construction materials required. After describing the construction methods, we explore the effect of the size reduction on sensor accuracy relative to the original shield design using results from a field trial conducted under high downward solar radiation conditions.

PROTOCOL:

1. Construction of the Radiation Shield

1.1. Using a utility knife, cut the corrugated plastic sheets into squares (**Figure 1A**). One 15 cm square and two 10 cm squares will be needed for each shield.

1.2. Cuts for the top layer of the small radiation shield (**Figure 1B**; left image):

1.2.1. On the 15 cm square, measure 4 cm from one edge and draw a line with a pencil. Use a straightedge as a guide to score along the line. (Herein, “scoring” means using a knife to make a cut that goes through only one layer of corrugated plastic sheet, rather than the entire sheet.) Henceforth this edge of the square will be referred to as the “top” (**Figure 1B**; left image).

1.2.2. Measure 3.8 cm from the edges that are perpendicular to the 4 cm line. Use a straightedge as a guide to score from the bottom up to the 4 cm line (**Figure 1B**; left image).

1.2.3. Draw a line from both corners above the 4 cm line to the junction of the 4 cm and 3.8 cm lines. Cut along this line (**Figure 1B**; left image).

1.3. Cuts for the middle and bottom layers of the small radiation shield (**Figure 1B**; middle and right images):

1.3.1. Using a straightedge, draw a 6 cm square in the middle of each 10 cm square (**Figure 1B**; middle and right images).

1.3.2. Score all around the 6 cm square, and from each corner of the 6 cm square to the outer corners of the 10 cm square (**Figure 1B**; middle and right images).

1.4. Use aluminum foil tape to completely cover the scored side of the 15 cm square and one of the 10 cm squares, and the un-scored side of the other 10 cm square.

1.5. Using a 1/4” drill bit, drill holes as shown in **Figure 1C**, in each of the shield layers.

1.6. Attach a temperature sensor to the underside of the 10 cm square, which is taped on the scored side and has the two holes drilled into the middle, by running the cable tie through the eyelet of the sensor housing (or its mounting device) and through the holes in the 10 cm square (**Figure 1D**).

1.7. Folding the sheets.

1.7.1. Fold the 15 cm sheet along the scored lines. Pressure may be needed in case the tape makes the sides tight and difficult to fold.

1.7.2. Tuck the small triangular flaps on the inside of the larger back flap. When this is done correctly, only taped sides are visible from above. The cut edge of the back flap should be flush with the folded sides.

1.7.3. Use another layer of aluminum tape to secure the folded sides to the back flap. The back flaps could also be stapled together, with a heavy-duty stapler, for added strength.

1.7.4. Take the 10 cm sheets and pinch the sides together along the diagonal scored line. Using a heavy-duty stapler, staple the pinched sides together (**Figure 1E**). The end product will have a square-bowl shape.

1.8. Tying the sheets together with 20 cm cable ties.

1.8.1. Beginning with the 10 cm sheet taped on the unscored side, with three holes, place the taped side down. Thread a cable tie through the left back hole of both 10 cm sheets. Leave 2 cm vertical spacing between the two sheets to ensure air flow around the temperature sensor. Repeat this step for the back right hole (**Figure 1E**; middle and right images).

1.8.2. Take the 15 cm sheet and pass a cable tie through the two side-by-side holes, in the back left (**Figure 1E**; left image). Attach this tie to the 10 cm sheets, also leaving 2 cm of space between the 15 cm sheet and the top of the upper 10 cm sheet. Repeat this step for the two side-by-side holes in the back right (**Figure 1E**; left image).

1.8.3. Finally, pass one cable tie through all three holes in the front of the sheets (shown by the arrow; **Figure 1E**). Tighten the cable tie, ensuring the space is even between all three sheets (**Figure 1F**).

1.9. Drill additional holes into the back end of the final assembled product to facilitate mounting, where needed. Wherever the shield is mounted, ensure that the three sheets lay parallel to the ground.

REPRESENTATIVE RESULTS:

Representative results using thermochrons outfitted with the new, smaller shield design, the original larger shield design, and the thermochrons with no radiation shield are shown in **Figures 2 and 3**. These data were recorded at a fully exposed rural location near Raleigh, NC (35.728°N, 78.680°W), and were affixed to a well-calibrated permanent weather station outfitted with a VAISALA platinum resistance air temperature sensor (HMP45C) mounted inside a wind-aspirated multiplate radiation shield[7]. In **Figure 2a**, boxplots are shown of the differences in recorded temperatures between four sensors using the small radiation shield, and the permanent weather station. Positive biases are found across all four tested sensors (mean bias = 0.56 °C), but are similar to those found using the original, larger shield design (**Figure 2b**; mean = 0.56 °C), and are much less than the biases of the unshielded sensors (**Figure 2c**; mean = 1.23 °C). The small shields result in the sensors recording some outlier warm temperatures relative to the original shield design (**Figure 2d**), although the overall differences are small (mean bias = 0.16 °C).

[Place **Figure 2** here]

In **Figure 3**, the diurnal nature of the biases is apparent in the time series. As in **Figure 2**, temperature differences are shown between the themochrons outfitted with the small and large radiation shields and the calibrated permanent weather station (**Figures 3a, 3b**). Warm biases are strongest during periods of peak solar radiation, but in both cases are much less than the biases of the unshielded sensors (**Figure 3c**). The mean temperature difference between all combinations of sensors outfitted with the small radiation shield compared to the original design (solid black line, **Figure 3d**) is 0.002 °C and 0.06 °C for daytime hours (0700-2000 h LST). Interestingly, the largest differences with respect to the hourly estimated standard deviation (dashed lines, **Figure 3d**), are at 1400 and 0800 LST. The large differences in the afternoon during the heat of the day are to be expected considering the smaller size of the radiation shield. However, the source of the additional large differences in the morning soon after sunrise is not clear and could be due to sub-optimal shield-sensor angles (*i.e.,* the thermochrons were not parallel to the ground) which would expose the thermochrons to additional heating.

[Place **Figure 3** here]

FIGURE AND TABLE LEGENDS:

Figure 1: Step-by-step instructions to construct a small radiation shield. (A) 15 cm and 10 cm squares are cut out of the large sheet of corrugated plastic. **(B)** The 15 cm sheets are then cut and scored, and the 10 cm sheets are scored to allow bending of the shield to the correct shape. **(C)** Holes are drilled on each sheet. **(D)** The sensor is tied to one of the 10 cm sheets. **(E)** The shield is assembled using several cable ties. **(F) T**he final shield is ready for installation.

Figure 2: Example boxplot results from a field experiment comparing temperature differences using different radiation shield treatments. Distribution of temperature differences between the thermochrons with **(A)** the small radiation shield design **(B)** the original large radiation shield, and **(C)** no shields and the calibrated, permanent weather station recorded in August 2015 at a sunny, exposed location in Raleigh, NC. **(D)** shows the distribution of recorded temperature differences between the four thermochrons outfitted with the small radiation shield and the large shield-outfitted thermochron that had the smallest bias (*i.e.,* Sensor 3 in **B**). Differences above 7 °C are excluded from the plot in **C** (values extend up to 10.6 ^{o}C).

Figure 3: Example time series results from a field experiment comparing temperature differences using different radiation shield treatments. Time series of temperature differences between the thermochrons with **(A)** the small radiation shield design, **(B)** the original large radiation shield, and **(C)** no shields and the calibrated, permanent weather station recorded in August 2015 at a sunny, exposed location in Raleigh, NC. The mean (solid black line) and two standard deviations (estimated for each hour; dashed lines) of the temperature differences between all combinations of shielded thermochrons (n = 4 small shields, n = 5 large shields) are

shown in **(D)**. Note scale change in the ordinate axis in **D** compared to **A** through **C**.

DISCUSSION:

The accuracy and repeatability of air temperature measurements depend on the use of an appropriate solar shield that protects the sensor from direct and reflected solar radiation. Here we describe the construction of such a shield that is more compact in size, less expensive, or faster to construct than similar, previously described devices[6], without sacrificing accuracy. 94% of the recorded temperatures for the thermochrons outfitted with the smaller shield were within 1.0 °C of the best performing thermochron outfitted with the original larger, radiation shield, and 71% of the observations were within 0.25 °C.

The design of this shield, like that of its larger precursor, is a variation on the widely used, passively aspirated Gill shield. Ideal properties of a passive shield include shading the sensor from solar radiation from all angles; allowing air to flow freely through the shield; and absorbing minimal radiation into the shield material[8]. Design is often a compromise between shading and airflow. Designs that maximize passive airflow prevent complete shading and risk direct heating of the sensor; those with complete shielding hinder airflow and risk heating within-shield air relative to the air at large.

As a passively ventilated shield, the small radiation shield is inaccurate at low wind speeds (less than 1-2 ms^{-1}), when lack of ventilation promotes radiative heating of the air within the shield relative to the air at large[7]. This is a universal source of bias in passively ventilated shields, including costly manufactured ones. This bias is overcome in mechanically aspirated shields, but their electric requirements are generally prohibitive in replicated field studies. Biases in passive shields can be addressed through model-based corrections[5,9,10]. Such corrections, however, require simultaneous measurement of wind speed and shortwave radiation, which may also be impractical in the kinds of studies that rely on custom-fabricated shields. A final option is simply to accurately report shielding methods and acknowledge bias so that any reader attempting to compare temperatures reported across different studies can make informed interpretations.

Compared to a manufactured Gill shield, the small radiation shield described here has a daytime bias of 0.81 °C compared to a bias of 0.75 °C for thermochrons outfitted with the original shield design[7]. In direct comparison, its performance was nearly indistinguishable from that of the previously described large radiation shield, but represents significant savings in materials. We built the small radiation shields for $1.36 US (2015 dollars) each in materials, including corrugated plastic, aluminum tape, and cable ties. In contrast, the original large radiation shield, because of the larger quantities of plastic and aluminum, would cost $3 US (the authors' 2013 estimate) to $4.75 US (our estimate)[6]. Cost estimates do not include the logger itself, its manufacturer-specified mounting bracket, or any structure upon which the shield might be mounted in the field.

Additional examples exist of custom-fabricated shields that have been well tested against manufactured shields[11]. In an 11-day test of a different handmade Gill shield[11], two-thirds of all air temperature measurements in this shield were within 1.0 °C of those measured in a manufactured Gill shield. In our small radiation shield, accuracy of iButtons was similar, with 83% of measurements within 1 °C of reference weather-station instruments at the sun-exposed site. The handmade Gill shield took its creators 45 minutes to construct, and would cost $2 US (our estimate) to $4 US (the authors' 2007 estimate) in materials. Again, the small radiation shield provides savings in materials and construction time.

Although we did not test for effects of variations in small radiation shield parameters, theory predicts that changes in materials, plate spacing, and fold angles would alter the ability of the shield to block radiation and allow airflow, and would yield results different from those reported here. Maximal shading of the sensor from both direct and reflected solar radiation requires the use of all three plates, folded as indicated, to block not only radiation from above, but also low-angle radiation from the sides and reflected radiation from beneath. Protection from reflected radiation is particularly important when sensors are deployed over snow, sand, pavement, and other non-vegetated surfaces[7, 12]. Air flow within the shield is dictated by plate shape and spacing[8]; in the current design, any change to plate folding and spacing would influence air flow. Finally, use of a white material with aluminum-coated outer surfaces minimizes radiative heating of the shield itself; complete coverage of the top and bottom shield surfaces with reflective aluminum tape is essential to replicate this property. Shields need to be kept clean, or accumulation of dirt, bird droppings, and mold will alter their reflectance[8]. Finally, we also caution that, for comparability among multiple sensors in an array, they need to be deployed with the shield plates parallel to the ground and at a consistent elevation above ground—not always straightforward when the surface vegetation itself varies in height[10].

Further improvements upon this shield design are undoubtedly possible. The use of clear coatings over an aluminum surface to improve thermal properties of radiation shields has long been known[13]. In tests with the large radiation shield however, other authors detected no benefit of additional coatings (mylar, white paint) over the aluminum tape alone[6]. The addition of rigid foam spacers between the plates, previously described in a custom-fabricated Gill shield[11], is another potential modification that could standardize the design and prevent shifting of the plates in strong wind. A limitation of this shield is that its construction requires mounting on a horizontal bar or branch; it would be difficult, for example, to suspend this shield assembly from above while maintaining its correct orientation. Finally, for bulkier data loggers, the addition of another small interior plate with a cutout in the center could be desirable to create more space for the logger without altering plate spacing. Any of these changes would incur additional costs and construction time, and would require testing against the original standard or a calibrated weather station to assess performance.

We also stress that the current design was evaluated under a certain range of environmental conditions and any extrapolations of radiation shield performance outside of those conditions should be made with caution. In particular, this shield's design, in both this study and in the original paper where the larger version was introduced[6] were tested at high summer solar angles typically found at latitudes equatorward of ~45 degrees latitude. In areas with low seasonal solar angles, long daylengths, or both (such as experienced at high latitudes or in different seasons), different approaches to shield construction may be more appropriate.

With the advent of small, inexpensive temperature loggers, biologists have increasingly sought to assess air temperature at the fine spatial scales relevant to individual organisms and local ecological processes. Understanding microclimatic variation in air temperature can provide insights into local biological responses to recent and projected climate change. While additional thermal variables—such as soil, surface, or body temperature, each with its own accuracy considerations—may also be measured, air temperature is a common currency across studies of historical, current, and projected climates. Consistent use of radiation shields with well-documented properties will ensure that results of different studies can be meaningfully compared.

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DISCLOSURES:
The authors have nothing to disclose.

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Figure 1

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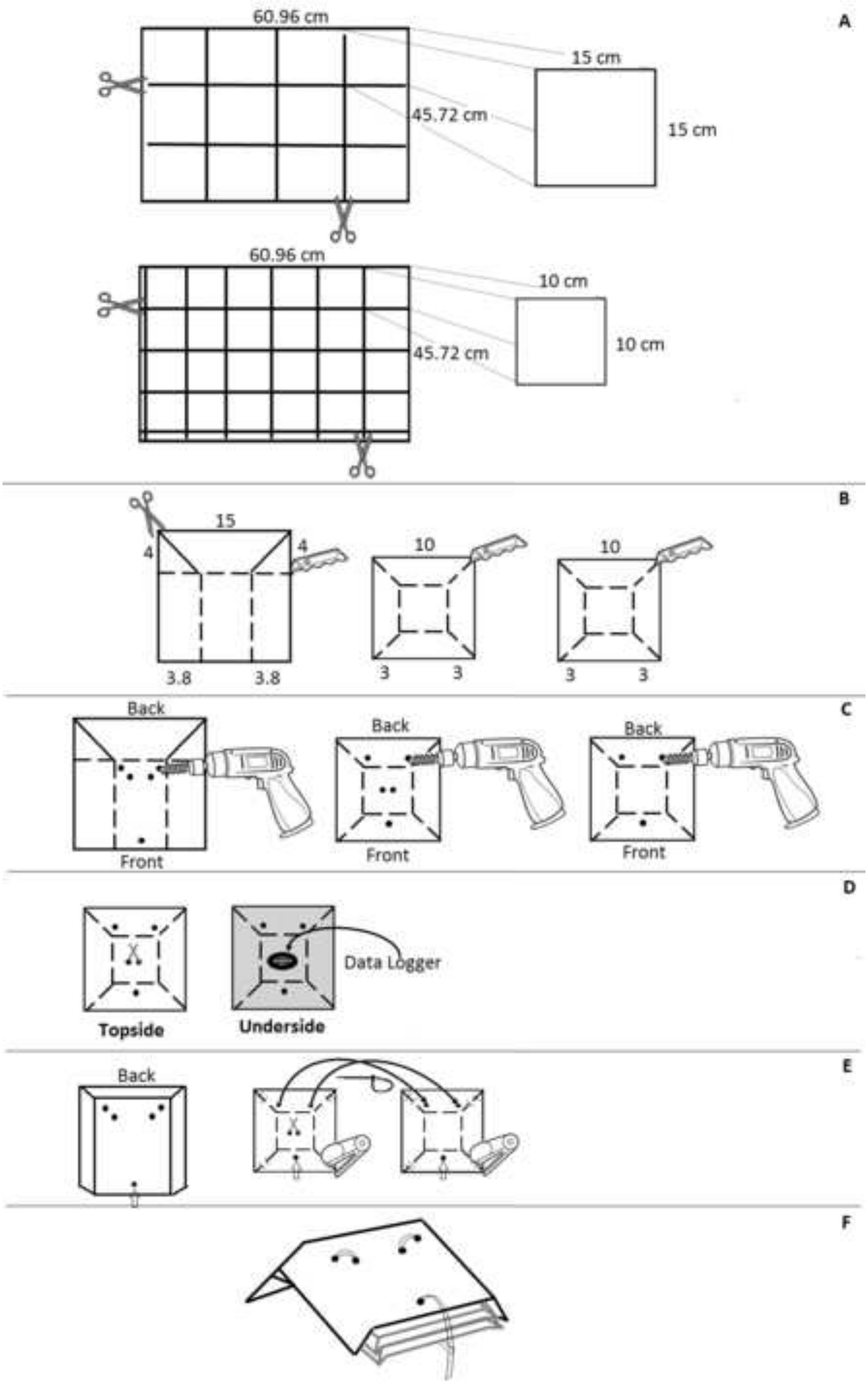

Figure 2

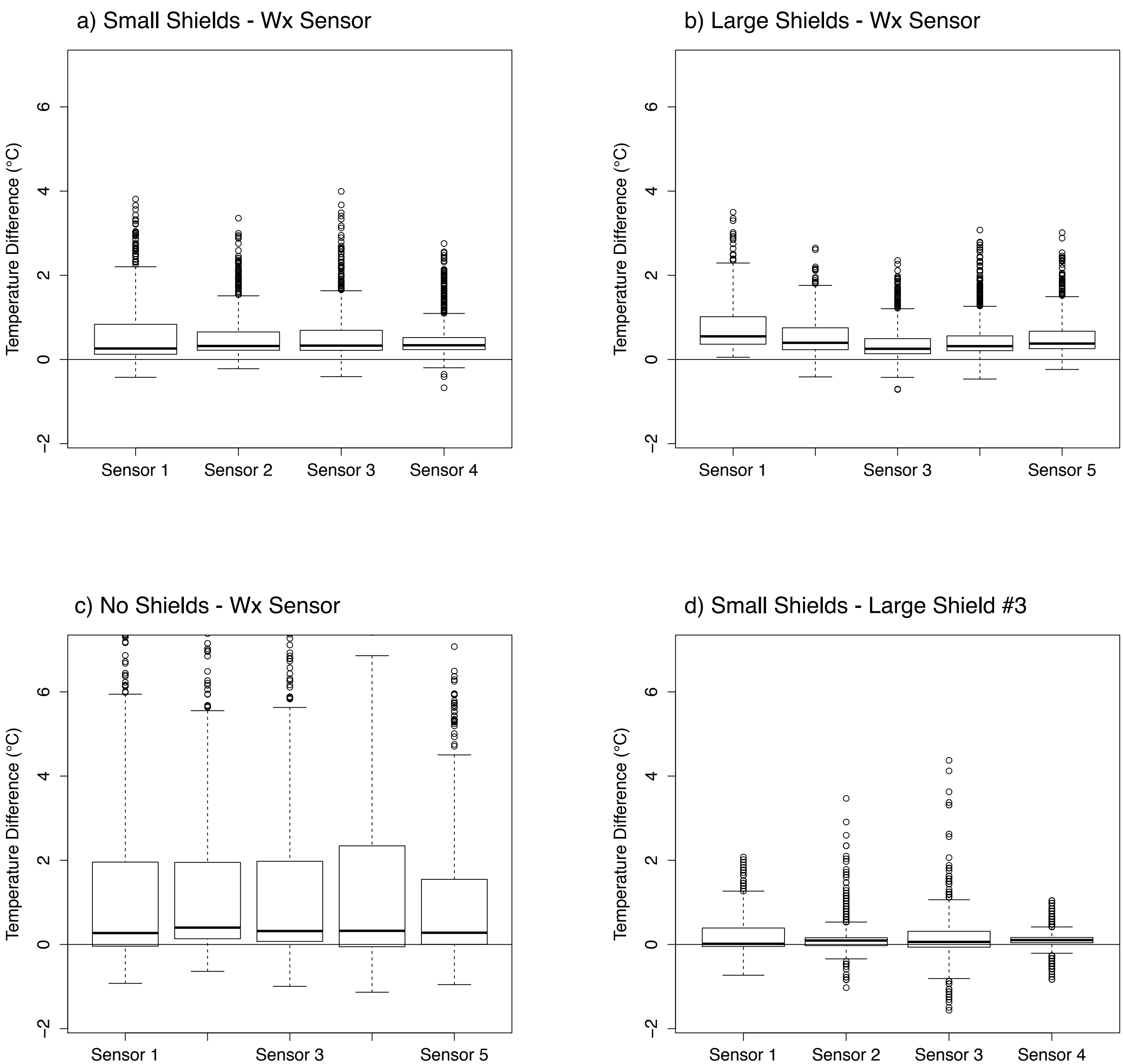
a) Small Shields - Wx Sensor
b) Large Shields - Wx Sensor
c) No Shields - Wx Sensor
d) Small Shields - Large Shield #3
Temperature Difference (°C)
−2
0
2
4
6
Sensor 1
Sensor 2
Sensor 3
Sensor 4
Sensor 5

Figure 3

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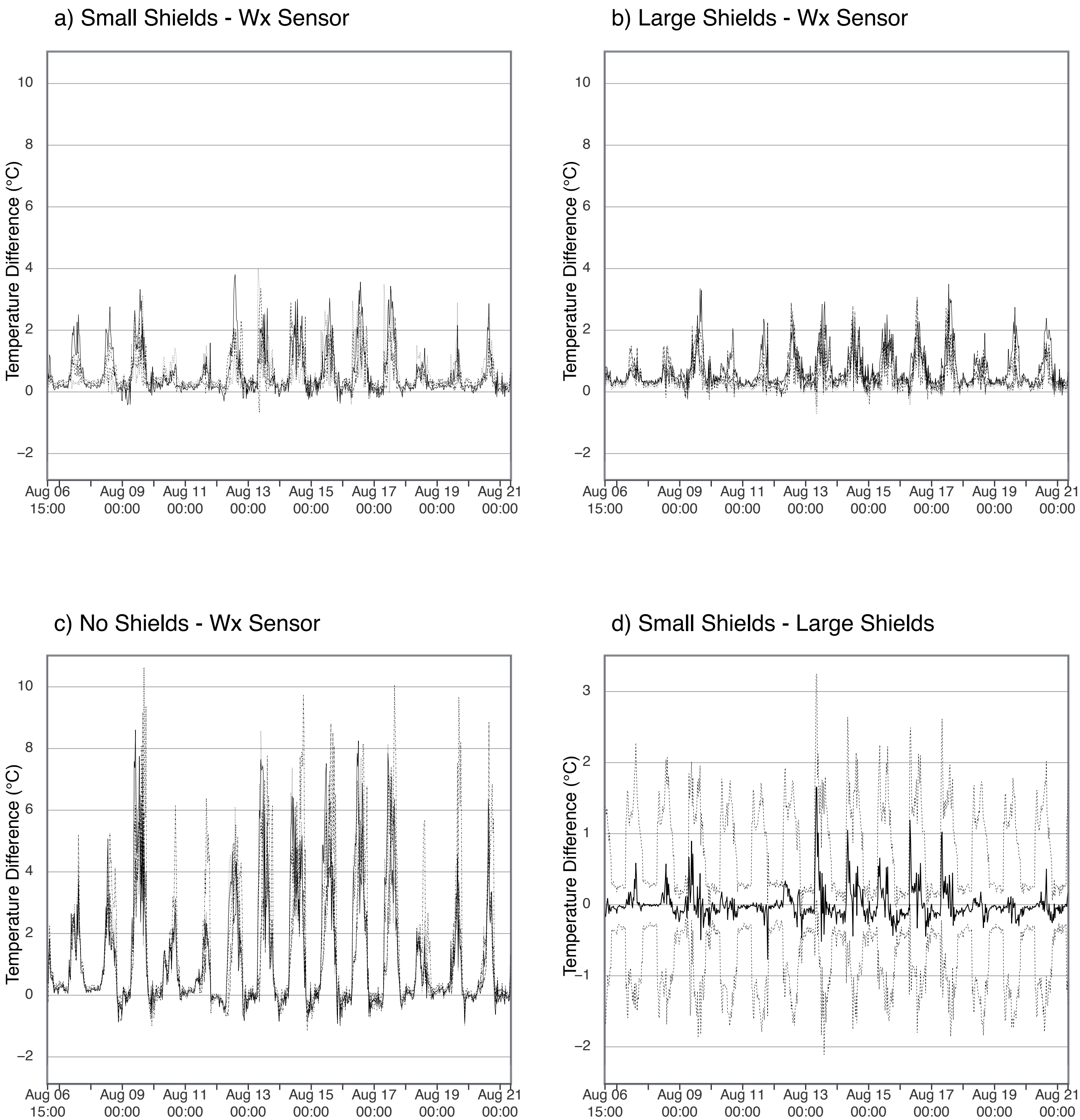

Name of Material/ Equipment	Company	Catalog Number	Comments/Descriptio
Multipurpose Aluminum Foil Tape	Nashua	1087671	48 mm width
8" cable ties	DTOL	GEN86371	NA
Corrugated plastic sheet	Highway Traffic supply	hts18X24COROW	White sheet 18"L x 24"W, 5-pack
Standard utility knife	NA	NA	NA
Standard Scissors	NA	NA	NA
Heavy duty stapler	Swingline	552277715	NA

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Article Title: construction of a low-cost radiation shield for air temperature sensors in ecological field studies

Signature: [signature] Date: 6/5/18

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Dear Dr. Steindel,

Please accept this revised version of our manuscript titled "Construction of a compact low-cost radiation shield for air-temperature sensors in ecological field studies" to be considered for publication in *JoVE*. We have addressed all the comments made yourself and the reviewers in the attached "Response to Reviewers" document, and have made the associated changes in our revised manuscript.

Thank you for the opportunity to revise this manuscript. We hope you feel that it is now acceptable for publication.

Adam J. Terando, Sara G. Prado and Elsa Youngsteadt

Editorial comments:
Changes to be made by the Author(s):
1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues. The JoVE editor will not copy-edit your manuscript and any errors in the submitted revision may be present in the published version.

Response: Thank you for the suggestion, we have done so.

2. Figures 2 and 3: Please increase the size of the text in figures to make it easier to read.

Response: We have revised these two figures to increase the font size. In addition, we have extended the axis range in Figures 3a-3c so that all values are displayed in 3c (this was in response to a reviewer comment).

3. Please include a space between all numbers and their corresponding units: 4 mm, 0.56 °C; etc.

Response: We have added the spaces.

4. Please remove all commercial language from your manuscript and use generic terms instead. All commercial products should be sufficiently referenced in the Table of Materials and Reagents.
For example: Coroplast, Nashua 322, etc.

Response: We have removed any reference to commercial product names.

5. 1: What is used to cut?

Response: Clarified**:** 'Using a utility knife, cut the corrugated plastic sheets into squares (Fig. 1A). One 15 cm square and two 10 cm squares will be needed for each shield.**'**

6. Please ensure that the references appear as the following: [Lastname, F.I., LastName, F.I., LastName, F.I. Article Title. Source. Volume (Issue), FirstPage – LastPage (YEAR).] For more than 6 authors, list only the first author then et al.

Response: We are using the JOVE reference style to ensure that the references are written as per journal requirements.

Response to reviewers:

Reviewer #1:

Manuscript Summary:
This paper describes a radiation shield for Thermochrons made of corrugated plastic. The description is complete and appears easy to follow.

Major Concerns:
There are a large number of ways to make radiation shields. For example, a more conventional structure similar to a Gill multiplate shield could be made with plastic hors d'oeuver plates, white spray paint for plastics, pony beads and #6 threaded rod and nuts or plain rod and push nuts. I don't know how the cost would compare with the one herein described.

Response: We agree that there are many ways to fabricate custom radiation shields. Few of the resulting designs, however, have been tested for performance in the field--or if they have, the results of that validation are rarely published. We explored the issue of reporting and validating shield design in the ecological literature as part of a previous study (Terando et al. 2017, Ecology & Evolution, 7:9890-9904). Thus, in the current manuscript, in the discussion, we compared the cost of the focal small radshield only to the cost of other handmade shields with published information about bias and specific construction materials. We have added a sentence to the introduction to emphasize the focus on shields that have been field-tested for bias (currently lines 72-75).

I can't really comment on whether the author's design is an improvement or how well it works without building one and using more precise temperature sensors than Thermochrons to compare it with a Gill radiation shield or an aspirated arrangement. A naked thermochron indeed suffers severe radiation heating in the sun, so most anything would look good by comparison.

Response: We appreciate the need for caution in evaluating radiation shields. However, we present this shield specifically for use with Thermochrons (e.g., see line 82) because these sensors are widely--and increasingly--used in replicated sensor arrays in ecological field studies. (Again, data on iButton use in the ecological literature are presented in our previous *Ecology and Evolutio*n study.) Therefore, we believe that ibuttons in other shield configurations, as well as the weather station sensor, are appropriate comparisons for the current manuscript. In our previous study, we also compared a number of other custom-fabricated shields, which performed poorly by comparison and are not included in the current report; we have now made a note of this in line 84 so that readers will be aware of the additional comparisons that were made.

Reviewer #2:

Manuscript Summary:
The authors set out to inform the readership how to construct a small radiation

shield for (mainly temperature) sensor. Given the amount of low cost temperature sensors coming available recently, this is a timely and much needed addition to the scientific literature.

Minor Concerns:
- in line 65 the authors claim that only by shielding temperature sensors one can correctly measure air temperature. De Jong et al (dx.doi.org/10.5194/amt-8-335-2015) show that by using a clever setup and some corrections one can retrieve air-temperature from a multi-sensor array without shielding. (disclosure: de Jong was supervised during his MSc by me. This work was done after his MSc).

Response: Thank you for pointing out this reference. We have revised the manuscript to reflect this work. Lines 65-70 now read:
'Near-surface air temperature sensors typically require some type of solar radiation shielding to prevent direct heating of the sensor element, which would result in erroneously warm measurements. Common ways to limit sensor bias include: 1) using existing environmental features such as trees for shading, 2) bias correction and sensor calibration as in De Jong et al. (2015), that derived corrections based on the thermal properties of sensors, and 3) the use of manufactured or custom fabricated shields (Terando et al. 2017).'

- in line 80-88 the authors list that using a smaller shield does not significantly reduce accuracy. This statement is the conclusion of the experiments done in section "Representative Results". The way I read the statement in the introduction was as if it was a fact from previous studies that using a smaller shield does not significantly reduce accuracy. I would therefore suggest the authors change the wording of lines 80-88 such that it is clear that the claims on accuracy are what they test in this paper, ie. "in this paper, after providing the readers with a protocol on how to construct the shields, we study the effect on the accuracy by [experimental design]". In the results they can than elaborate on the numerical results.

Response: This is a very good suggestion and we thank the reviewer for pointing this out. We have revised this section to now read (Lines 86-95):

"The design protocol proposed here reduces the dimensions of the radiation shield by 50%. Such a reduction in size has several benefits: 1) it is less conspicuous and therefore less susceptible to tampering, 2) it can be more feasibly used in a wider variety of ecological settings where space is limited (e.g., on smaller urban street trees), 3) it is more accurate than other published shielding methods that attempt to minimize shield size or construction costs(Terando et al. 2017), and 4) it is less expensive than the original, larger design due to the reduced quantity of construction materials required. After describing the construction methods, the effect of the size reduction on sensor accuracy relative to the original shield design is explored using results from a field trial conducted under high downward solar radiation conditions."

Reviewer #3:

Manuscript Summary:
The authors provide an interesting adaptation to the burgeoning field of constructed radiation shields which aims to be smaller and cheaper to construct than other alternatives available. The authors test the performance of their radiation shield against a series of alternative approaches and validate using high-accuracy weather station between August 6th and August 21st in the same year. The authors provide a good summary of potential biases in shield configurations and sensor selection but less so in terms of their own evaluation method. The authors show that their newly constructed shield performed similar to another more expensive and larger constructed sensor and was comparable if not better than some of the other alternatives proposed in other studies. Unfortunately, the authors did not adequately test their radiation shield adequately for me to feel comfortable with it becoming widely-used. Likewise, as the authors noted, the radiation shield needed to be adapted to allow for more accurate sensors (ibuttons are notoriously unreliable) such as Hobo pendants to be housed within it. As such, I find this study shows that they have constructed a low-cost shield which was only tested for ibuttons during a brief summer period at a low-latitude field site and therefore does not warrant widespread usage.

Major Concerns:
Inadequate testing of radiation shield suitability: Half a month in August is insufficient for evaluating the suitability of this radiation shield. This is particularly problematic because the selected study area is at a low-latitude and therefore sun angles would differ considerably throughout the year at this site versus farther north. This radiation shield also needs to be tested in the winter and particularly in conditions where snow and/or freezing precipitation may accumulate. It would seem to be problematic that the low-cost radiation shield proposed in this study would be published and therefore given a 'stamp of approval' without having been tested for even a year-long period and only in a very limited environmental setting. As most ecologists are not able to access their sites throughout the winter (farther north), the lack of evaluation of the biases associated with accumulation of snow and/or changes in sun angles is a significant problem with this study. As such, I cannot recommend acceptance despite the authors having presented an interesting design.

Response: We thank the reviewer for their thoughtful comments. While our testing was limited to a single site in the mid-latitudes (here we're defining mid-latitudes as lying between approximately 25^{o}N and 50^{o}N), we do feel the results are indicative of sensor-shield performance across a wide range of conditions experienced by field ecologists. Testing the shield under high radiation conditions (i.e. summer), in our opinion, is advantageous because it is under these conditions that the highest sensor biases are likely to occur if our shield was poorly designed or had fatal flaws compared to the original design from (Holden et al. 2013).Furthermore, the original experiment (detailed in (Terando et al. 2017)) tested shield-sensor accuracy at multiple locations, both sunny and shaded, and under a range of impervious surface conditions (see Figures 3 and 5 and supplementary information from that study for relevant results). The small Radshield performed similarly to the original shield design in all cases. So there is replication across several environmental gradients which suggests the results should be robust in many other settings. Finally, we have included a caveated paragraph in the discussion that discusses the limitation of the testing conditions and how our results (and shield design) may not apply in areas with low solar angles or long daylengths (or both).

Minor Concerns:
Excluding the major concerns above, the manuscript is well written and figures are well-constructed although some of the large values are truncated due to a limited y-axis in both figures.

Response: We have revised Figure 3 so all values are present in the plots. In Figure 2, we have added text to the figure caption to indicate that not all values are shown in Figure 2c, and have noted the range of values.