Response to Referee Comments

We thank the three referees for the constructive criticism and suggestions to improve the manuscript. The major critique of all reviewers is the need for greater discussion of the potential limitations and benefits of this approach, particularly in regards to how the mirrors will work in different climate environments and in the presence of vegetation. Presented here is a **General Summary** of the major responses to all three reviews followed by specific point by point response to reviewer comments.

General Summary:
The most significant change we have made to the manuscript is to expand the discussion and conclusions to include specific detail on what was achieved with the mirror, what the limitations may be, and methods for optimizing and improving mirror design and implementation. Specifically, we added a subsection to the Results and Discussion, "**Section 3.3 Mirror success, limitations, and future directions**".

Mirror successes include:

- The mirrors are inexpensive to construct and can be easily installed in any number of field settings;
- The infrared mirrors yielded significant heating and drying of soil surface and shallow subsurface relative to un-warmed control treatments, with an average soil warming of 4 to 7*C and average decrease in soil moisture by 1 to 6%, depending on soil heat capacity.

Mirror limitations include:

- Periods of shading from the wooden frame;
- Relatively uncontrolled heating of the soil surface that is sun angle dependent;
- Poor constraint on how the effective the mirrors will work in areas with relatively dense understory vegetation;
- Unknown potential for scaling to cover larger areas and relatively poor constraint on the actual area heated by the mirror.

Future directions include:

- Redesign of the mirror frame to minimize shading. Most shading appeared to derive from the framing at the bottom of the mirror; the shading can be minimized by redesign of the mirror frame, such as only framing on the sides of the mirror;
- Empirical measures of the heated area with an array of thermocouples and possibly and IR camera to measure the exact area heated by the mirror and any temperature gradients that exist at the warming boundaries;
- Installation of mirrors in areas with more complete vegetative cover, including both grasses and shrubs/trees, to determine effectiveness for soil warming in such settings;

- Numerical modeling that incorporates various mirror size, angle, sun angle, latitude, and cloud cover to optimize mirrors for specific environmental settings.

Additionally, we clarified the replicated plot experiment, in terms of clearly defining what is meant by in situ mesocoms, and in terms of the statistical analyses and treatment of data. We feel these changes address referee concerns and greatly improve the manuscript.

Specific Responses:
Response to Anonymous Referee #1
…I think the discussion and conclusion are lacking the following two reflections:
1. I think that the proof of concept presented in the article is restricted to the present latitude and climatic regime. As for now the discussion is not reflecting considerations about latitude and climate regime. In tundra environments it is typically much cloudier and rainy and the sun inclination is much different. This will affect the usability of the mirrors and your statements in the discussion and conclusion should reflect this.
We noted in the conclusions that additional modeling is needed to fully test a range of environmental conditions on the effects of the IR mirrors. We now expand the discussion and conclusion sections to include greater discussion of the possible constraints of the current field tests of the mirrors.

2. I do understand that your target is to simply increase the surface and subsurface temperature reflecting the IPCC global average temperature increase. However, on a local scale the climate changes might be a bit more nuanced and therefor it would be interesting with some thoughts about how realistic the pattern of warming from the mirrors is? Would a global climate change induced warming create same type of heat pattern as the mirrors do, i.e. an amplification of the daily temperature oscillation? What about precipitation patterns, which clearly also affect the mirrors?
The aim of the study is to present an inexpensive alternative to surface and near subsurface soil heating. We note that a major driver of soil heating research is the need to understand soil physical, chemical, and biological response to climate warming. The aim was not to replicate IPCC global average increase per se, but rather to simply present a method for soil heating that has the potential to contribute to facilitate field based climate warming/change experiments. It is a given that warming trends will vary with local climate and landscape settings. The mirrors mimic any local environment and simply add more IR energy to the soil surface such that local microclimate effects are maintained. It is clear that further study is needed to quantify the relative contribution of atmospheric moisture and shading by cloud cover on the IR energy reflected back to the surface and how this manifests as changes in soil temperature, but that is beyond the scope of the current proof-of-concept note presented here. The discussion and conclusion sections have been expanded to reflect this.

All soil heating methods are impacted by precipitation and soil moisture content because of the tremendous heat capacity of water such that any local soil surface/subsurface temperature increase due to input of heat energy will be attenuated by water content. This is basic physics and not necessarily a limitation of this specific method. However, what the results do clearly indicate is that the mirrors enhance soil evaporation/soil drying, processes that are predicted to occur with climate warming, particularly in the arid and semiarid regions of the US Southwest.

The rest is a mix of critical comments concerning presentation of data and minor things that will increase the readability of the article, presented here in chronological order.
P.430 line 5-6: it is a detail but be consistent with numbers. Most of the dimensions given for the mirrors are without decimal digits, which makes it seemingly unnecessary to write that: The glass panels were mounted in the frame at a height of 15.25 cm above ground. Stay with the same number of digits. Dropping the decimal digits would be better.
This was changed to be consistent, text now reads 15 cm above the ground.

P. 430 line 7: a typo: not and, but an
Ok – fixed.

P.430 line 14. In my opinion pictures and drawing are extremely useful to enhance the readability of technical descriptions, such as the mirror frame setup. Since the setup of the mirrors is central to your study I would suggest adding a schematic drawing of the various setups you tried.
OK – photo of three mirror setup now included in Figure 1 in addition to the photo of the replicated field trial mirror array.

P.430 line 15. A reference would be appropriate.
OK – line edited to include "according to manufacturer specifications."

P. 431 line 15, p. 432 line 15 and 19. As I read the Copernicus citing guidelines websites should be referenced just as other sources with a name and year, and I find it disturbing to read long internet links as references in the text.
Actually – this is incorrect. Looking through recently published papers – we copied the method presented in those.

P.432 line 9-11. Soil amendments? It is not clear if the "mirror and soil treatments" you later mention (p. 434 line 8) refers to these soil amendments or to the fact that two different soil types are used. Is it crucial to know about this larger project for conveying the information about your study? If a reference exists it could be relevant here as well.
This section has been rewritten to clear up experimental design and analysis ambiguities. Specific text has been inserted below in Response to Referee #3.

P. 432 line 23-25: (somehow related to the comment above I think) It is not clear what a mesocosm is (and is it important to know it for understanding you study?). Is the mesocosm a micro-climate amendment construction or is a simply a soil pit covered with a geo-textile? How is the geotextile fabric influencing the plot? A brief explanation next to the term would be useful.
Greater explanation was included here to clarify what is meant by mesocosm.

P. 432 line 25-27. How many mesocosms did you use, and how many for each treatment type?
This section was amended to include the number of replicate mesocosms for each treatment – "…four replicates."

P.433 line 1. Why adding two mirrors, when you in the initial trials used one? And how was the influence of the shading using two mirrors relative to the shading observed with one mirror from the initial trials?
Two mirrors were used to have complete coverage for the studied mesocosms. It is assumed the relative shading is the same as the one mirror trial – with each frame shading the same relative area. This is now stated in the text.

P. 433 line 4. Introduce the abbreviation first time it is mentioned.
OK - fixed.

P. 433 line 11 and 14. According to the manuscript guidelines equations should be numbered, be on a separate line, with Arabic numerals in parenthesis on the right hand side.
OK – fixed.

P. 433 line 22-24. Why did you use two different methods for measuring soil temperatures – please argue for your decision. Considering the conclusions from the initial trials with both negative and positive temperature changes, it would have been interesting to have a higher measurement frequency I think, and it would give a higher certainty of the temperature trends. Of those six dates of temperature measurements how many measurements per date?
We agree it would be interesting and beneficial to have the continuous temperature records for the replicated mesocosm component of the research. However, resources were not available to equip all of the mesocoms with dataloggers and thermocouples. Therefore, we used the handheld thermometer as an alternative.

P. 435 line 8-16. Why are you reporting some numbers (delta T) with standard deviation, while others not. Seems inconsistent.
OK – this was changed to be consistent throughout the manuscript.

P. 435 line 14. A typo: not measure but measured.
Ok – fixed.

P.434 line 6. Write IR mirror plot, instead of only IR plot, so the naming of the experiment is consistent.
OK – fixed.

P. 434 line 10-12. Summarizing by date is not later presented in the results. And the calculated significant differences are also not presented.
This section has been rewritten for clarity – the exact text is inserted below in the response to Referee #3. This is simply describing how the data how handled in that to calculate dT and dV for each day, we first needed to average the surface temperature and moisture data by treatment for each day. Significant differences were then tested for averaging all days of observation. These data are presented in Figures 5 and 6 and Table 2.

P. 436 line 26. A significant negative trend, calls for a statistical quantification.
OK – this paragraph was modified to include statistical quantification of this correlation.

P. 437 line 16-21. A sentence of four lines! Please reformulate as this is quite interesting.
OK – now split into two sentences for clarity.

P. 438 line 1-3. As mentioned in the beginning: I would like a modification to this statement, since your setup depends on the sun inclination and a majority of cloud free days. In for instance tundra environment or basically agricultural systems on other latitudes the cloud cover and sun inclination might be less favorable for your experimental setup. I think this should be reflected in the conclusion.
The conclusion was modified to reflect this – and this statement edited.

Table 1. Under comment b: why are you using three different letters to indicate significant differences. Please explain what A, B and C stands for.
The letters should not have been included in this table as these means were not compared. This was a mistake in the table and the letters have been deleted.

Figure 2. Would be helpful with a colour scheme that works in black and white too.
After testing various colors – the presented blue to red spectrum provides the clearest contrast. We choose not to change the color scheme because no alternate shading seemed to unambiguiously give the same effect and we wished to avoid presenting it as multiple panels.

Figure 3. The secondary y-axis to show the amount of rain is missing. Would be helpful with a colour scheme that works in black and white too.
A secondary axis was added to the right hand side of the figure. As above, the color scheme was retained as the most unambiguous yet information-rich option.

Figure 5. For the significant negative trend please add a statistical quantification, R2- value or the p-value.

We did not add this information to the figure, but rather included clarification in the text as noted.

Response to Referee #2:

The note, Passive soil heating using an inexpensive infrared mirror design, uses glass panels and solar reflection to passively heat the adjacent soil for climate change experimentation. I agree with the authors that a less expensive and complicated method is needed. However, their method alone does may adequately resolve this need universally. For one, the mirror not only shades certain regions, but it likely focuses solar radiation unevenly across the experimental area. Second, it can only warm the soil when and where there is sunlight present. Third, it may or may not be scalable.

The reviewer makes several good points – addressed in more detail below – and we note that an ideal heating method does not exist, as noted in the introduction and summary of other heating methods, each has its limitations. The technique presented here is simply a cheap alternative to existing heating methods and the point of this short communication is to present the method, demonstrate that is can be used to heat the soil surface, and describe its limitations.

As the authors note, the system itself results in shading of the soil surface at certain times of the day. They did produce a significant heating effect but this was only monitored in a 1-D soil profile. Would the in situ temperature sensors randomly instrumented within the 0.91m plots? I'm curious how spatially variable the T-increase is. Between the shading and focusing, there is a lot of potential to induce thermal gradients in many directions. How analogous to global warming would this be? Future direction might include thermal imaging to capture the spatial representativeness of the passive heating.

We agree the absolute spatial extent of the heating was not directly measured, and have added a statement in the conclusions that thermal imaging of the surface near the mirror would provide an excellent means to constrain this variable. This can also be approached through numerical modeling exercises that take into account sun angle and mirror angle as noted in the conclusions. The radiated area likely changes during time of year with angle of the sun and numerical modeling exercises that vary sun and mirror angle, mirror orientation, and mirror size would further constrain this variable. The short communication here is meant to demonstrate proof of concept that this technique can be used to warm the soil surface, a complete set of numerical modeling runs is beyond the scope of what is presented here.

The authors do show significant heating, but it is somewhat uncontrollable both in its extremes and its duration. Figure 3 shows the majority of heating only happens around noon when the sun is highest. Unfortunately, global warming doesn't necessarily operate as such. For arid locations, as is here, it will increase mean daily soil T, but primarily during peak sun hours. Is that sufficient for climate change studies? I'm not sure. And what limitation are there in more humid or northern regions where clouds limit the effectiveness of passive heating?

The effectiveness of the mirrors in persistently cloudy areas is unknown and may limit the application of this technique to arid and semiarid and subhumid ecosystems. The effectiveness of the mirrors in such environments could be tested empirically and through numerical modeling. There is a general trend in the average hourly data from the one-mirror test plot of increasing heating of both surface and subsurface with increased solar radiation suggesting heating may be limited in cloudy systems. This is reflected in the modified conclusion section.

As for the mirror, it must absorb some spectra of incoming radiation and reflect others. Or does incoming equal outgoing?
As stated in the methods "The glass absorbs ultraviolet light and the film reflects up to 72% of incoming long wave solar radiation towards the soil surface according to manufacturer specifications."

Lastly, the study focuses on 2 bare soils and relatively small plots. To upscale, do you simply need a bigger mirror? And would it effect vegetation? You might burn vegetation in highly focused areas. The authors could investigate or advise the reader on the appropriate placement and size of the mirror. Is there a particular angle we should consider given our particular latitude?
The assumption is that the radiated area can be increased simply by using a larger mirror, although limitations on glass size and stability will become an issue with larger pieces of glass. The method is meant to facilitate in situ warming of small experimental plots – heating an entire ecosystem is beyond the scope of this technique and most, if not all, other passive heating techniques. The mirror does not refocus high energy incoming radiation, rather reflects long wave radiation and it is highly unlikely that a focused area of long wave radiation will burn the vegetation. In fact, we had small seedlings growing in the mirror plots, and not visible burning of vegetative tissue was noted. A statement in this regard was added to the methods section. The placement, size, and orientation of the mirrors could be optimized through numerical modeling as noted above.

Generally, the manuscript is well-written and its tables and figures are excellent. In particular, the temperature contour plots are really nice. The conclusions and discussion are somewhat lacking. Obviously, a reflective mirror in the desert will increase the soil where that reflected radiation is sent. But they could expand their recommendation of the mirror placement, size and orientation. They should also discuss the limitations of their study and the mirror system in general. Ultimately some addition modeling or optimization of its design would really help but for this note it's not necessary.
We have expanded the discussion and conclusions to include sections on what was achieved with the mirror, what the limitations may be, and methods for optimizing and improving mirror design and implementation.

Figure 3c and 3d: the precipitation bars are missing units. I'm not sure if they'll fit – it's a very busy figure.
We added precipitation units to the right hand side of the figure.

Response to Anonymous Referee #3

The note "Passive soil heating using an inexpensive infrared mirror design – a proof of concept" by Rasmussen et al. describes a new innovative way of heating the soil surface and subsurface using infrared mirrors. The authors describe a step by step improvement of the experimental setup by adjusting mirror angles and the number of mirrors to increase soil temperature by simultaneously reducing artificial soil cooling. The setup was tested on 3 different soil types in Arizona at the Karsten Turfgrass Research Facility. It was convincingly shown that bare soil temperatures can be increased up to ~7oC. The increase in temperature is however dampened by increased soil moisture and increased humidity. However, the presented experimental setup seems to be a good initiative to make future warming experiments easier to maintain and more cost effective. For a wider usage of mirrors as alternative to currently existing methods across ecosystems, the system however needs to be tested on soils inhabited by plants to evaluate if the degrees of warming can actually be achieved under naturally occurring conditions.

Abstract –

P428, L1-2: "climate warming" appears twice in one sentence, please be precise. –

Done – this sentence was reworded to "There is need to understand the soil system response of soil systems to predicted climate warming in order for modeling soil process response to predicted climate warming."

P428, L9: how do you know that it is suitable for low canopy vegetation as you only tested the mirrors on bare soil? Same in the discussion section p438. –

This sentence was modified to remove the "low canopy vegetation" statement.

P428, L9: what is several soils? State number of soils and the broad spectrum to give the reader an idea about the system you're talking about. –

Sentence modified to "Mirror tests were performed on several three soils of varying texture, organic matter content, and heat capacity in a warm semiarid environment."

P428 L13: it would be relevant that you also induced potential cooling and that you, despite the cooling, still found an overall heating effect of 4-6 degrees

Added an additional statement to the abstract "Partial shading from the mirror frame did produce periods of relative cooling at specific times of the day, but overall the mirrors yielded a net soil warming."

Introduction: -

P430, L2: your second experiment is in mesocosms, that's not field conditions. Please add information.

This is incorrect. The mesocosms were not under controlled conditions, rather they were exposed to field climate conditions. This qualifier was added to this sentence.

Materials and Methods: -
61x61 cm is fairly small, especially when you want to justify that studying biogeochemical cycling in soil due to warming needs to be addressed. Please add the reason for this relatively small area. –
This initial test and field study was performed as a proof of concept and we limited the experiment to inexpensive cuts of glass available at any local hardware store. The relatively small size of the mirror is also the reason why we used two mirrors per ~1 m^2 mesocosm. The text was updated to indicate this.

P431 first paragraph: the explanation of location and climate overly detailed. Would a summary table for all studied sites be an option? –
We feel this amount of detail is warranted to fully describe the environment in which the mirrors were tested.

P431, L28: refer to Table1 and Fig 1. –
Figure 1 was updated to also include the three mirror configuration used initially and is now referenced in this section.

Section "initial field trials": how many plots did you measure? One control and one mirror treatment? Or more? Please add information. - Please add the same information for the replicated plots – was n=2, or 3 or?? It's relevant for the statistics in any case. –
This information has been added.

P432, L27: you mention mirror treatments for the replicated plots. Though, you don't show any results for this. Please either add results (if relevant) or, remove that you did the mirror tests here too. –
This appears to be a misreading of the sentence. The word treatments refers to soil type, control, and mirror as the treatments. The word treatment was removed for clarity.

P433, L4: what is LPSA? –
Fixed in the text and changed to laser particle size analysis.

P433, L12: what information gain did you get from the "volumetric heat capacity"? Anything useful to conclude from? Please add in discussion. –
It discussed at some length in the results and discussion. This is the heat capacity of the soil – a measure of how much heat energy is required to increase the temperature of the material. A clarifying sentence has been added to the end of this paragraph "These data provide a direct measure of the amount of heat required to warm the soil system, such that for soils of varying heat capacity receiving the same amount of heat energy, the soil with a greater heat capacity will record a decreased temperature increase relative to the soil with a lower heat capacity."

P433, L24: Why did you measure "surface soil temperature" at 1m height? Do you mean 1 cm? – The IR meter measures the temperature of the surface it is pointed towards, not the air around it. The temperature of the soil surface was measured at the same height across all plots to maintain measurement uniformity.

P434, L6: - do you mean a one-sample t-test? And if so, would your H0 be that deltaT is different from 0? If so, why would you not do a two sample t-test where you have the control and mirror plots as sample population each? If I interpret this wrong, please clarify in the text. – P434, L8: "soil treatments" – do you mean soil types? Or did you treat the soils differently? – P434, L10: you used a simple one way t-test – same as above. Though, would you not expect soil type and water content to interact? In that case, an ANOVA would be more appropriate. Further, are the data normally distributed with equal variances to do a t-test? - What statistic software did you use?

Section 2.3 was rewritten to clarify how the data were handled and in terms of clarifying what soil treatment refers to:

The relative soil heating by the IR mirrors in the initial field trials was calculated as:

$$\Delta T = T_{IR} - T_C, \quad (2)$$

where ΔT is the relative increase or decrease in soil temperature, T_{IR} is temperature in the IR mirror plot, and T_C is temperature in the control plot, both in degrees Celsius. Statistical analyses for the initial field trial included simple summary statistics for ΔT values on an hourly basis and correlation of ΔT to meteorological variables collected at the nearby AZMET station.

Statistical analyses for the replicated plot experiment included summary of soil temperature and moisture by soil type, with means comparison of surface ΔT and the difference in soil moisture between mirror and control treatments by soil type. Prior to statistical analysis, temperature and moisture data for the four replicate plots of mirror and control treatments for each soil type were averaged by date. The relative difference in surface temperature, ΔT, and soil moisture, $\Delta \Theta_v$, between mirror and control plots was calculated as the difference between the means for each treatment for each soil type. Significant differences in ΔT and $\Delta \Theta_v$ by soil type were determined on the means of all observation dates using an unequal variance t-test. Additionally, ΔT and $\Delta \Theta_v$ were correlated with local meteorological variables from the AZMET station. All statistical analyses were performed using JMP Pro 11.0.0 (SAS Institute, Cary, NC).

Results: -

P435, L15: please specify that the results you're quickly presenting/concluding on here are from the replicated plot experiment – it's a bit confusing otherwise. –

They are not from the replicated plot experiment – the mean and standard deviations are derived from the time series collected during the initial field trial.

P435, L21: is the 2300 a time, or a number of hourly readings? Didn't you mention before that you conducted readings every 15min? –

It is the number of hourly readings. Yes the data were collected every 15 min, but the data were summarized on an hourly basis. This was clarified in section 2.3.

P435, L21: 64-67% of the measurement period resulted in soil warming. The remaining 46-43% - how much of this was deltaT=0 or cooling? –
That is the remaining 33-36% that is less than zero or cooling. The data are reported in the table as greater than or equal to zero. The majority of this cooling was between -1 to -2*C, with less 2% of the surface and 0.7% of the subsurface measurements indicating a cooling of greater than 2*C. Table 1 has been updated to include these numbers and the text in this section modified as such.

P436, LL12-14: you conclude that the mirrors were most effective under conditions – can you follow up on this point in the discussion and add what you think in which ecosystems these mirrors could actually be really helpful and where not (based on humidity and rain patterns) –
The discussion and conclusions have been expanded to include this information.

P437, L7 onwards: would this be the paragraph to say something about volumetric heat capacity instead of mainly discussing water content? – you draw a big conclusion from about the effect of heat capacity, but I miss a bit of background for someone not familiar with the soils and measurements per se.
This paragraph does explicitly discuss heat capacity – see text starting at L15:
"The CHIR soils also exhibited a greater volumetric heat capacity in the solid phase that would limit the transfer of heat energy to soil water and vaporization. In contrast, the HATH soils exhibited fewer coarse fragments, greater clay and silt content, and greater porosity, indicating greater water holding capacity in addition to a lower volumetric soil heat capacity of the solid fraction. These factors favor warming of the soil and greater transfer of absorbed energy to soil water, favoring soil water vaporization."

Discussion: Further possible points that would be valuable to address: - Plot size limitations? What would be the biggest plot being warmed with these mirrors without too big artefacts? - What would be a further step for improvement? - introducing vegetation as well? warming bare soil is a good first trial but vegetation will automatically keep moisture and higher humidity in the sub-canopy would occur, influencing the results towards cooling? Any assumptions from the trials? - Who would be interested in small plots? - can this be up-scaled to biologically/chemically relevant scales?
The discussion section has been expanded to include much of this discussion. Also – the size of the plots used in the field experiment are biologically, chemically, and physically relevant and are a common approach used in field studies (e.g., compare a ~1 m x 1 m x 30 cm plot used here to chemical and biological experiments performed in the laboratory in centrifuge tubes and mason jars) .

Figures and Tables
Table1: - could you extend the table for the % of cooling – just to get an idea about the method - subscript b: “significant differences” – are these the differences between mirror treatments or different from deltaT=0?
This has been added and the statistical comparison data corrected.

Figure2: add information that this information resulted from your trial experiment.
This change was made.

Figure3: - add information that these results are from you replicated plot experiment. - Can panels c and d have the same y axis scale? - The precipitation bars coming from the tope are unconventional.
Done. It is quite common to have precip. values coming from the top – particularly in the hydrological and vadose zone sciences.

Figure4: - Are all the plots necessary? It seems one of them would be enough to make your point. Rest can go into a supplement?
We feel all of the plots are necessary because each represents a significant finding.

Figures5 and 6: - Can you put this data in a small table instead? Or add to table 2.
The figures are more effective at presenting the distributions, with median and quantiles clearly expressed. Means and standard deviations are already reported in Table 2.

Passive soil heating using an inexpensive infrared mirror design – a proof of concept

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Abstract

There is need to understand ~~the~~ soil system response ~~of soil systems~~ to ~~predicted climate~~ warming in order to~~for~~ model~~ing~~ soil process response to predicted climate warming. Current methods for soil warming include expensive and difficult to implement active and passive techniques. Here we test a simple, inexpensive in situ passive soil heating approach, based on easy to construct infrared mirrors that do not require automation or enclosures. The infrared mirrors consisted of 61 x 61 cm glass panels coated with infrared reflecting film. The mirrors as constructed are effective for soil heating in environments typified by open canopy ~~and low canopy vegetation~~. Mirror tests were performed on ~~several~~ three soils of varying texture, organic matter content, and heat capacity in a warm semiarid environment. Results indicated that the infrared mirrors yielded significant heating and drying of soil surface and shallow subsurface relative to un-warmed control treatments, and that warming and drying effects was soil specific with greater potential warming on soils with lower volumetric heat capacity. Partial shading from the mirror frame did produce periods of relative cooling at specific times of the day, but overall the mirrors yielded a net soil warming. ~~Atmospheric and soil moisture attenuated mirror induced soil warming.~~ The results demonstrate proof-of-concept that the infrared mirrors may be used to passively heat the near soil surface, providing an inexpensive, low-maintenance alternative to other passive and active soil heating technologies.

1 Introduction

Climate change and warming present significant challenges to understanding future ecosystem response, function, and management. The most recent projections suggest up to a 5 °C warming by the end of this century, with mean winter and summer warming of 3.8 °C and 3.3 °C, respectively (IPCC, 2014). Given these projections, there is pressing need to understand the response of soil systems to warming, particularly changes in soil-water and -energy budgets, and soil biogeochemical processes such as carbon and nitrogen cycling. Experimental methods for soil and ecosystem warming include temperature controlled environments in laboratory and greenhouse settings, moving intact soil cores across natural environmental gradients, and heating of soils in situ using various active and passive approaches (Aronson and McNulty, 2009). All of these methods have their short-comings, e.g., extrapolating results from controlled environments to the field, requirement of aboveground enclosures for passive in situ soil heating, and equipment and operational costs associated with active in situ heating. Currently, an inexpensive and effective alternative for in situ soil heating that does not require an aboveground enclosure is lacking.

Soil and ecosystem heating methods vary widely and have been reviewed in detail in Rustad et al. (2001), Shaver et al. (2000) and Aronson and McNulty (2009). Here we highlight several of the main passive and active methods used in previous field studies as context for the approach tested in this work. Many studies apply active heating methods such as infrared heaters (Harte et al., 1995), cables buried in the soil (Peterjohn et al., 1993), with more recent approaches including a combination of steam injection and passive aboveground enclosures (Hanson et al., 2011). Active methods effectively heat above- and below-ground systems with significant changes observed as a result of heating in plant species composition, soil respiration, and soil-water content (Shaver et al., 2000). However, these methods are expensive in terms of equipment set up, operational costs and energy consumption, and require proximity and access to electricity. Passive methods generally include open top chambers and greenhouses placed over mesocosm plots in the field (Kennedy, 1995); however these approaches exclude and minimize the turbulent transfer of air, energy and water vapor, and the movement of mass into and out of the experimental enclosure. Another passive heating approach consists of nighttime trapping of longwave radiation from the soil with an IR reflective sheet above the soil surface that effectively warms the soil overnight (Beier et al., 2004). However, this requires an automated system to lower the IR sheet over the soil surface in the evening and to raise the IR sheet in the morning.

Here we present a simple, inexpensive in situ passive soil heating approach based on easy to construct IR mirrors that do not require automation or enclosures. The objective of this work was to empirically test the efficacy of these mirrors for heating the soil surface and shallow subsoil under field climate conditions.

2 Materials and Methods

2.1 Infrared mirror design

The infrared mirrors consisted of 61 x 61 cm glass panels mounted in a 5 X 5 cm redwood board frame (Fig 1). The size of the mirrors were limited to relatively small glass panels for stability and ease of transfer for this proof-of-concept study, but future applications could implement larger glass panels for more permanent installations. The glass panels were mounted in the frame at a height of 15~~.25~~ cm above the ground surface; with the 5 X 5 redwood frame this leaves an~~d~~ air gap of 10 cm between the bottom of the frame and the ground to allow of air flow and mixing around the base of the panel. The panel glass consisted of common double strength window glass 3 mm thick. The side of the glass away from the plot was covered with Gila Titanium heat control window film (Eastman Chemical Performance Films Division, Gila Film Products, St. Louis, MO, USA). The frames in the field were mounted facing true south, tilted back 10° from vertical (top of frame tilts away from the plot), and secured with metal t-posts. The glass absorbs ultraviolet light and the film reflects up to 72% of incoming long wave ~~solar~~ radiation towards the soil surface according to manufacturer specifications.

2.2 Field experiments

The mirrors were tested using a series of field experiments designed to quantify the effect of mirrors on surface and shallow subsurface soil temperature. The experiments consisted of a set of initial field trials followed by a larger scale test with multiple replicated plots on different soil types. The size of the mirrors is best suited to heating soil in low-stature ecosystems, making them ideal for grassland, short scrub, tundra, and agriculture studies.

2.2.1 Initial field trials

Initial field trials were carried out at the Karsten Turfgrass Research Facility located at the University of Arizona Campus Agricultural Center (CAC) in Tucson, AZ at 32° 16’ 51.77” N, 110° 56’1 3.14” W, at an elevation of 715 m a.s.l. The average climate at this location includes a mean annual air temperature of 22.4 °C, mean annual potential evapotranspiration of 1,945 mm yr^{-1}, and mean annual precipitation of 275 mm yr^{-1} characterized by a bimodal precipitation regime where ~50% of precipitation derives from cool, winter rains and ~50% arrives during the summer as part of the North American Monsoon, with warm dry periods in the spring and fall. Meteorological data for 2013, the year of observation, fell within climatological norms with a mean temperature of 20.4 °C, potential evapotranspiration of 1,933 mm, and annual precipitation of 190 mm. Meteorological data were measured hourly at the CAC using a weather station managed as part of the Arizona Meteorological Network following standard techniques. The station is <0.5 km from the study site and data are freely available online (AZMET, 2013~~;~~, http://ag.arizona.edu/azmet/). The soil at the study area was classified as a coarse-loamy over skeletal, mixed, superactive, calcareous, hyperthermic Typic Torrifluvent (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx), with a fine sandy loam surface soil that contains 4-7% clay based on hand texturing, and < 0.5% organic matter. The parent material was granitic alluvium from the Rillito River and associated local drainages.

The mirrors were placed in an area free of vegetation and groundcover to facilitate direct heating of the soil surface. The initial mirror array consisted of one replicate three mirrors facing south; the central mirror facing due south, with a mirror on each side at an angle of 130° relative to the south facing mirror (Fig. 1). The side mirrors resulted in significant shading of the plot in morning and early evening. As such, following an initial monitoring period of three months starting in March 2013, the side mirrors were removed in sequence, leaving only the central south facing mirror. Data were collected for an additional three months starting in June 2013 following side mirror removal.

Surface and shallow subsurface soil temperature were recorded using 12-bit Temperature Smart Sensor (S-TMB-M006) attached to an HOBO Micro Station Data Logger (H21-002; Onset Computer Corporation, Bourne, MA, USA) set to record on a 15-minute interval. The surface thermocouple was placed directly on the soil surface and the shallow subsurface probe was placed 5 cm below the soil surface. Control thermocouples were placed adjacent to the mirror plot and linked to the same data-logger; roughly 1 m separated the control and test plots.

2.2.2 Replicated plots

The replicated field experiment was also located at the CAC in a field adjacent to the test plot location. The replicted field experiment ~~and~~ was part of a larger project examining the role of soil amendments on two different soils on native vegetation establishment in stockpiled topsoil ~~removed and stockpiled~~ from an open pit mine. The two soils used in this experiment were collected at 31° 50' 34.30" N, 110° 45' 05.96" W, 1615 m a.s.l., and 31° 49' 20.48" N, 110° 44' 03.62" W, 1500 m. a.s.l., and mapped as the Chiricahua and Hathaway soil series, respectively (USDA Web Soil Survey, accessed 2015, http://websoilsurvey.sc.egov.usda.gov/~~App/WebSoilSurvey.aspx~~). The Chiricahua soil (CHIR) was derived from a mix of metamorphic rocks and classified as an Ustic Haplargid; the Hathaway soil (HATH) was derived from mixed sedimentary rocks, largely sandstone, and classified as an Aridic Calciustoll (USDA Official Soil Series Descriptions, accessed 2015, https://soilseries.sc.egov.usda.gov/osdname.asp). The soils were excavated mechanically to a depth 1.75 m below the soil surface and delivered to the CAC. Soils were sieved in the field to remove coarse fragments > 15 cm in diameter before placement in experimental mesocosms.

The replicated field plots consisted of mesocosms constructed in place at the CAC. The mesocoms were located in an open field and subject to ambient climatic conditions. The mesocoms consisted of square evacations that were 0.91 m on a side and excavated to a depth of 30 cm below the soil surface. The square excavation was lined in porous geotextile fabric that allows for water flow but prevents soil in the mesocom from mixing with the exant soil. The mesocosms were backfilled with the Chiricahua and Hathaway soil material up to the level of the soil surface (Fig. 1). ~~Soils were added to a depth of 30 cm to mesocosms 0.91 m on a side after the existing surface had been removed and covered with geotextile fabric.~~

The replicated field plot experimental design ~~was~~ consisted of a randomized complete block design, with each mesocosm randomly assigned to soil type (either Chiracahua or Hathaway), control (no mirror), and mirror (IR mirrors), with four replicates of each treatment ~~treatments~~. Plots with IR mirrors ~~treatments~~ were equipped with two adjacent IR mirrors oriented due south, tilted back 10° from vertical, and secured with metal t-posts (Fig 1). Two mirrors were used to ensure greater coverage of the mesocosm with re-radiated IR energy. It was assumed that the shading effects from the mirror frame was minimal.

The CHIR and HATH soils varied in texture and coarse fraction content, color, and organic matter. Particle size analysis was quantified by laser particle size analysis~~LPSA~~ following removal of organic matter. Weight percent coarse fragments was quantified as the fraction not passing a 2 mm sieve. Dry and moist soil color were measured using a Spectron CE-590 spectroradiometer (Spectron Instruments, Denver, CO) and converted to Munsell notation, and organic matter quantified as loss on ignition (LOI) following 2 hr combustion at 500 °C. Soil properties were measured at University of Arizona Center for Environmental Physics and Mineralogy. Soil color was used to estimate dry and moist soil albedo (0.3-2.8 μm) (α) following Post et al. (2000) as: $\alpha = 0.069v - 0.114$, where v is the Munsell soil value. The volumetric heat capacity of the different soils in each mesocosm, C_T, was calculated as (Jury et al., 1991; Kluitenberg, 2002):

$$C_T = (C_O X_O + C_S X_S + C_R X_R)(1 - \phi_T), \qquad (1)$$

where C_O, C_S, and C_R are the volumetric heat capacities of organic matter, soil, and rock with values of 2.5, 1.9, and 2.4 kJ kg^{-1} K^{-1}, respectively (Eppelbaum et al., 2014; Kluitenberg, 2002), X_O , X_S , X_R are the volume fractions organic matter, soil, and rock in the mesocosm, and φ_T is the total porosity of the mesocosm calculated assuming the volume rock fraction has zero porosity and soil bulk density calculated following Rawls (1983). The values for C_T were calculated assuming a zero water content to provide a dry reference volumetric heat capacity for each soil type. These data provide a direct measure of the amount of heat required to warm the soil system, such that for soils of varying heat capacity receiving the same amount of heat energy, the soil with a greater heat capacity will record a decreased temperature increase relative to the soil with a lower heat capacity.

Repeated measures of surface soil temperature were recorded with a handheld IR thermometer (Cen-Tech model 60725, Cen-Tech, Camarillo, CA, USA) from a height of approximately 1 meter above the soil surface on six dates between August 20 and September 24, 2013. The IR thermometer was used in the replicated field plots due to the fact that the relatively high number of replicates limited instalation of thermocouples and dataloggers for all replicate plots. Repeated measures of soil moisture measured were recorded using FieldScout TDR 100 Soil Moisture Meter (Spectrum Technologies Inc. Plainfield, IL, USA) with 10 cm probes on sixteen dates between August 22 and October 15, 2013.

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2.3 Data manipulation and statistical analyses

The relative soil heating by the IR mirrors in the initial field trials was calculated as:

$$\Delta T = T_{IR} - T_C, \qquad (2)$$

where ΔT is the relative increase or decrease in soil temperature, T_{IR} is temperature in the IR mirror plot, and T_C is temperature in the control plot, both in degrees Celsius. Statistical analyses for the initial field trial included simple summary statistics for ΔT values and correlation of ΔT to meteorological variables collected at the nearby AZMET station.

Statistical analyses for the replicated plot experiment included summary of soil temperature and moisture by soil type, with means comparison of surface ΔT and the difference in soil moisture between mirror and control, $\Delta\Theta_v$, treatments by soil type. Prior to statistical analysis, temperature and moisture data for the four replicate plots of mirror and control treatments for each soil type were averaged by date. The relative difference in surface temperature, ΔT, and soil moisture, $\Delta\Theta_v$, between mirror and control plots was calculated as the difference between the means for each treatment for each soil type. Significant differences in ΔT and $\Delta\Theta_v$ by soil type were determined on the means of all observation dates using an unequal variance t-test. Additionally, ΔT and $\Delta\Theta_v$ were correlated with local meteorological variables from the AZMET station. All statistical analyses were performed using JMP Pro 11.0.0 (SAS Institute, Cary, NC)~~The relative soil heating by the IR mirrors in the initial field trials was calculated as: $\Delta T = T_{IR} - T_C$; where ΔT is the relative increase or decrease in soil temperature, T_{IR} is temperature in the IR mirror plot, and T_C is temperature in the control plot, both in degrees Celsius. Statistical analyses included simple summary statistics for ΔT values, means comparison of control and IR plot temperature using a one-way t-test, and correlation of ΔT to meteorological variables collected at the nearby AZMET station.~~

~~Summary statistics by mirror and soil treatments were determined for the replicated field plots, with means comparison of surface soil temperature and soil moisture (Θ_v) among soil and mirror treatments using simple one-way t-tests. Temperature and moisture data were further summarized by date and the relative difference in surface temperature, ΔT, and soil moisture, $\Delta\Theta_v$, calculated as the difference in the means for each treatment. Significance differences in ΔT and $\Delta\Theta_v$ between soil types were determined averaging across all dates of observation. Furthermore, ΔT and $\Delta\Theta_v$ were correlated with local meteorological variables from the AZMET station.~~.

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3 Results and Discussion

3.1 Initial field trials

The initial field trial with the three mirror array yielded substantial warming of the shallow subsurface soil (5 cm depth), with maximum midday warming near 17 °C relative to the unheated control plot (Fig. 2). Heating was greatest between the hours of 1100 and 1300 hrs when the sun was at its highest point in the sky with a mean ΔT of 1.1 °C. However, as the year progressed from early spring to summer and the sun moved further to the north, substantial cooling of the mirror plot was observed in the morning and evening hours, with a concurrent reduction in midday heating (Fig 2). In particular, the afternoon temperature differential indicated the mirror plots were up to 5 °C cooler at a 5 cm depth than the control plot. The morning and afternoon cooling was due to shading from the side mirrors oriented at 130° relative to the central south facing mirror.

We conducted several short-term experiments with the three mirror array to try and address the morning and afternoon shading. The first experiment simply included changing the angle of the side mirrors from 130° to 160° relative to the central south facing mirror, between days 141 and 154. Opening the mirrors did reduce the amount of shading and increase the hours of warming, but yielded a mean ΔT value near -0.2 °C, with brief periods of 4-5 °C cooling in the afternoon hours (Table 1). The second experiment ran from day 154 to 164 and included removing the west panel to try and eliminate the afternoon cooling trend. This experiment did yield a reduction in both morning and afternoon cooling and returned the mean ΔT to an overall warming trend of 0.5 °C.

The final field trial experiment consisted of removing both side mirrors, leaving just the one south facing mirror. In this instance, soil temperature was measured both directly at the soil surface and at a 5 cm depth. The data indicated mean ΔT values of 0.5 ~~± 1.6~~ and 0.3 ~~± 0.9~~ °C at the surface (Fig. 3a) and 5 cm depth (Fig. 3b; Table 1). Both surface and 5 cm depth temperatures exhibited the greatest heating at midday, with maximum ΔT values near 10 °C and 5 °C, respectively. Periods of cooling were still evident in the morning and afternoon hours. Detailed observation of diurnal ΔT trends indicate cooling between the hours of 0800 and 1000 that was then overcome by heating during the midday hours. Of the ~2,300 hourly average ΔT values, 64% and 67% of observations were ≥ 0 °C for surface and subsurface soils, respectively, such that the majority of observations indicated warming (Table 1). The majority of hours that indicated cooling exhibited ΔT values bewteen -1 °C and -2 °C, with less than 2% and 0.7% of surface and subsurface measurements, respectively, recording cooling greater than -2 °C.

Comparing the one-mirror ΔT values to meteorological variables indicated that the relative cooling in mirror plots was greatest during periods of high atmospheric moisture and following precipitation events when surface soils were moist (Fig 4a). This was evidenced by significant negative trends in ΔT with both mean daily dewpoint (Fig 4b) and daily minimum relative humidity (Fig 4c). Both of these values provide a measure of atmospheric moisture content, with the mean daily dewpoint a daily average and minimum relative humidity providing a measure of atmospheric humidity at the hottest point in the day. These data clearly indicate that the warming effect of the mirror was minimized or negated with a wet atmosphere. This trend was particularly evident in the 5 cm depth ΔT values following rainfall events. Detailed diurnal analysis of 5 cm ΔT values indicated that during wet periods following rainfall events the midday heating from the mirror was not enough to overcome any cooling associated with morning and afternoon shading. These data were consistent with both atmospheric and soil moisture limiting temperature increases in the shallow subsurface. Furthermore, the increased energy transfer to the soil in the mirror plot may also have increased evaporation rates that would buffer any warming as energy was consumed via vaporization (e.g., Wåhlin et al., 2010). However, soil moisture was not monitored during the initial field trials. These data highlight that the greatest warming impact of mirrors was during periods with dry soil and atmospheric conditions, and also suggest the potential for changes in surface soil water balance that would lead to more evaporation and soil drying in the mirror treatments.

3.2 Replicated plot experiments

The replicated field plot experiments indicated significant heating of the soil surface with an average ΔT of +5.5 °C (Fig. 5; Table 2). These measurements were single time points collected during the midday time period; as such they represent near maximum temperature differentials based on the continuous data patterns collected in the initial field trial. The relative warming also varied significantly by soil type, with HATH exhibiting ΔT of +6.8 °C and CHIR exhibiting ΔT values of +4.1 °C (Table 2). The CHIR plots contained a larger fraction of rock fragments, lower estimated total plot porosity, and higher heat capacity that would also limit temperature change per unit of additional IR radiation (Jury et al., 1991) (Table 2).

The replicated field plot ΔT values exhibited a ~~significant~~ general negative trend with increasing minimum daily relative humidity across all sampled dates ($r = -0.32$) (Fig. 5), confirming the field test trials where warming from the mirrors was attenuated by atmospheric and soil moisture. The date that deviated most substantially from this overall trend was the last date collected on day 267, noted in Fig. 5. This measurement date was preceded by the largest series of rainfall events during the observation period that corresponded to increased soil moisture content in both the CHIR and HATH soils. The lack of differential heating at this time period despite relatively low minimum relative humidity values was thus likely controlled by soil moisture content. Excluding this day, the correlation between ΔT and minimum daily relative humidity increased and became significant ($r = -0.66$; $P<0.05$).

Soil moisture data indicated a relative drying trend in the mirror plots, with significantly greater drying in the HATH relative to the CHIR soils (Fig. 6; Table 2). The CHIR soils exhibited high rock fragment content, coarse textured fine-earth fraction, and only 13% total mesocosm porosity leading to both a limited water holding capacity and faster drainage relative to the HATH mesocoms (Table 2). This was confirmed by soil moisture data from the control mesocoms that indicated CHIR soils averaged 13.6 ~~± 5.9~~% volumetric water content relative to 22.7 ~~± 10.4~~% in the HATH soils and that for each day of observation, the CHIR soils were drier than the HATH soils by 5 to 15% volumetric water content. The CHIR soils also exhibited a greater volumetric heat capacity in the solid phase that would limit the transfer of heat energy to soil water and vaporization. In contrast, the HATH soils exhibited fewer coarse fragments, greater clay and silt content, and greater porosity, indicating greater water holding capacity in addition to a lower volumetric soil heat capacity of the solid fraction. These factors ~~that~~ favor~~s~~ warming of the soil and greater transfer of absorbed energy to soil water, favoring soil water vaporization. The drying results are similar to results of Harte et al. (1995) and Verburg et al. (1999) that found significant drying with IR lamps and soil heating cables, respectively.

3.3 Mirror success, limitations, and future directions

The results from this proof of concept study indicated that the IR mirrors do effectively heat the near soil surface, but also highlights a number of limitations and future directions for research to improve mirror implementation in the field.

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Mirror successes include:

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- The mirrors are inexpensive to construct and can be easily installed in any number of field settings;
- The infrared mirrors yielded significant heating and drying of soil surface and shallow subsurface relative to un-warmed control treatments, with an average soil warming of 4 to 7 °C, and average decrease in soil moisture by 1 to 6%, depending on soil heat capacity.

Mirror limitations include:

- Periods of shading from the wooden frame;
- Relatively uncontrolled heating of the soil surface that is sun angle dependent;
- Poor constraint on how the mirrors will work in areas with relatively dense understory vegetation;
- Unknown potential for scaling to cover larger areas and relatively poor constraint on the actual area heated by the mirror.

Future research directions include:

- Redesign of the mirror frame to minimize shading. Most shading appeared to derive from the framing at the bottom of the mirror; the shading can be minimized by redesign of the mirror frame, such as only framing on the sides of the mirror;
- Empirical measures of the heated area with an array of thermocouples and possibly an IR camera to measure the exact area heated by the mirror and any temperature gradients that exist at the warming boundaries;
- Installation of mirrors in areas with more complete vegetative cover, including both grasses and shrubs/trees, to determine effectiveness for soil warming in vegetated settings;
- Numerical modeling that incorporates various mirror size, angle, sun angle, latitude, and cloud cover to optimize mirrors for specific environmental settings.

4 Conclusions

The results presented here demonstrate proof-of-concept that the infrared mirrors tested here may be used to passively heat the near soil surface, providing an inexpensive, low-maintenance alternative to other passive and active soil heating technologies. The mirrors as constructed were effective for soil heating in environments typified by open canopy and low canopy vegetation, similar to those present in ~~such as~~ agriculture systems, desert grassland and scrub ecosystems~~, and possibly tundra~~. Heating from the infrared mirrors significantly

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impacted both soil warming and drying, similar to trends expected with a warming climate. Key conclusions include:

- The infrared mirrors yielded significant heating and drying of soil surface and shallow subsurface relative to un-warmed control treatments;
- Atmospheric and soil moisture attenuated IR mirror-induced soil warming;
- The warming and drying effects of the infrared mirrors was soil specific, with greater potential impact on soils with lower volumetric heat capacity.

It is important to note that the initial field trials indicated soil warming from the infrared mirrors was more pronounced in winter months when the sun was further to the south, and that periods of shading related to the frame and mirror orientation were apparent in morning and evening hours. The efficacy of soil heating with the infrared mirrors could be improved with detailed numerical modeling of coupled soil-atmosphere energy and water balances that take into account latitude, seasonal changes in sun position, and soil moisture and heat capacity, e.g., using a model such as HYDRUS 1D. Such modeling would facilitate optimization of mirror angle, size, and orientation to reach the desired experimental soil warming and drying response. ~~,~~Additional modeling coupled with field instation of infrared mirrors in different environments have the potential to mak~~eing~~ ~~these~~ this type of infrared mirror~~s~~ a powerful tool for experimental warming of open canopy and low vegetation canopy systems.

Acknowledgements

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References

Aronson, E. L. and McNulty, S. G.: Appropriate experimental ecosystem warming methods by ecosystem, objective, and practicality, Agr Forest Meteorol, 149, 1791-1799, 2009.

Beier, C., Emmett, B., Gundersen, P., Tietema, A., Penuelas, J., Estiarte, M., Gordon, C., Gorissen, A., Llorens, L., Roda, F., and Williams, D.: Novel approaches to study climate change effects on terrestrial ecosystems in the field: Drought and passive nighttime warming, Ecosystems, 7, 583-597, 2004.

Eppelbaum, L. V., Kutasov, I. M., and Pilchin, A.: Applied geothermics, 2014.

Hanson, P. J., Childs, K. W., Wullschleger, S. D., Riggs, J. S., Thomas, W. K., Todd, D. E., and Warren, J. M.: A method for experimental heating of intact soil profiles for application to climate change experiments, Global Change Biology, 17, 1083-1096, 2011.

Harte, J., Torn, M. S., Chang, F. R., Feifarek, B., Kinzig, A. P., Shaw, R., and Shen, K.: Global Warming and Soil Microclimate - Results from a Meadow-Warming Experiment, Ecological Applications, 5, 132-150, 1995.

IPCC: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. CoreWritingTeam, Pachauri, R. K., and Meyer, L. A. (Eds.), IPCC, Geneva, Switzerland, 2014.

Jury, W. A., Gardner, W. R., and Gardner, W. H.: Soil physics, J. Wiley, New York, 1991.

Kennedy, A. D.: Simulated Climate-Change - Are Passive Greenhouses a Valid Microcosm for Testing the Biological Effects of Environmental Perturbations, Global Change Biology, 1, 29-42, 1995.

Kluitenberg, G. J.: Heat capacity and specific heat. In: Methods of Soil Analysis. Part 4 - Physical Methods, Dane, J. H. and Topp, G. C. (Eds.), 5, Soil Science Science of America, Madison, WI, 2002.

Peterjohn, W. T., Melillo, J. M., Bowles, F. P., and Steudler, P. A.: Soil Warming and Trace Gas Fluxes - Experimental-Design and Preliminary Flux Results, Oecologia, 93, 18-24, 1993.

Post, D. F., Fimbres, A., Matthias, A. D., Sano, E. E., Accioly, L., Batchily, A. K., and Ferreira, L. G.: Predicting soil albedo from soil color and spectral reflectance data, Soil Science Society of America Journal, 64, 1027-1034, 2000.

Rawls, W. J.: Estimating Soil Bulk-Density from Particle-Size Analysis and Organic-Matter Content, Soil Science, 135, 123-125, 1983.

Rustad, L. E., Campbell, J. L., Marion, G. M., Norby, R. J., Mitchell, M. J., Hartley, A. E., Cornelissen, J. H. C., Gurevitch, J., and Gcte-News: A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming, Oecologia, 126, 543-562, 2001.

Shaver, G. R., Canadell, J., Chapin, F. S., Gurevitch, J., Harte, J., Henry, G., Ineson, P., Jonasson, S., Melillo, J., Pitelka, L., and Rustad, L.: Global warming and terrestrial ecosystems: A conceptual framework for analysis, Bioscience, 50, 871-882, 2000.

Verburg, P. S. J., Van Loon, W. K. P., and Lukewille, A.: The CLIMEX soil-heating experiment: soil response after 2 years of treatment, Biol. Fertil. Soils, 28, 271-276, 1999.

Wåhlin, A. K., Johansson, A. M., Aas, E., Brostrom, G., Weber, J. E. H., and Grue, J.: Horizontal convection in water heated by infrared radiation and cooled by evaporation: scaling analysis and experimental results, Tellus A, 62, 154-169, 2010.

Table 1. Summary of ΔT statistics for the initial set of field trials measuring soil heating resulting from infrared mirrors.

Treatment	n† (hrs)	Mean ΔT‡	Minimum ΔT	Maximum ΔT	Fraction Time ΔT ≥ 0°C (%)
		(°C)	(°C)	(°C)	
Three mirrors - 130°	1898	1.1 ± 3.6 A	-9.2	16.9	75
Three mirrors - 160°	299	-0.2 ± 2.3 C	-8.2	2.9	59
Two mirrors	253	0.5 ± 1.4 B	-5.1	3.8	70
One mirror	2320	0.3 ± 0.9 B	-2.6	4.5	67

†Number of hours measured for each treatment.

‡Means one standard deviation. Letters indicate significant differences using an unequal variance t-test.

Table 2. Summary of soil properties for the two soil types included in the replicated field plot experiment.

Soil type	Texture class	LOI†	Org. C†	Rock†	Sand	Silt	Clay	Munsell Color		Soil Albedo		ϕ_T	C_T
		---------------------- (wt. %) ----------------------						Dry	Moist	Dry	Moist	(%)	(MJ m^{-3} K^{-1})
Chiricahua - CHIR	sandy loam	3.5 ± 0.01	0.7 ± 0.01	72 ± 3.2	69.1	24.4	6.4	6.90YR 3.61/2.64	5.52YR 2.75/2.6	0.135	0.076	13.2	2.02
Hathaway - HATH	sandy loam	4.3 ± 0.05	1.0 ± 0.02	43 ± 3.6	59.7	30.9	9.4	7.7YR 3.88/1.82	7.29YR 2.61/1.74	0.154	0.066	31.4	1.50

†Loss on ignition (LOI), organic carbon, and rock fragments. Values are mean of three replicates reporting one standard deviation

‡Means and one standard deviation. Letters indicate significant differences using an unequal variance t-test.

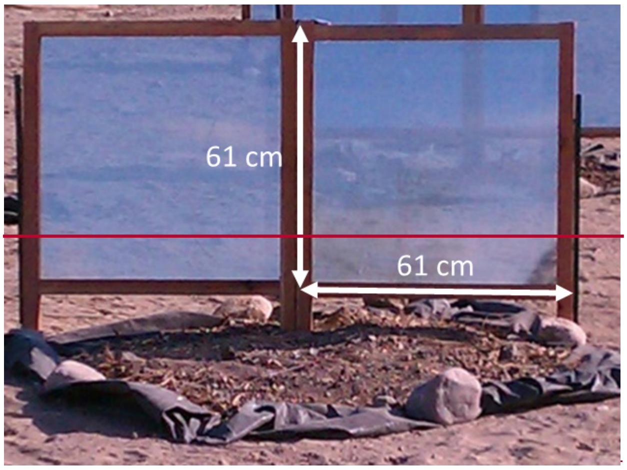

Figure 1. Example of the infrared mirror design showing a) the initial three mirror array and b) the two 61 x 61 cm panel design that was implemented for the replicated plot field trial. The photo in a) was taken mid-afternoon with the sun to the west and the photo in b) was taken mid-morning with the sun to the east; note the shading induced by the mirror frame in both photos.~~Figure 1. Example of the infrared mirror design showing the two 61 x 61 cm panel design that was implemented for the replicated plot field trial. This photo was taken mid-morning with the sun to the east; note the shading induced by the mirror frame in the experimental plot~~

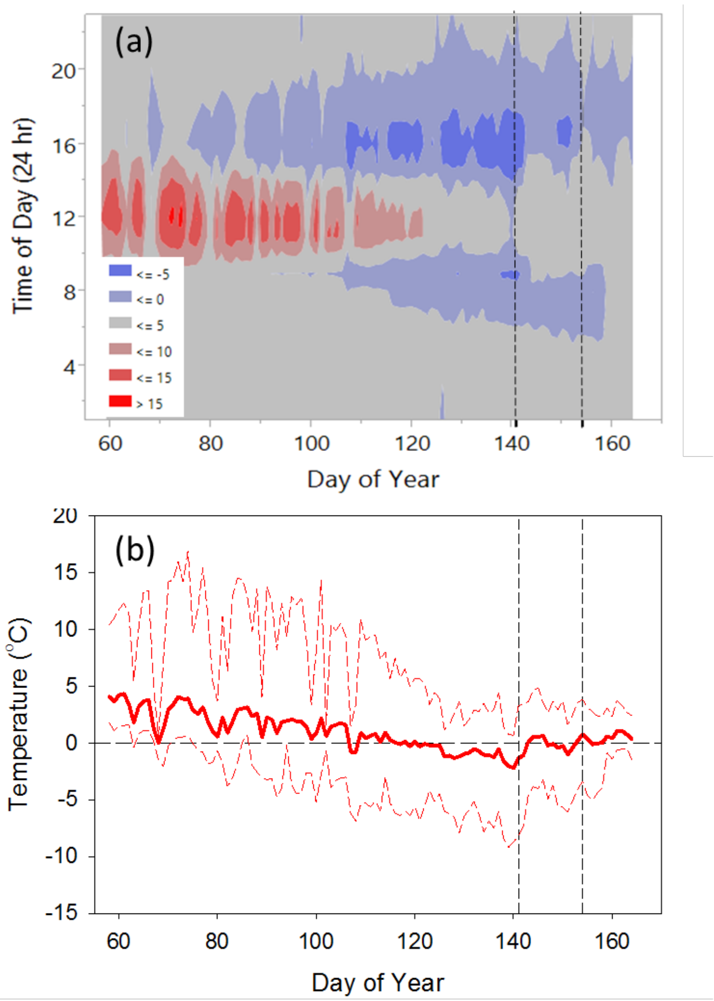

Figure 2. Contour plot of relative soil heating, ΔT (°C), by day of year and time of day (a) and daily mean (bold red line) and minimum and maximum (dashed lines) ΔT by day of year (b). The vertical dashed lines in (a) and (b) represent changes from the three mirror array, to the two mirror array, and finally the one mirror array.

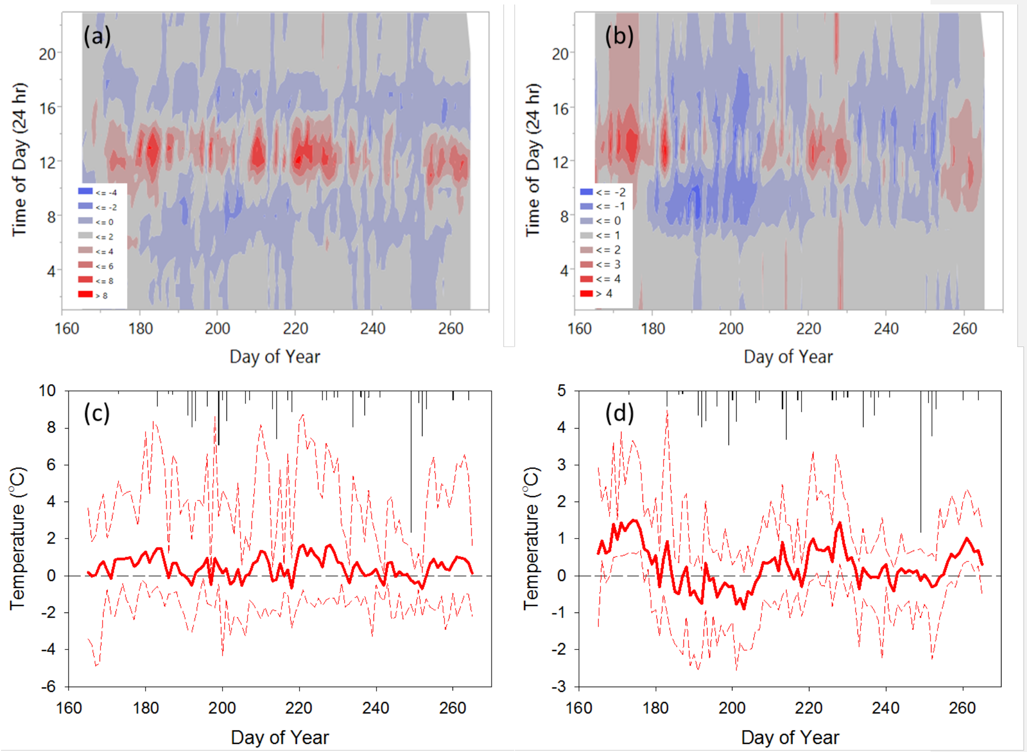

Figure 3. Contour plot of relative soil heating, ΔT (°C), by day of year and time of day for soil surface (a) and shallow subsurface (5 cm depth) (b) for the one infrared mirror array. Daily mean (bold) and minimum and maximum (dashed lines) ΔT values for the surface (c) and shallow subsurface (b). Black bars on the upper x-axis are daily precipitation totals from the nearby meteorological station.

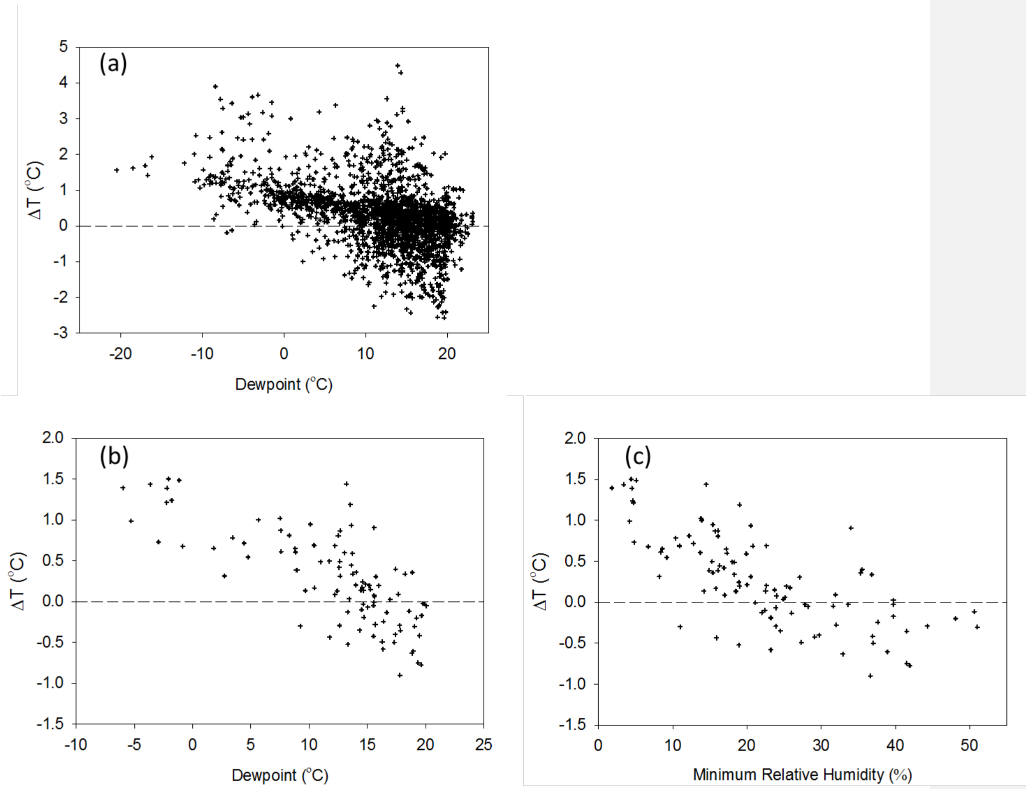

Figure 4. Relative soil heating, ΔT (°C), compared to dewpoint (°C) for all hourly measurements from the one panel array (a). Daily average ΔT relative to daily average dewpoint and daily minimum relative humidity (%). The dashed line on the y-axis indicates a ΔT value of zero with values greater than zero indicating heating and values less than zero indicating cooling as a result of the infrared mirror treatment.

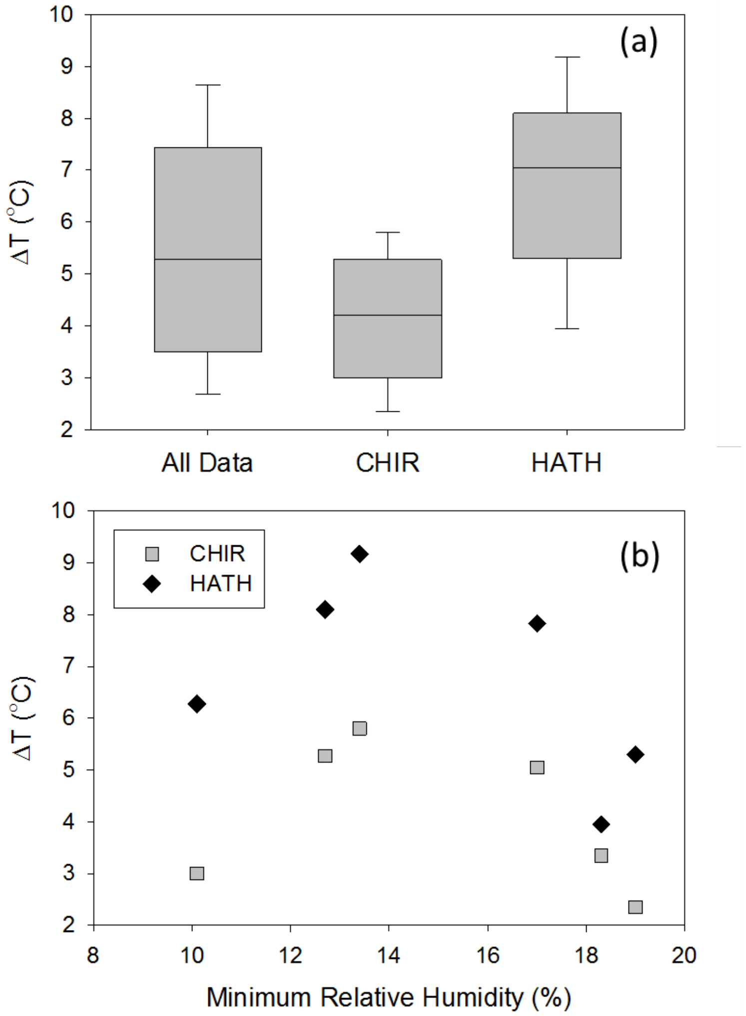

Figure 5. Box plots of relative soil heating, ΔT (°C), for all data from the replicated field experiment (All Data) and for data separated by soil type (Chiricahua, CHIR; and Hathaway, HATH) (a), and mean daily relative soil heating ΔT compared to daily minimum relative humidity for the two soil types (b).

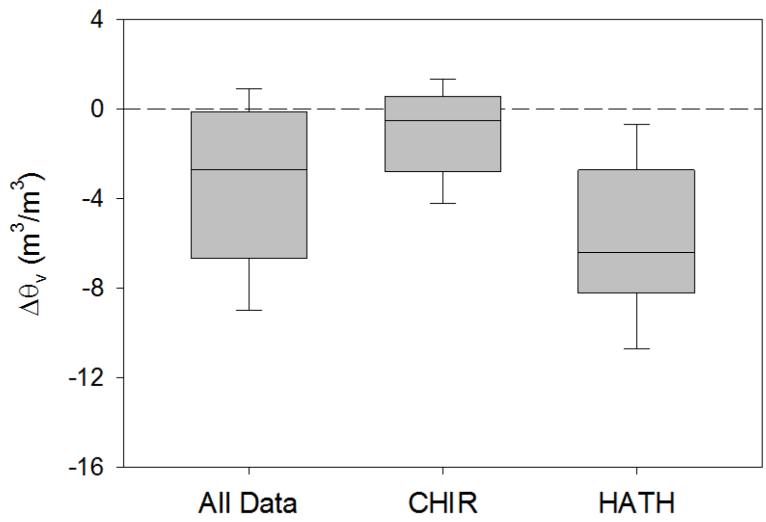

Figure 6. Box plots of relative change in volumetric soil water content, $\Delta\Theta_v$ (m^3 m^{-3}), for all for all data from the replicated field experiment (All Data) and for data separated by soil type (Chiricahua, CHIR; and Hathaway, HATH).