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Interactive comment on "Passive soil heating using an inexpensive infrared mirror design – a proof of concept" *by* C. Rasmussen et al.

C. Rasmussen et al.

crasmuss@cals.arizona.edu

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Response to Referee Comments (posted here as plain text - also uploaded as a pdf as a Supplement to maintain formatting of original text):

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. OK – this was changed to match specifications.

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.

âĂČ 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. âĂČ 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 âĹij7oC. 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 mˆ2 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: ∆T=T_IR-T_C, (2) where ∆T is the relative increase or decrease in soil temperature, TIR is temperature in the IR mirror plot, and TC is temperature in the control plot, both in degrees Celsius. Statistical analyses for the initial field trial included simple summary statistics for ∆T values on an hourly basis and correlation of ∆T 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 ∆T 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, ∆T, and soil moisture, ∆Ïťv, between mirror and control plots was calculated as the difference between the means for each treatment

for each soil type. Significant differences in ∆T and ∆Ïťv by soil type were determined on the means of all observation dates using an unequal variance t-test. Additionally, ∆T and ∆Ïťv 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.

Please also note the supplement to this comment:
http://www.soil-discuss.net/2/C386/2015/soild-2-C386-2015-supplement.pdf

Interactive comment on SOIL Discuss., 2, 427, 2015.