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To:

Dr. Verma, Editor-in-Chief

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Dear Dr. Verma,

We would like to thank you for the opportunity to revise our original submission of our manuscript 2017-18850, and to thank the two reviewers for the very helpful and constructive comments and feedback that they provided. Enclosed please find our revised manuscript entitled “Rapid growth of the U.S. Wildland Urban Interface increases wildfire risk” which we resubmit for potential publication as a research report in PNAS. Thanks to the reviewers’ great suggestions, we feel that the manuscript has substantially improved, and we are excited to share this new version with you.

In the following pages, we state in detail how we revised the manuscript in response to each comment. We followed the reviewer suggestions in almost every point, and added, for example, detailed information on possible solutions, new figures, and a discussion of the synergistic effects of housing growth and climate change. We also conducted substantial new analyses, as suggested by one reviewer, and calculate the houses within the burned areas mapped by the BAECV burned area dataset instead of the MTBS dataset that we had originally used. However, that analyses revealed problems with the BAECV dataset that resulted in erroneous estimates of the number of houses that were affected by fires. That is why we decided not to include the BAECV-based results in our revised manuscript and retained the MTBS-based results instead. Please see our response to the reviewer comment for further details. We hope that you will agree with our decision.

All authors have read the revised manuscript, agree with our resubmission to PNAS, and have no conflicts of interest. All of the figures are in color and we have funds available to cover the cost of publication. We are excited to present our revised manuscript to you and look forward to your response.

Your sincerely,



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Reviewer #1:

Comments:
Overall this paper would make an excellent contribution to PNAS. Given the recent spate of devastating wildfires in the U.S., particularly in California, it is incredibly important to highlight how we are building in flammable landscapes, making people and homes vulnerable to wildfires. I have a few major suggestions for improvement: i) incorporate small fires into the calculation for estimating the number of homes at risk, as the MTBS product is biased towards fires that are farther from the WUI; ii) provide a change detection map at the scale of the U.S. (with a scale smaller than states) rather than just the three highlighted regions; and iii) explicitly discuss the recent wildfire disasters in California and perhaps a few others, as important examples where lives and homes were at great risk from fires. Addressing these major comments would make this work a significant advance and appeal to a broader audience. Below are additional, minor comments.

*Response: Thank you for these very kind evaluation of the overall contribution of our manuscript (!), and for the excellent suggestions how to strengthen it. We embraced all three suggestions, and revised the manuscript accordingly. Please see our responses below for details how we revised the manuscript exactly in response to each suggestion.*

Title:

1. "Exacerbates wildfire problems" is pretty vague. Here's an alternate suggestion that highlights more what the paper focuses on: Rapid growth of the U.S. Wildland Urban Interface exposes more homes to wildfire

*Response: We agree latter part of the title was too vague. However, increasing number of homes not only “expose more homes to wildfire” but will also result in more wildfires due to more human ignitions. This is why we opted to change the latter part of the title to “increases wildfire risk”*

Main text:

2. Page 1, paragraph 1: Does the WUI only consider forests and shrublands? Not grasslands, or other vegetation that is also flammable?

*Response: The WUI includes all types of wildland vegetation, forests and shrublands were meant as examples, not a comprehensive list in this sentence. However, we see how our original wording could lead to false interpretations and replaced ‘forests and shrublands’ with ‘wildland vegetation.’*

*In addition, we now state all the NLCD classes that were included as ‘wildland vegetation’ on page 5 of our manuscript where we describe our methods briefly.*

3. Page 1, paragraph 2: The discussion of "other environmental problems" seems like an afterthought and is really not well developed. I would cut this sentence and focus on the wildfire consequences for the WUI.

*Response: Re-reading how we had presented the ‘other environmental problems’, we agree that it felt added on. However, rather than cutting this paragraph (it wasn’t just a single sentence), we opted to revise the writing to make it stand on its own. While it is certainly true that wildfires are the most commonly discussed issue in the WUI, the concept (and the federal definition!) of the WUI pertains to many more environmental issues than just wildfires. We feel that pointing out this breadth is important, rather than distracting, and may help making our results on WUI growth relevant for ecologists who are not focused on wildfires.*

4. Page 4: It would be helpful to have an example of the increase in wildland vegetation around existing developed areas, as it's not intuitive where/when this would happen. And then the second part of those "two major questions" seems a little forced, since it's hard to imagine that scenario playing out on large scales.

*Response: Great point! We agree that an example was lacking, and added a sentence to point out the case of the New England states, where forest cover has increased over large areas in recent decades due to the abandonment of former farmfields.*

5. Page 6: "...wildfire and other environmental issues are particularly vexing" - what does that mean? Please clarify.

*Response: We apologize for this confusing statement. Rather than elaborating on this point, we opted to delete the sentence since it was part of a paragraph where we present our results. The comparison how problematic interface versus intermix WUI are seemed to fit better in the discussion part of our manuscript.*

6. Page 7: Authors state: "Many of these new houses were built before the wildfires occurred...." There's a lot of speculation in this sentence. Is there any evidence to support when those homes were built or firefighting response?

*Response: Guilty as charged. No, there is no evidence to support when homes were built relative to when the fires occurred. While we have the exact dates of the fires, we do not have the exact dates of when the homes were built. In response, we revised the sentence and removed any speculation about when the houses were built, and simply state that – and explain why – both houses built before and after the fires occurred are of concern.*

7. Page 8: There are several unsupported statements in the first paragraph regarding seasonal homeownership, family size, retirees, telecommuting. Are there social science papers that can be cited to back up these statements?

*Response: Thank you for pointing this omission of references out! We agree that additional references were necessary in this paragraph, and added them in our revision.*

Methods:

8. The authors may be vastly underestimating the number of homes that are within fire perimeters by using the MTBS product. The MTBS product captures only large events (>400 ha in the West and >200 ha in the East), which tend to be biased towards fires in more remote locations, particularly lightning-ignited fires in the wildlands in the West. Smaller fires, more often human-started and suppressed sooner, tend to be closer to the WUI. I would expect that if you used the new BAECV (Hawbaker et al. 2017) product you would have many, many more homes within fire perimeters. In fact, I was surprised that the authors did not use this product, since one of the co-authors produced it. Redoing this part of the analysis with the BAECV product, which includes smaller fires, would give a more profound estimate of the current risk to homes in the WUI. If it's not possible to use that fire product, then at the very least I would recommend stating that the estimate of 177,000 exposed homes in 1990 and 286,000 homes in 2010 is likely a very conservative estimate because it is biased towards large events that are more likely distant from the WUI.

*Response:* *Thank you for this excellent suggestion.  We agree that compared to the MTBS data, the BAECV data provide a more systematic record of burned areas through time and the BAECV data include small fires (i.e., those smaller than 1000 acres in the West and 500 acres in the East), which could be important in areas with high housing density.*

*In response to this comment, we calculated the number of homes within fire perimeters based on the BAECV dataset instead of the MTBS dataset. As noted in the comment, co-author Hawbaker was the lead developed of the BAECV dataset, and he conducted those calculations. The results were generally consistent with our previous calculations based on the MTBS dataset, but the absolute numbers changed greatly.  For example, there were 286,000 houses in 2010 within MTBS fire perimeters, versus 777,000 in BAECV perimeters.  While we had expected a somewhat larger number of houses within fire perimeters, this difference was much larger than we had expected, given that the burned area according to the BAECV is only 37% larger than that mapped by the MTBS.*

*Unfortunately, in examining our BAECV results in more detail, we found that the BAECV includes a substantial number of small fire perimeters in urban areas, and at least some of these fires are commission errors, i.e., they do not reflect actual fires. However, because these fire perimeters occur in areas with high housing density, they increased the number of houses within fire perimeters greatly.*

*Ultimately, this reflects the different nature of the BAECV and the MTBS data. The BAECV is based on an automatic classification, and as such includes errors of omission and commission. The MTBS data are hand-digitized, and that means that commission errors are unlikely, but omission errors are inherent.*

*Given these findings, and the lack of a validation of the BAECV dataset for urban areas at this point, we opted to retain the MTBS-based results in our revised manuscript. We simply were not confident enough in the BAECV-based results to include them in our manuscript.*

*Having said that, we fully agree with the reviewer that our results are a conservative estimate because the MTBS dataset does not include small fires, and we revised the text to state this more clearly.*

Discussion:

9. Can the authors please provide some discussion about how this work relates to the projections of WUI doubling by 2030 (Theobald and Romme 2007). Is that a reasonable trajectory? Or would the observed rates of change in this study lead to a different projected estimate? Also, can the authors speak to the estimate that 84% of potential WUI lands have yet to be undeveloped in the West (Gude et al. 2008). Does this align with your current estimates?

*Response: Thank you, we agree that the comparison with those two studies was missing from our discussion. In response to this comment, we added the following sentence: “*Our findings are generally in alignment with prior studies that had found rapid past WUI growth (Hammer), and widespread potential for future WUI growth (Gude, Theobald), even though absolute numbers are not comparable because of differences in WUI definitions, datasets, and time periods (Stewart).”

10. Page 9: An important conclusion that is not stated is the importance of changing the incentive structure via insurance. As we have floodplain maps there's an opportunity to establish firescape maps that can be used to incentivize changes in where we develop.

*Response: Thank you for this excellent suggestion, which matches a comment by reviewer no. 2, who asked for more concrete solutions. Indeed, we have had discussions with representatives from insurance companies about this very issue in recent weeks. In response to this comment, we added text about changing incentive structures via insurances to the discussion.*

Figures:

11. Figure 1: The call-out boxes of the 3 locations are fascinating. First, it would be wonderful to see some aggregation at the scale of the U.S. to show where the WUI expansion and contraction are happening. The static map of 2010 WUI is highly detailed, yet the focus of the paper is on the change across decades. The state-level information provided in Figure 3 is informative, but there is so much rich detail lost at this scale. I think it would be very valuable to have a figure that provides calculations of % increase from 1990 to 2010 in larger units than census block, but finer than states, perhaps at a 25, 50, or 100 km grid scale. Second, the highlighted regions are an important opportunity to explore how the WUI contributed to the wildfire disasters in Santa Rosa, CA. There are many factors that contributed, but this is an important study that could shed some light on that event. I would recommend the authors show this area, rather than Sacramento, as a way to make the results timely. Note, the legend references Spokane, WA - which must have been in a prior version of the figure. Also, the grey for non-WUI is hard to distinguish from the black, perhaps a lighter grey?

*Response: Thank you for the great ideas how to improve our figures. In response, we added one map that shows the WUI change at the Census block level, and we changed the zoom-in and now show Santa Rosa, CA instead of Sacramento. We also changed the legend, and apologize for the error (Spokane) in our original submission.*

12. Figure 3: As stated above state-level estimates are important, but a lot of interesting detail is washed out. I would recommend 25-100 km grid and aggregating to that.

*Response: We agree that there was a need to present more details, and added the new map at the census block level. In the main manuscript, we opted to retain the state-level map here, because many policy decisions are made at the state level.*

*However, we do see the point that an intermediate resolution is also interesting, and provide a county-level map in the online appendix. In addition, we are making our data available online on our mapserver allowing readers to zoom in to specific areas at the original resolution of the data.*

References in review:

Gude P, Rasker R, Van den Noort J (2008) Potential for future development on fire-prone lands. J For 106(4):198-205

*Response: Thank you for providing this reference!*

Reviewer #2:

Comments:
General Comments

The paper provides a very useful and clear description of the rapid rate of change in size, population, and housing in the Wildland Urban Interface in the US between 1990 and 2010. This rate of change is framed as a particular problem for wildfire risk and management, but is linked (briefly) to other environmental problems. The results are very clear as presented and add a new dimension to the work on and understanding of the WUI, i.e., the rate and drivers of change. The results underscore the importance of housing development as the key driver of change in the WUI.

*Response: Thank you for these very kind words, which are greatly appreciated!*

There is some inconsistency, and even timidness, in the links between the way the problem is framed, the questions that motivate the analysis, and the results as presented. In particular, while the importance of the WUI growth process in affecting "wildfire problems" is mentioned in the title and introduction, the research questions on Page 4 don't mention wildfires at all, despite later inclusion of an analysis of growth within fire polygons of the last 25 years. This link between WUI and wildfires needs to be consistently addressed. The analysis of WUI growth relative to fire polygons needs to be motivated by a research question and the results linked back to how it improves our understanding of the clear growth in WUI for wildfire problems. In other words, I think there is a third question that is addressed and needs to be stated, e.g., something like "How is WUI growth spatial related to recent wildfire locations?"

*Response: Thank you for this suggestion! Re-reading our manuscript in light of this comment, we fully agree, and we added a third research question as suggested.*

Given the claim on page 6 that "The intermix WUI is where wildfire and other environmental issues are particularly vexing" I would have expected and liked to see a breakdown of the fire-polygon analysis (page 7) by WUI growth vis a vis intermix and interface WUI. Were fires, in fact, more common in the intermix, and how was WUI growth in fire polygons distributed amongst intermix and interface areas?

*Response: Thank you very much for this suggestion as well! We agree that a breakdown of the fire polygon analysis by intermix vs. interface WUI is very interesting, and we added this information to the manuscript. Excellent idea!*

The paper provides a very useful empirical result, but misses important context in two ways that I would have liked to see better addressed. I don't think addressing these requires significant additions to length, but does involve some modification to the paper. First, while there is mention of climate change impacts on fire frequency in the first paragraph, the rest of the paper largely drops attention to the implications of this work for climate change adaptation planning. Both WUI growth and climate change will affect wildfire, and this compounding of processes makes this work particularly compelling. Unfortunately, the paper doesn't return to the compounding or the relevance of the work in climate adaptation. I did find myself wondering in the discussion about increasing expenditures on suppression and fire fighting (pg 3) about attribution amongst climate and WUI-growth drivers. The analysis cannot support conclusions along these lines, but I think acknowledging and pointing to the significance of the WUI growth in combination with climate change (more than in the first paragraph, would be helpful.

*Response: We agree that we had failed to return in the discussion to the important point that both climate change and WUI growth are compounding effects increasing wildfire risk. In response, we added the following text to the discussion:*

*“Hence increased wildfire ignitions rates due to WUI expansion will initiate more wildfires in vegetation that is more susceptible to fire spread, leading to larger burned area overall, and possibly more severe fire behavior. This means that WUI growth and climate change together will compound the problems related to wildfires in the WUI.”*

Second, the conclusions of this work, as with others like it refer to "lack of land use planning" (pg 7), and fails to go any further to address the constraints and opportunities there in. On one hand, the authors could address the specific policy mechanisms that could be explored, e.g., zoning to restrict development, density limits on development, vegetation management requirements, and insurance programs. On the other hand, the strong home rule in land use planning that means that planning is done at the local level, and rural communities are often unable or unwilling to pursue programs that restrict property rates. This later condition places serious constraints on any policy response to the concerns raised in the paper. What then are the realistic ways forward?

*Response: Point well taken! The question what are realistic ways forward is very important question indeed. Looking back at our original manuscript, we agree that in avoiding to be prescriptive in our discussion of policies, we ended up indeed a little too cautious, and failed to point out at least options. In response to this comment, we state the following in the revised manuscript:
“As WUI growth continues, there are many management options and policy tools to consider to address both wildfire and other environmental problems. Just as WUI-related problems involve actors (e.g., homeowners, community leaders) at many levels, so too must their solutions involve actors at multiple levels (i.e., local, regional, state, national) (3, 8). Homeowners can reduce their individual fire risk by removing vegetation directly adjacent to their house (i.e., the home ignition zone, (3, 31)), changing roofing and building materials, and following additional Firewise recommendations (32). In order to limit some of the other environmental problems associated with living in the WUI, homeowners can keep cats inside and dogs on a leash, limit fertilizer and pesticide use, and landscape with native plants (9). To reduce wildfire impacts, communities can coordinate fuel reduction efforts, educate homeowners, train firefighters, and establish wildfire management plans. Insurance companies can offer reduced premiums for communities taking mitigation action, to incentivize community-level efforts to reduce wildfire losses. Communities and local jurisdictions could anticipate wildfires and environmental impacts more explicitly when planning future land use, to avoid housing expansion in high-risk wildfire areas and other environmentally sensitive areas (33). State and federal agencies typically do not regulate development directly but can allocate resources to areas experiencing rapid WUI growth, support local and regional planning efforts, and provide research and information necessary to help communities adapt to fire-prone environments. Agencies managing public lands could consider targeted purchases of private inholdings to limit future housing growth within the administrative boundaries of public lands, which has been particularly rapid (34). In summary, there are many concrete management actions and policy responses that can limit the negative effects of WUI growth on wildfire risk and other environmental problems, but changes will require efforts at all levels, i.e., by home owners and community leaders, local and county governments, and state and federal agencies.”*

Specific comments

Pg 3, second paragraph: last sentence is redundant of the first in the same paragraph.

*Response: Agreed, thank you for pointing this out. We replaced the last sentence of that paragraph.*

Pg. 5, first line: mention that the spatial unit of the analysis is 2010 census blocks so the reader doesn't have to fish for it.

*Response: Thank you for this suggestion! We added the information that the spatial units of our analysis were the 2010 Census Blocks in two places in the suggested paragraph, and agree that that level of precision in our writing was lacking.*

Pg. 5, middle second paragraph: The comparison of WUI growth with "any other major land use type" is incorrect. First, the comparison is with change in NLCD types, and these are land cover categories, not land use types. Second, reference to "any other land use" implies inclusion of WUI in a mutually exclusive classification of land use. Because it's not a mutually exclusive scheme, there are many other possible land use classes, some of which may be growing faster than WUI, but you didn't test them all. You could modify to more accurately say "WUI area growth is faster than that of any of the land cover categories included in the NLCD."

*Response: We fully agree, and apologize for the incorrect statement in our original submission. We revised the text as suggested by the reviewer, and are grateful for the very constructive comment.*

Pg. 7: "reduced housing density" needs some explanation. This could be a result of actually loss of housing units or changes in block boundaries (despite harmonization, assumptions in the harmonization process could be faulty and result in spurious reductions). Some indication of which is which would be helpful, even if best guess. If you think actual reductions on the ground are the cause of some, some reference to that process would be helpful.

*Response: Thank you for this comment. The question of why housing density declined is a fascinating one. Our take on this question is that some of these declines are real, and declines are also reported at the county scale (i.e., a scale for which no harmonization is necessary). But yes, some of these declines may be artefacts. However, they are more likely to be artefacts of the Census data itself, rather than the harmonization process, which was designed to be conservative and to allocate housing units so that changes (both increases and decreases) were minimized. As to how prevalent those to causes are, we really don’t know though. In response to the comment, we thus added the following sentence: “*Housing density may have declined due to actual removal of housing units, but also potentially due to enumeration errors in the Census data.”

p. 8, bottom of first paragraph: replace "as in whole" with "as a whole." Also, reconcile reduced % growth of all three measures 2000-2010 vs 1990-2000 (fig 2) with increased numbers referenced here.

*Response: We replaced the text as suggested, thanks. The difference of lower growth in the figure, versus the text stating higher numbers, was due to the fact that the figure shows growth in percent, but the text referred to absolute growth, i.e., the total number of homes. While growth in percent was higher in the 1990s (as shown in the figure), the total number of homes added to the WUI was higher in the 2000s. The reason the 2000s growth in percent was lower was that the base, i.e., the number of houses in 2000, was higher than in 1990. In response to the comment, we revised the text and now state that* ***absolute*** *growth was higher in the 2000s. Thank you for alerting us to this confusing statement in our original manuscript.*