Response to Anonymous Referee #2

We greatly appreciate the reviewer for providing constructive comments, which have helped us improve the paper quality significantly. We have addressed all of the comments carefully, as detailed below. The original comments are in black and our responses are in blue. Major changes made in the revised manuscript are in red color.

Major Comments:

Comment 1:

Introduction Lines 82-100: The authors selectively represent the literature on fire-count based crop residue burning emission inventories and fail to discuss their shortcomings. Most notably they fail to discuss the work of Lui et al. 2019 and 2020 (Tianjia Liu et al 2019 Res. Commun. 1 011007 DOI 10.1088/2515-7620/ab056c, Tianjia Liu et al 2020 Atmospheric Environment X https://doi.org/10.1016/j.aeaoa.2020.100091) which showed relatively high emission error which can be more than 95% of the total ignitions in particular in scenarios where farmers deploy partial burns (row burns or heap burns) instead of burning the full field to avoid fire detection. Even in the case of full burns farmers avoid detection via shift the timing of the burn to avoid the satellite overpasses, or preferably burn when the sky is overcast/very hazy to avoid detection. These papers have also dealt with algorithms to correct for the under detection.

Response:

We have expanded the discussion of the shortcomings of developing emissions inventories based on burned area or fire spot counts in the *Introduction*, alongside

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relevant literature, which reads: "However, the aforementioned datasets remain inadequate for accurately capturing small-area, short-duration open straw burning, particularly in scattered farmlands (Wiedinmyer et al., 2014). It should also be noted that meteorological disturbances, such as cloud cover and rainfall, can reduce the accuracy of these products (Schroeder et al., 2014; Ying et al., 2019). Furthermore, straw burning during non-satellite transit periods, on cloudy days, at night, and under heavy haze may not be captured in these datasets (Liu et al., 2020). For example, Liu et al. (2019) found that same-day omission error of MODIS burned area product could be as high as 95% for agricultural fire detection during the post-monsoon season in northwestern India."

Subsequently, we have also added algorithms to correct for the under-detection, which reads: "The FRP algorithm has been optimized by integrating multi-source satellite fire spot data, field survey data, and ground observation data, and combined with advanced modeling techniques to improve the accuracy of emission inventory for open straw burning. For example, Liu et al. (2020) revised FRP by combining household survey results with satellite observations in northern India to capture small fires, fill cloud/haze gaps in satellite observations, and adjust partial-field burns and diurnal cycle of fire activity disturbances. Yang et al. (2020) improved the FRP algorithm by calibrating the contributions of open straw burning to ground observation data in Northeast China based on model simulation results using the coupled Weather Research and Forecasting model and Community Multiscale Air Quality (WRF-CMAQ) model."

Comment 2:

Introduction Lines 82-100: The authors fail to discuss the strength and weaknesses of various fire detection satellite products available particularly with respect to crop residue burning fires which in the case of China include a geostationary satellite (Chen et al. 2022 https://doi.org/10.1016/j.atmosenv.2021.118838, Zhang, T., de Jong, M. C., Wooster, M. J., Xu, W., and Wang, L.: Trends in eastern China agricultural fire emissions derived from a combination of geostationary (Himawari) and polar (VIIRS) orbiter fire radiative power products, Atmos. Chem. Phys., 20, 10687–10705, https://doi.org/10.5194/acp-20-10687-2020, 2020.). It needs to be noted that the selected product MODIS has the lowest detection efficiency of al all available products, but even the most high resolution product VIIRs still under-detects crop residue fires compared to actual ignitions.

Response:

We have added a discussion of the strengths and weaknesses of various fire detection satellite products in *the Introduction*, as well as relevant literature, as follows: "MODIS and VIIRS, both operating in polar orbits, provide only two observations per day. MODIS has provided 1 km resolution fire data since 2000, which is suitable for long-term trend analyses (Chen et al., 2012); while VIIRS has provided fire data at a 375 m resolution since 2012, which is more suitable for detecting small fires (Chen et al., 2022). Himawari-8 (Geostationary orbit) has provided 10-minute temporal resolution and 2 km spatial resolution fire data since 2015, ideal for real-time monitoring across

the Asia-Pacific region (Zhang et al., 2020). However, the aforementioned datasets remain inadequate for accurately capturing small-area, short-duration open straw burning, particularly in scattered farmlands (Wiedinmyer et al., 2014)."

The MODIS fire spot product (version 6.1), which provides the longest historical data and high spatial resolution, and improved detection of small fires (https://modis-fire.umd.edu/files/MODIS_C6_C6.1_Fire_User_Guide_1.0.pdf), is the most suitable data for the long-term spatial and temporal distribution characterization of open straw burning in this study. Moreover, the modified FRP method selected in this study corrects for emissions based on ground observation data, which can effectively compensate for emissions from fires missed by remote sensing detection (Yang et al. 2020)."

Comment 3:

Introduction Lines 82-100: The authors also fail to discuss the strategy of developing hybrid inventories (Kumar et al. 2021 https://doi.org/10.1016/j.scitotenv.2021.148064) that use the more accurate bottom-up data from field surveys to estimate the total amount of crop residue burned and the resulting emissions but use the spatio-temporal patterns in fire counts to distribute these emissions in space and time.

Response:

We have expanded a discussion on the strategy of developing hybrid inventories in the *Introduction*, supported by relevant literature, as follows: "Several studies have also developed a hybrid inventory strategy using the "bottom-up" approach to allocate

GHGs emissions spatially and temporally based on BA or FC (Jin et al., 2018; Zhang et al., 2019; Kumar et al., 2021). These approaches have significantly improved the spatiotemporal resolutions of the emission inventories for open straw burning (Wu et al., 2023)."

Comment 4:

Methods: While the authors discuss both VIIRS and MODIS fire counts in their introduction they only use MODIS fire counts in their work. Crop residue burning fires are both small and transient and the relatively large 1 x 1 km footprint of the MODIS satellite leads to high under detection. Shifting from using MODIS towards using VIIRS typically doubles the crop residue burning estimates. For robust estimates the authors need to at the very least use both these satellites and the geostationary satellite and contrast the results (see: Tianjia Liu et al 2020 Atmospheric Environment X https://doi.org/10.1016/j.aeaoa.2020.100091 for a case study from India)

Response:

We have extracted VIIRS fire spots using the novel method and estimated CO_2 emissions from open straw burning through the modified FRP algorithm. This algorithm can effectively correct the FRP detection errors between MODIS and VIIRS. We have also compared the results of calculations based on these two data in *Section 3.3*, which reads "Our estimated total CO_2 emissions from 2012 to 2020 with MODIS (161 Tg) or with VIIRS (165 Tg) were much lower than that (~ 523 Tg) estimated by Liu et al. (2022), the latter was based on a modified FRP algorithm and fire spot

products by VIIRS, which has limitations in its traditional straw extraction methods in accurately identifying fire spots during certain times of the year."
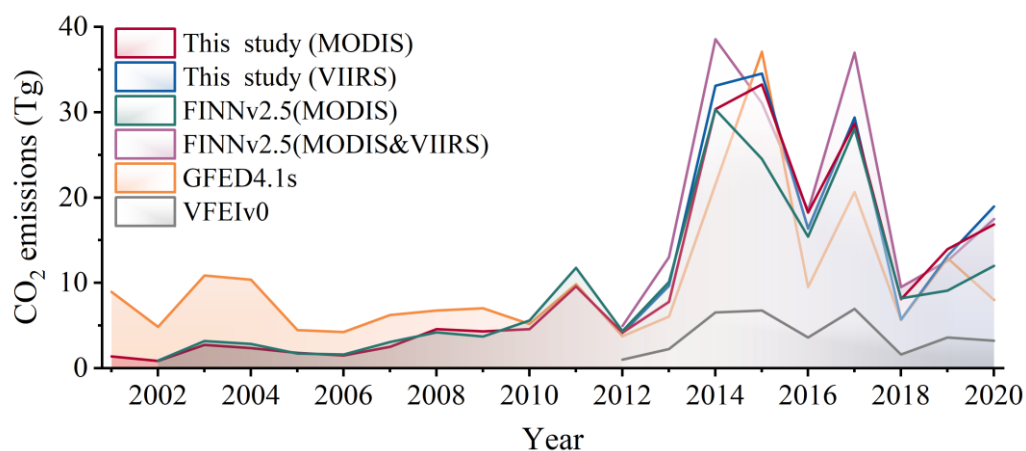

Fig. 6 Annual total emissions of CO_2 from open straw burning (agricultural waste burning) in Northeast China from this study with MODIS (red, 2001-2020) and VIIRS (blue, 2012-2020), the Fire Inventory from NCAR version 2.5 (FINNv2.5) with MODIS-only (green, 2002-2020), FINNv2.5 with MODIS and VIIRS (purple, 2012-2020), Global Fire Emissions Database Version 4.1 (GFED4.1s) (orange, 2001-2020), and VIIRS-based Fire Emission Inventory version 0 (VFEIv0) (grey, 2012-2020).

The Himawari-8 fire spot data is unsuitable for the modified FRP algorithm in this study due to its high temporal resolution and low spatial resolution, which can result in missed small fires and duplicated fire records.

Comment 5:

Results and Discussions: The authors need to contrast their MODIS based estimates with VIIRS based estimates arrived at using the same methodology. The 5% overestimation due to the wrong inclusion of off-season fire pales in comparison to the

likely underestimation that the usage of such a coarse fire product causes. The number

of detected crop residue fires more than double with the shift to VIIRS.

Response:

We have added a comparison of CO_2 emissions based on MODIS data with those based on VIIRS data in *Section 3.3*, revealing a small emissions gap.

The novel method we propose, which incorporates crop cycle information into the extraction and classification of fire spots from open straw burning not only improves the accuracy of emission inventories but also provides regulators with accurate characterization of the spatial and temporal distribution of various straw burning. We estimated emissions of GHGs using a modified FRP algorithm that is based on FRP detection rather than the number of fire spots.

Comment 6:

Results and Discussions: While comparing their data with existing emission inventories such as FINN the authors use the old MODIS based version of the inventory instead of the current VIIRS base FINN version of the inventory v2.5 the authors need to shift their comparison to the current version (Wiedinmyer, C., Kimura, Y., McDonald-Buller, E. C., Emmons, L. K., Buchholz, R. R., Tang, W., Seto, K., Joseph, M. B., Barsanti, K. C., Carlton, A. G., and Yokelson, R.: The Fire Inventory from NCAR version 2.5: an updated global fire emissions model for climate and chemistry applications, Geosci. Model Dev., 16, 3873–3891, https://doi.org/10.5194/gmd-16-3873-2023, 2023). It is important to note that FINNv2.5 estimates are significantly higher than FINNv1.5

estimates and that the authors are making their own estimate look better by cherry picking the old version to compare their estimate with.

Also the authors need to compare with other inventories e.g. GFED, and VFEIv0 Ferrada, G. A., Zhou, M., Wang, J., Lyapustin, A., Wang, Y., Freitas, S. R., and Carmichael, G. R.: Introducing the VIIRS-based Fire Emission Inventory version 0 (VFEIv0), Geosci. Model Dev., 15, 8085–8109, https://doi.org/10.5194/gmd-15-8085-2022, 2022

The authors need to compare with other regional estimates e.g. Zhang, T., de Jong, M. C., Wooster, M. J., Xu, W., and Wang, L.: Trends in eastern China agricultural fire emissions derived from a combination of geostationary (Himawari) and polar (VIIRS) orbiter fire radiative power products, Atmos. Chem. Phys., 20, 10687–10705, https://doi.org/10.5194/acp-20-10687-2020, 2020.

Response:

We have added comparisons of the results of this study with emission inventories such as FINNv2.5, GFED4.1s, and VFELv0, as well as other regional studies, which reads: "Our estimated CO_2 emission from 2002 to 2020 in Northeast China (196 Tg) was slightly lower than that (195 Tg) estimated by Global Fire Emissions Database Version 4.1 (GFED4.1s) by van der Werf et al. (2017), and slightly higher than that (181 Tg) estimated from the Fire Inventory from NCAR version 2.5 (FINNv2.5) by Wiedinmyer et al. (2023), which addresses the underestimation of open biomass burning in China

by the older version FINNv1.5 (Stavrakou et al., 2016; Yang et al., 2020) (**Fig. 6**). However, our estimated total CO_2 emission from 2012 to 2020 was significantly higher than that (35.6 Tg) estimated by VIIRS-based Fire Emission Inventory version 0 (VFEIv0) by Ferrada et al. (2022), which relies on the traditional FRP algorithm (Fig. 6). Furthermore, Northeast China surpassed East China (27.1 Tg) as the highest emitter from open straw burning in China since 2014, with CO_2 emissions reaching 30.4 Tg (Zhang et al. 2020)."

Comment 7:

Results and Discussions: The authors need to discuss whether increase in detection avoidance strategies (e.g. shifting of preferred hour of the day for burning in comparison to the MODIS /VIIRS overpasses and or the office hours of officials tasked with enforcing the burning ban) played a role in the "reduction" in crop residue burning cases. This can be done by contrasting between the local time of the detected crop residue burns from the geostationary satellite with the overpasses of the other satellites (See Figure 9 Chen et al) such Figures can be drawn for different years to detect time shifts.

Response:

We have added a discussion in *Section 3.1*, which reads: "However, the "sudden drop" in fire spots should also be partially attributed to strategies employed by farmers to avoid detection by satellite and government regulations, such as burning straw on smaller scales and in more dispersed areas, or during non-transit times of the satellites

(Liu et al. 2019; Liu et al. 2020). Chen et al. (2022) also found that farmers in East China frequently burned straw in 2019 during non-transit times of MODIS/VIIRS satellites, as indicated by Himawari satellite data."

Comment 8:

Results and Discussions: The authors need to discuss to which degree the shift to smaller fires and/or dispersed fires may have contribute towards the drop in fire counts and whether the drop is due to actual reductions in the scale of the activity or an increasing under detection of crop residue burning fires. Synchronized burns of several neighboring fields within the same satellite footprint are much easier to detect with satellites than small dispersed fires. Is the drop in detected fires actually matched by air quality improvements of the same scale? If there is a shift in the fire detection efficiency then hybrid inventories that combine bottom up estimates of the amount burnt with satellite tools that help distributing the emission with the correct spatio-temporal patterns may actually be superior.

Response:

We have investigated whether the decline in detected fire spots corresponds to proportional improvements in air quality, which reads: "To further verify the reliability of the "sudden drop" in fire spots in Northeast China, we analyzed the trend of particulate matter concentrations (PM_{10} and $PM_{2.5}$) during the periods of open straw burning from 2014 to 2020 in Northeast China (**Fig. S2**). Atmospheric particulate matter concentrations during autumn open straw burning in Northeast China decreased

with a "sudden drop" in fire spots (**Fig. S2(c)**). However, a similar trend was not observed in spring (**Fig. S2(b)**), possibly due to limitations in fire spot detection by current satellite techniques and avoidance strategies."
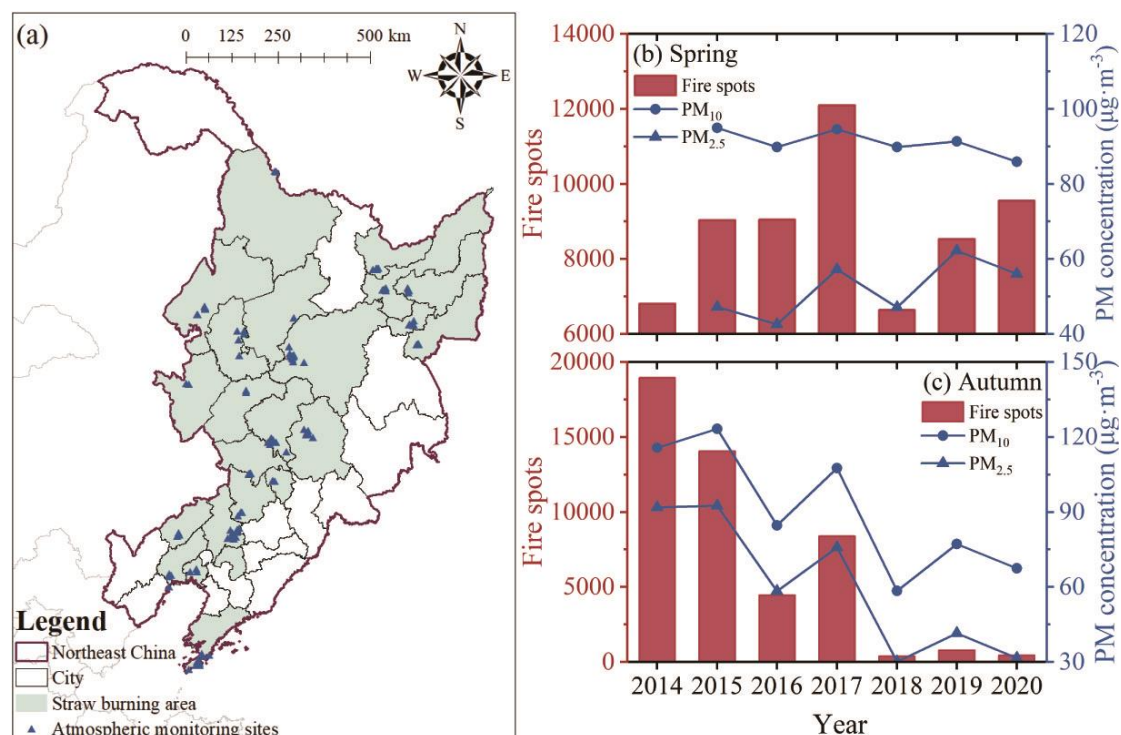

Fig. S2 (a) Spatial distribution of atmospheric monitoring sites in straw burning areas in Northeast China; (b) and (c) represent the variations of fire spots and particulate matter (PM$_{10}$ and PM$_{2.5}$) concentrations (http://www.cnemc.cn) during the period of open straw burning in spring and autumn, respectively, in Northeast China from 2014 to 2020.

We have added the advantages of hybrid inventory, which reads: "Kumar et al. (2021) suggested that a hybrid inventory, which accurately allocates emissions estimated using the "bottom-up" approach based on satellite data, may be more advantageous in this scenario."