Response to Anonymous Referee #1

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:

Section 3.1 and Figure 2 – The authors have not described how the errors were calculated. Furthermore, the justification of some of the coefficients needs to be further detailed and not simply justified by a previous citation. For example, line 185.

Response:

We have added a description of the traditional method for fire spot extraction in *Section 2.1*, which reads: "Furthermore, fire spots from open straw burning were extracted using the traditional method that does not integrate crop cycle information. Only the current year's ChinaCropArea1 km data was extracted to Fire spots (MCD14ML). Then, fire spots occurring on agricultural land with growing crops were identified as open straw burning."

We have also added a description of the calculation method for the error in ***Fig. 2***, which reads: "The error is calculated as the number of fire spots identified by the traditional method minus those extracted by the novel method."

We have added a description of the justification of the coefficients selected in *Section*

2.2, which reads: "*α* is a correction factor used to adjust for *FRP* detection errors between MODIS and VIIRS, which is given a value of 2.5 following Vadrevu and Lasko (2018), indicating that the *FRP* VIIRS sum is 2.5 times of the *FRP* MODIS sum;" and "f_{FRP} is a correction factor that is used to adjust the underestimated emissions by fire spots, and Yang et al. (2020) determined an optimal value of 5 for f_{FRP} by calibrating the contributions of open straw burning to ground observation data in Northeast China using WRF-CMAQ

Comment 2:

Figure 3c – This is a very interesting plot and a unique way to show the fire activity. However, in Spring 2014, there was a very distinct cut-off with a yellow section at the start of the cut-off. This tells me that this could be a data artifact, and the authors should re-download the data to see if there was a disruption with the data download. The science quality MCD14ML data downloaded from the University of Maryland's FUOCO SFTP site is the more robust data and contains the "type" column which the authors should use to filter out any non-vegetation fire activity within the cropland area (see User Guide section 5.5 and others - https://modis-fire.umd.edu/files/MODIS_C6_C6.1_Fire_User_Guide_1.0.pdf).

Response:

We re-downloaded science quality MCD14ML data from the University of Maryland's FUOCO SFTP site, which are described in the revised manuscript as follows: "The MODIS fire product (MCD14ML, Collection 6.1) was selected from 1 January 2001 to

31 December 2020 for the whole region of Northeast China (Giglio et al., 2016, sftp://fuoco.geog.umd.edu)."

We then filtered out any non-vegetation fire activity within the cropland area, which is described in *Section 2.1* as follows: "The dataset, with a spatial resolution of about 1 km^2, includes essential variables, such as latitude, longitude, acquisition date and time (in UTC), satellite (Aqua or Terra), FRP, and fire type (presumably vegetation fire, active volcano, other static land source, and offshore), among others (https://modis-fire.umd.edu/files/MODIS_C6_C6.1_Fire_User_Guide_1.0.pdf). Non-vegetation fire activities (active volcano, other static land source, and offshore) were then filtered out from the selected dataset for subsequent analysis."

Subsequently, we re-analyzed the spatial and temporal distributions of fire spots, the emission inventory of GHGs, and the driving factors of open straw burning based on the corrected fire spot data in *Sections 3.1*, *3.2*, and *3.4*, respectively.

In **Fig. 3(c)**, the distinct yellow cut-off observed in Spring 2014 was not a data artifact caused by errors in the fire spot data, but rather caused by the expansion of the bean distribution data from Heilongjiang Province to the whole region of Northeast China. We have added a clarification in *Section 2.1*, which reads "Considering that Northeast China is a major bean-producing area, we also compiled bean distribution datasets (Li et al., 2021; Xuan et al., 2023). However, bean distribution in Jilin and Liaoning provinces was not recorded during 2001-2012 in this dataset. The dataset was extended to the whole region of Northeast China (Heilongjiang, Jilin, and Liaoning provinces) after 2013."

Subsequently, we increased the resolution of the frequency distribution of burning dates for various straws from 10 days to 1 day to mitigate this error (**Fig. 3**), and modified the results for the frequency distribution of burning dates for bean straw in *Section 3.1*, as follows: “During **Period I** (2003-2012), the spring and autumn burning dates of bean straw in Heilongjiang Province were concentrated from mid-March to late April (DOY range of 70 to 120) and from early October to mid-November (DOY range of 270 to 320), respectively (**Fig. 3(c)**). During 2013-2020, the spring burning dates of bean straw in Northeast China were concentrated between early February and late April (DOY range of 30 to 120), while the autumn burning dates remained consistent with those during Period I in Heilongjiang Province (**Fig. 3(c)**).”

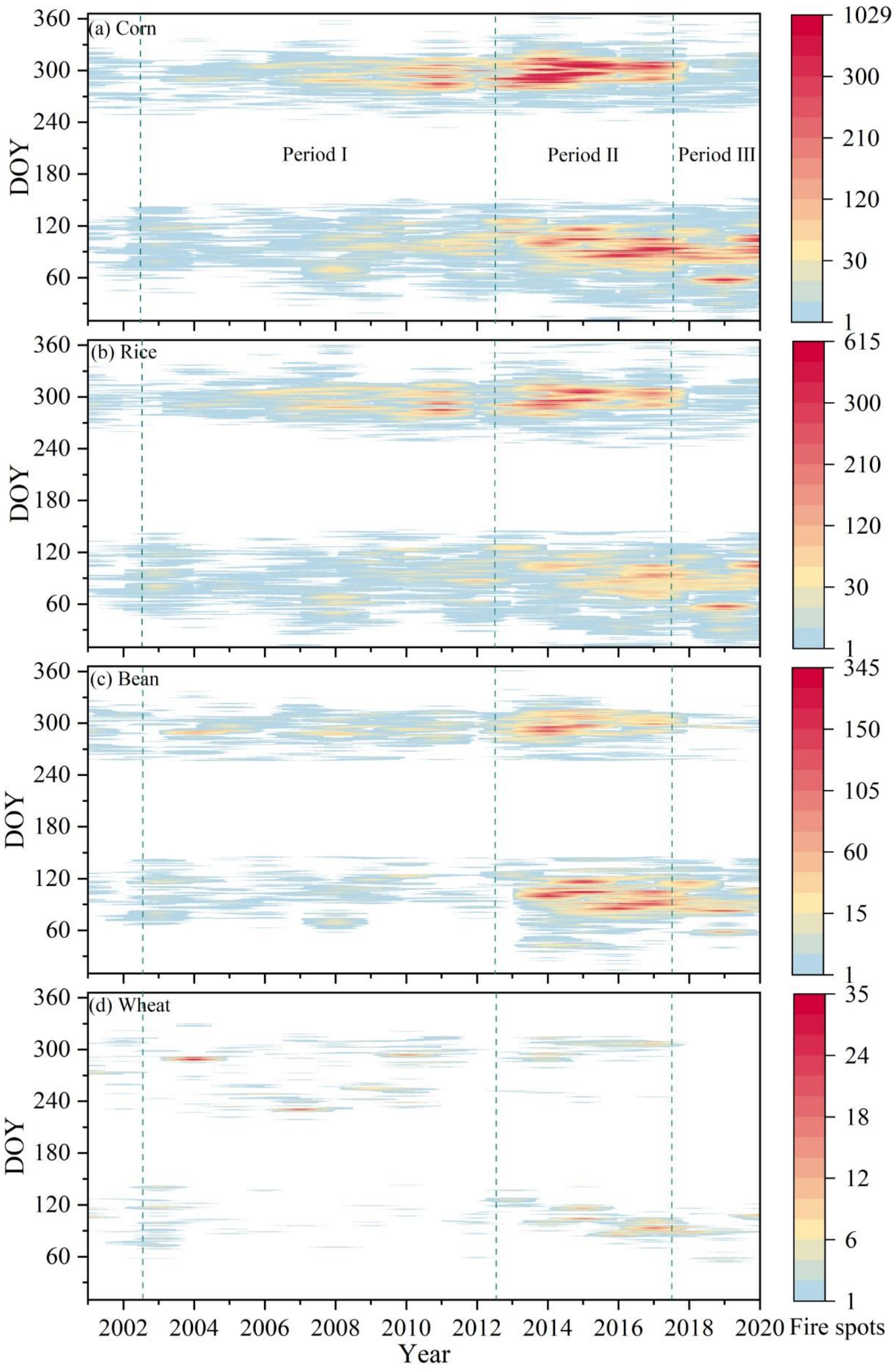

Fig. 3 The daily frequency distribution of fire spots from various straws burning: (a), (b), (c), and (d) represent corn, rice, bean, and wheat straw, respectively. Note: The x-axis is Year; the y-axis is DOY; and the daily number of fire spots for straw burning ranges from 1 to 1,029 for

corn, 1 to 615 for rice, 1 to 345 for beans, and 1 to 35 for wheat.

Comment 3:

2001 - 2003 data: The authors should consider only analyzing data from 2003 (or 2004 for a full year) onwards since both Aqua and Terra satellites were available. The lower number of fires in 2001 – 2003 is due to the Terra-only time period. All the statistics (especially the ones related to fire counts) and the trend analysis will be skewed because the first few years have significantly fewer fires purely based on the Terra-only period. Also, there was a 2-week window in August 2020 where MODIS Aqua failed, and therefore, you will be missing ~ 2 weeks' worth of fire counts within that peak burning time period (Section 8.4 - /https://modis-fire.umd.edu/files/MODIS_C61_BA_User_Guide_1.1.pdf). The authors need to add this as a limitation to the text.

Response:

We have added the limitations of MCD14ML in *Section 2.1*, which reads: "To clarify, the MCD14ML underestimated fire spots in 2001 and 2002 because only the Terra satellite was operational before 3 July 2002. Therefore, data for the years of 2003 to 2020 were used for developing annual emission inventories, with relevant results for 2001 and 2002 as reference only. Also, a failure of the Aqua satellite on 16 August 2020 led to the loss of fire spot data for about two weeks (https://modis-fire.umd.edu/files/MODIS_C61_BA_User_Guide_1.1.pdf). However, as August is a crop-growing period in Northeast China, this failure would not lead to an underestimation of fire spots from open straw burning."

Comment 4:

Figure 5 and text - All trend analysis will be skewed because of 2001 – 2003 data. Trends should just be considered from 2004 onward since Aqua data was only available from July 2003.

Response:

We have revised **Fig. 5** and the accompanying text to analyze only the results for 2003-2020, which reads: "During **Period I** (2003 - 2012), average annual CO_2-eq emission was at 4.20 Tg, and the cumulative CO_2-eq emission amounted to 42.0 Tg. During **Period II** (2013 - 2017), average annual CO_2-eq emission increased substantially to 26.1 Tg, and the cumulative emission during this period amounted to 130 Tg, which accounted for 59.9% of the total emissions over the two decades. During **Period III** (2018 - 2020), average annual CO_2-eq emissions decreased significantly to 14.3 Tg, and the cumulative emission during this period amounted to 42.8 Tg (**Fig. 5(a)**). ...... The combustion of corn and rice straw were identified as the primary contributors to CO_2-eq emissions, accounting for 51.1% and 30.8%, respectively, of the total emissions (**Fig. 5(b)**). Specifically, corn straw burning released 99.6, 9.06, and 2.42 Tg, while rice straw burning released 61.8, 3.78, and 1.27 Tg of CO_2, CO_2-eq for CH_4, and CO_2-eq for N_2O, respectively."

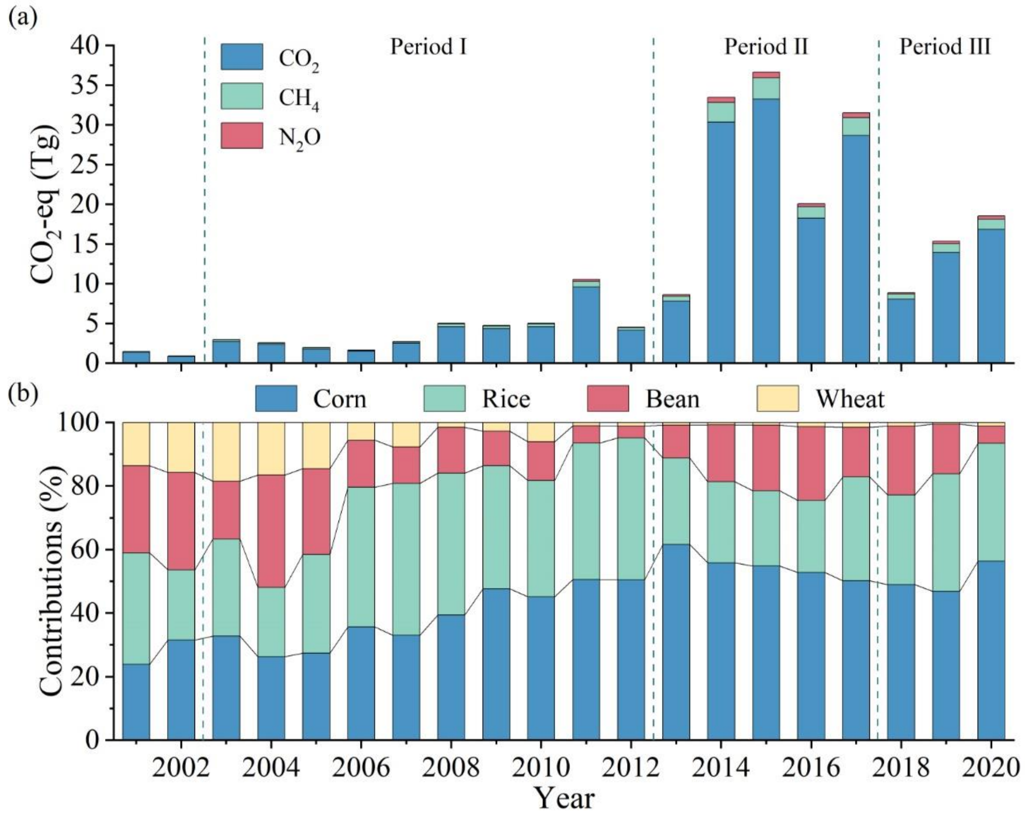

Fig. 5 (a) Regional total annual CO_2-eq emissions and (b) percentage contributions from open burning of individual crop straw type.

Comment 5:

Limitations and caveats: The authors need to add a section outlining the above-mentioned limitations and including the limitations of mapping crop residue burning using current remote sensing technology.

Response:

We have added a more formal section to outline the limitations regarding this novel method and remote sensing techniques in *Section 3.3*, which reads: "Although this study effectively improved the accuracy of emission inventory for open straw burning through the novel method that integrates crop cycle information into extraction and classification of fire spots and the modified FRP algorithm, certain limitations still exist. The uncertainty in this study stems mainly from the inherent limitations of satellite fire detection systems. The MODIS fire spot product, although widely used, is limited by its temporal resolution and tends to miss transient or small-scale fires. In addition, straw burning during non-satellite transit periods, on cloudy days, at night, and under heavy haze further exacerbates the underestimation of fire incidence, leading to potential gaps in emission inventories.

Additionally, the novel method that integrates crop cycle information into extraction and classification of fire spots presents a promising advancement. However, its applicability is constrained to regions where comprehensive and detailed crop data are available. In countries or regions lacking such agricultural information, this method may face challenges, thereby limiting its broader applicability. These factors underscore the need for continued refinement of satellite detection technologies and the expansion of agricultural data collection efforts to reduce uncertainties and enhance the robustness of emission inventories on regional to global scales."

Comment 6:

Validation or product intercomparison: The authors need to include a more formal section on validating their results and comparing them against other products. Are there other remote sensing sensors or on-the-ground station data that the authors can use to include a more high-resolution comparison?

Response:

We have added a more formal section to validate the results and compare them with other products 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. 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).”

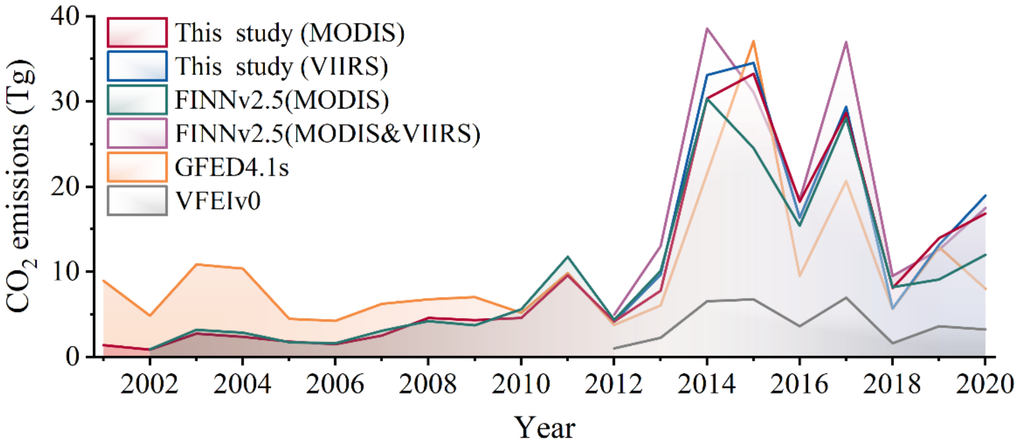

Fig. 6 Annual total emissions of CO$_2$ from open straw burning (agricultural waste burning) in Northeast China from this study with MODIS (red, 2001-2020) and VIIRS (blue, 2012-2020), the Fire Inventory from NCAR version 2.5 (FINNv2.5) with MODIS-only (green, 2002-2020), FINNv2.5 with MODIS and VIIRS (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).

Minor Comments:

Comment 7:

Line 36: change “elevated” to “evaluated”; Line 61: change "remains to be prevalent” to “remains prevalent”; Line 132: change to “China”; Line 422: change to “Period”.

Response:

We have corrected these grammatical and spelling errors and thoroughly checked the manuscript.

Comment 8:

Figure 3 (and others) - Make a note in the caption that the y-axis is different for each crop or that the scales are different.

Response:

We have added notes in the caption, which reads: “**Fig. 3** The daily frequency distribution of fire spots from various straws burning: (a), (b), (c), and (d) represent corn, rice, bean, and wheat straw, respectively. Note: The x-axis is Year; the y-axis is DOY; and the daily number of fire spots for straw burning ranges from 1 to 1,029 for corn, 1 to 615 for rice, 1 to 345 for beans, and 1 to 35 for wheat.”

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 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.”

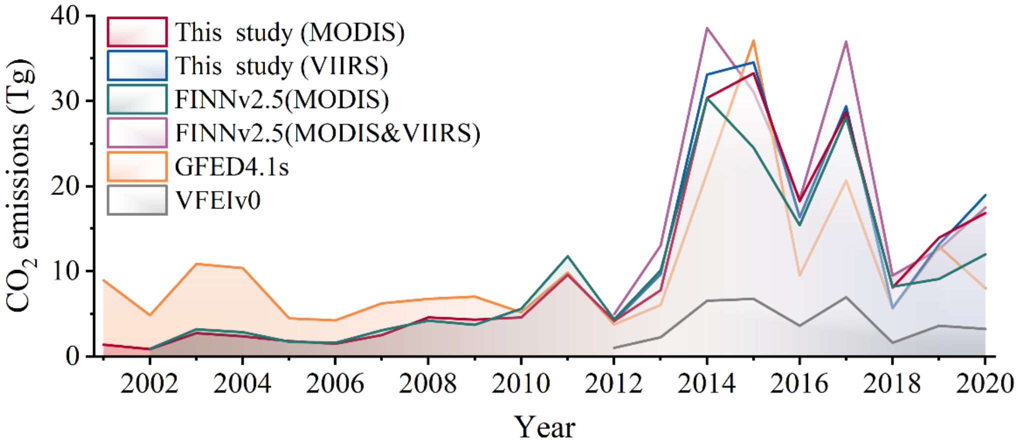

Fig. 6 Annual total emissions of CO_2 from open straw burning (agricultural waste burning) in Northeast China from this study with MODIS (red, 2001-2020) and VIIRS (blue, 2012-2020), the Fire Inventory from NCAR version 2.5 (FINNv2.5) with MODIS-only (green, 2002-2020), FINNv2.5 with MODIS and VIIRS (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.”

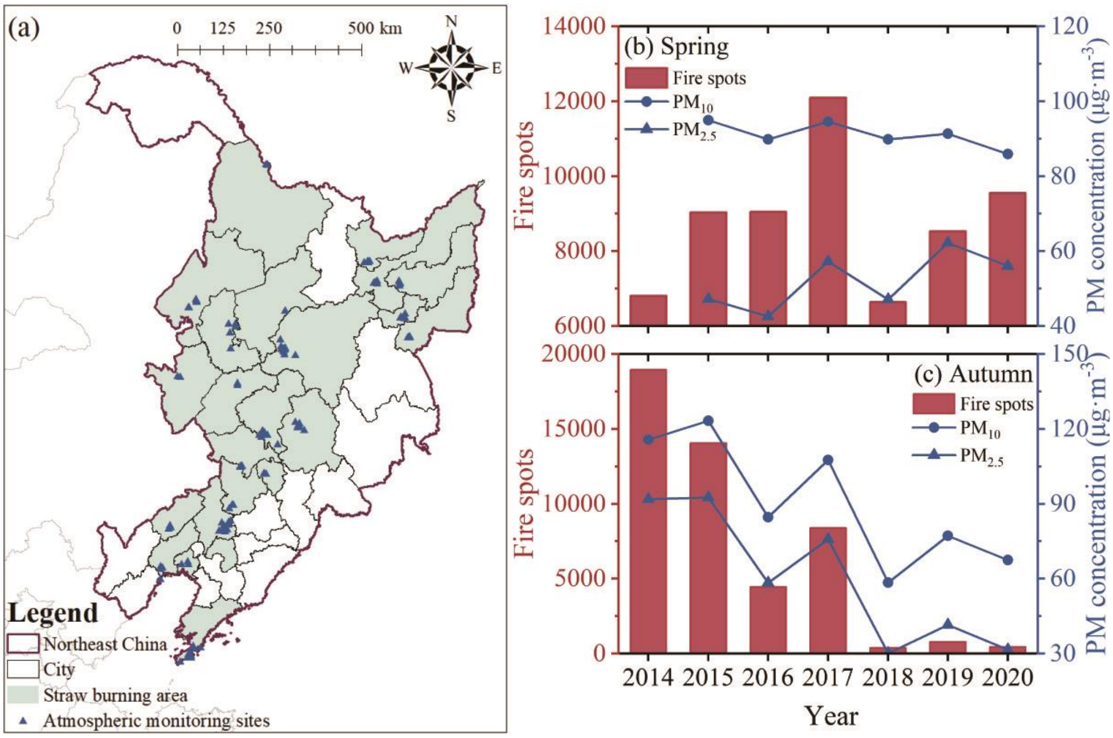

Fig. S2 (a) Spatial distribution of atmospheric monitoring sites in straw burning areas in Northeast China; (b) and (c) represent the variations of fire spots and particulate matter (PM_{10} and $PM_{2.5}$) concentrations (http://www.cnemc.cn) during the period of open straw burning in spring and autumn,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