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Title: Rice residue burning trajectories in Eastern India: Current realities, scenarios of change, and implications for air quality

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Abstract:

In 2019, the Government of India launched the National Clean Air Program (NCAP) to address the pervasive problem of poor air quality and the adverse effect on public health. Coordinated efforts to prevent agricultural burning of crop residues in Northwestern IGP (Indo-Gangetic Plain) have been implemented, but the practice is rapidly expanding into the populous Eastern IGP states, including Bihar, with uncertain consequences for regional air quality. This research has three objectives: (1) characterize historical rice residue burning trends since 2002 over space and time in Bihar State, (2) project future burning trajectories to 2050 under 'business as usual' and alternative scenarios of change, and (3) simulate air quality outcomes under each scenario to describe implications for public health. Six future burning scenarios were defined as maintenance of the 'status quo' fire extent, area expansion of burning at 'business as usual' rates, and a Northwest IGP analogue, of which both current rice yields and plausible yield intensification were considered for each case. The Community Earth System Model (CESM v2.1.0) was used to characterize the mid-century air quality impacts under each scenario. These analyses suggest that contemporary Bihar State burning levels contribute a small daily average proportion (8.1%) of the fine particle pollution load (i.e., $PM_{2.5}$, particles $< = 2.5$ µm) during the burning months, but up to as much as 62% on the worst of winter days in Bihar's capital region. With a projected 142% 'business as usual' increase in burned area extent anticipated for 2050, Bihar's capital region may experience the equivalent of 30 $PM_{2.5}$ additional exceedance days, according to the WHO standard (24-hour; exceedance level: 15 µg/m^3), due to rice residue burning alone in the October to December

period. If historical burning trends intensify and Bihar resembles the Northwest States of Punjab and Haryana by 2050, 46 days would exceed the WHO standard for $PM_{2.5}$ in Bihar's capital region.

1. **Introduction**

Rice residue burning occurs from October to December in the Northwestern Indo-Gangetic Plain (IGP), significantly contributing to poor regional air quality conditions during the fall and winter months (Liu et al., 2018; Montes, Sapkota, & Singh, 2022; Mor, Singh, Bishnoi, Bhukal, & Ravindra, 2022). In the late fall period when regional air quality is at its nadir, rice residue burning contributes to as much as 42% of the fine particulate matter ($PM_{2.5}$) – the most damaging air pollutant to public health (Bikkina et al., 2019). Other estimates for Delhi, suggest that fires contribute a range, depending on the method, of 7.0%–78% of the maximum observed $PM_{2.5}$ enhancements (i.e., pollution levels above an anthropogenic baseline) during the post-monsoon burning season (Cusworth et al., 2018).

Estimates suggests that $PM_{2.5}$ alone causes as many as 16,200 premature deaths annually in New Delhi (Guttikunda & Goel, 2013), while also contributing to a host of additional acute and chronic public health concerns ranging from respiratory infections to lung cancer (Nair, Bherwani, Mirza, Anjum, & Kumar, 2021). Residue burning also increases greenhouse gas emissions while degrading soil health and the production potential of agricultural systems (Jain, Bhatia, & Pathak, 2014; Pathak, Singh, Bhatia, & Jain, 2006).

While the practice of rice residue burning is pervasive in the dominant rice-wheat systems of the Northwest IGP (Shyamsundar et al., 2019), it is much less common in these same cropping systems in the Eastern IGP region of India (i.e., the states of West Bengal, Bihar, and adjacent areas of Uttar Pradesh). In the Northwest, factors such as combine harvesting (Kumar, Kumar, & Joshi, 2015; Liu et al., 2019), a shortening planting window for wheat, and crop intensification help perpetuate this practice (Balwinder-Singh, McDonald, Srivastava, & Gerard, 2019). Despite dedicated efforts to reduce burning through a combination of financial incentives and legal sanctions, there is little evidence from the Northwest that the practice is receding. Just as worrisome, drivers that have shifted the valorization of rice residues from a resource to a waste product in the Northwest may now be emerging in the Eastern IGP (Hindustan Times, 2021).

Given its relatively high rates of rural poverty and capacity for agricultural-led growth, the Eastern IGP is a development and food security priority region for the Government of India through initiatives like BGREI (Bringing the Green Revolution to Eastern India) that focus on enhancing the productivity of agricultural systems through technological change. Program initiatives in Bihar have included efforts related to direct seeded rice, zero tillage wheat, distribution of improved seed varieties, and assistance for farm machinery and implements (Pathak, Panda, & Nayak, 2019). The densely settled state of Bihar is of particular interest with the 2019 census documenting a population exceeding 124 million. With the state's capital and largest city, Patna, already among the most air-polluted metropolitan regions in India (Nair et al., 2021), a rapid expansion of residue burning may lead to significant consequences for public health. At present, Patna $PM_{2.5}$ concentrations exceed the daily NAAQS (National Ambient Air Quality Standards) threshold around 77% of the winter days (Arif, Kumar, Kumar, Eric, & Gourav, 2018) and contributes an estimated 1% to all-cause mortality rates (Nair et al., 2021).

The Bihar State government is aware of the risks associated with increasing agricultural burning, but the current extent of the practice and plausible scenarios of change have not yet fully informed state

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policies (Raj, 2018). The emergence of burning as a 'locked-in' problem without simple solutions in the Northwest IGP highlights the importance of preventative action aimed at avoiding burning in the Eastern IGP rather than attempting to reverse the practice only after it is broadly adopted (Downing et al., 2022). Technological lock-in is present in many economic sectors, including agricultural (Magrini, Béfort, & Nieddu, 2018), and is perpetuated by a series of dependency factors that make the technology difficult to disentangle from other dimensions of the system (Geels, 2011). For example, as access to mechanization technologies such as combine harvesting expand, burning is often practiced post-harvest as a quick and inexpensive method for clearing loose residues that remain in the field. New combine users often become 'locked-in' to burning because transitions to the combine have been made and there are few economically viable alternatives for residue management. Consequently, burning becomes an enabler for broader technological change that is difficult to displace.

By conceptualizing the practices of burning as a space-time process of technological change, it should be possible to make inferences about future spread based on historical patterns. Similar projection models have been developed for disease epidemiology and the biogeography of invasive species. The spread of burning practices can be conceptualized as having characteristics of epidemic models, where infection (i.e. 'adoption') emerges due to proximity, as well as 'influencing factor' models of technological change, where transitions are triggered by an individual's varying goals and needs independent of proximity (Geroski, 2000). Therefore, this research has three objectives: (1) characterize historical rice residue burning trends since 2002 over space and time in Bihar, (2) project future burning trajectories to 2050 under 'business as usual' and alternative scenarios of change, and (3) simulate air quality outcomes under each scenario to describe implications for public health. By employing an integrative assessment framework that centers on public health, this study endeavors to provide an evidence base to support early action for avoiding pervasive agricultural burning in the Eastern IGP before the practice 'locks in'.

2. Data and Methods

2.1. Study area

This study is situated in Bihar State, India. Located within the Eastern Indo-Gangetic Plain (EIGP), Bihar is one of the most densely-settled regions of the country. It is characterized by mixed crop-livestock systems, and rice-wheat crop rotations predominate (Erenstein & Thorpe, 2010). The largely rural population has some of the highest rates of malnutrition and rural poverty (TCI, 2022), coupled with some of the highest crop yield gaps in India (Jain et al., 2017; Pathak et al., 2003; TCI, 2022). Both private and public investments are working to close yield gaps through improved agronomic management, such as timely wheat planting (McDonald et al., 2022) and expanding the adoption of hybrid rice (Spielman, Ward, & Kolady, 2017).

2.2. Workflow overview

Figure 1 provides an overview of the data and methods used in this study. In Step 1, two satellite-derived active fire products were used to characterize the historical patterns of rice residue burning in Bihar across space and time. This understanding guided the conceptualization and development of the 2050 model projecting future rice residue burning to complete Step 1. In Step 2, emissions data were scaled according to the results from Step 1 to inform transport modeling of atmospheric pollution. Additional details on the workflow are provided in Section 2.4.

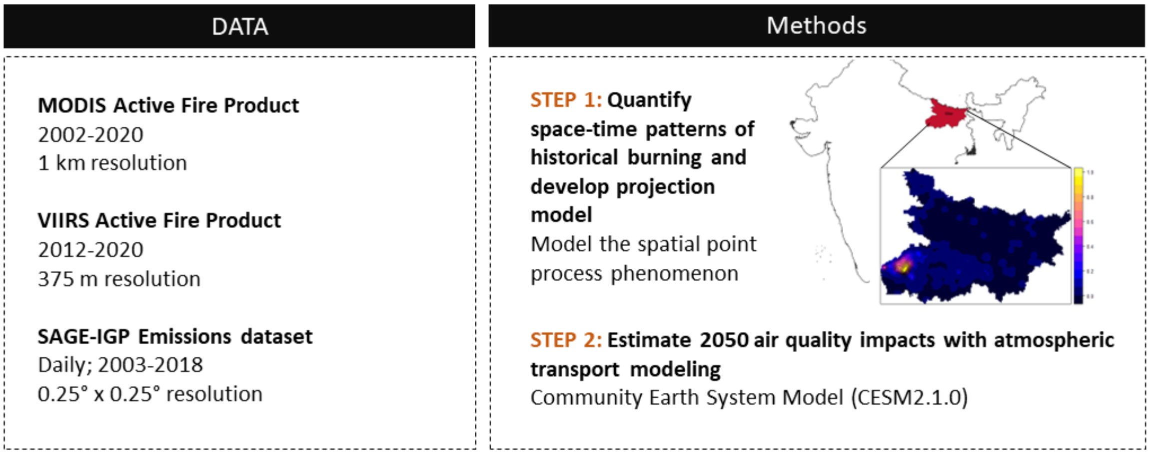

Figure 1. Schematic of the data and methods used in this study.

2.3 Data sources

2.3.1. MODIS and VIIRS Active Fire Products

Fire observations were assessed with the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua satellites, as well as the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor aboard the NASA/NOAA Suomi-National Polar-orbiting Partnership (S-NPP) satellite. Detection of active fires through thermal anomalies products is highly dependent on fire radiative power (FRP – radiant energy released per unit time) which, in turn, is sensitive to both the temperature and size of the fire event (Giglio, Schroeder, & Justice, 2016). These factors tend to be proportional to the mass of burning biomass, all other factors *ceteris paribus* (Wooster et al., 2005). MODIS active fire data is available at 1 km spatial resolution starting from February 2000 (Terra) and June 2002 (Aqua) to present with each satellite having two overpasses daily, with Terra having a morning daytime overpass, and Aqua having an early afternoon daytime overpass (Giglio, Descloitres, Justice, & Kaufman, 2003). MODIS data (MCD14ML) from 2002-2020 was used in this study. Launched October 2011, VIIRS has a shorter time-series but higher spatial resolution than MODIS. VIIRS has an approximate 12-hour temporal resolution, with time-series available from January 2012 to present. VIIRS has both 375 m and 750 m fire detection products. The 375 m resolution product has a higher probability of capturing low-intensity agricultural fires due to its finer spatial resolution, i.e., less averaging of fires with surrounding non-fire areas within the pixel (Schroeder, Oliva, Giglio, & Csiszar, 2014). VIIRS data (VNP14IMGTML) from 2012-2020 was used in this study. Active fire data was considered only for the months where rice residue burning takes place in Bihar, namely October, November, and December. See Text S1 for additional data processing and smoothing details.

2.3.2. SAGE-IGP emissions dataset

The SAGE-IGP (**S**urvey Constraints on FRP-based **A**gricultural Fire **E**missions in the **I**ndo-**G**angetic **P**lain) emission dataset (Liu, Mickley, Singh, Jain, Defries, & Marlier, 2020) was used to estimate fire emissions from the IGP from 2003 to 2018 (daily, 0.25° x 0.25° resolution). The dataset provides daily biomass burnt which is converted to daily emission (kg m^{-2} s^{-1}) estimates for black carbon (BC), organic carbon

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(OC), secondary organic aerosol precursor gases, and sulphur dioxide by using the emission factors ((g species emitted) (kg biomass consumed) $^{-1}$), as explained in Andreae (2019). The SAGE-IGP inventory is based on MODIS FRP and uses a combination of finer spatial resolution VIIRS fire radiative power (FRP), household interviews of current burning practices, crop statistics, cloud/haze gap-fill, and ground and satellite-based measurements of aerosols to provide the most complete estimation of agricultural fire activity across the IGP. The OC + BC emissions from SAGE-IGP was found to average 3.4 times (min: 0.6; max: 6.6) higher than other global fire emissions inventories, including GFASv1.2, GFEDv4s, FEERv1.0-G1.2, FINNv1.5, and QFEDv2.5r1 (Liu et al., 2020).

2.3.3. Atmospheric concentrations of particulates

Daily averaged atmospheric concentrations of $PM_{2.5}$ collected by the India System of Air Quality and Weather Forecasting and Research (SAFAR) at three ground observation stations in and around Patna: central Patna (IGSC Planetarium; 2015-2017), about 100 km south of Patna (Gaya; 2016-2017), and about 70 km north of Patna (Muzaffarpur, 2016-2017) were used for this study (Table S1).

2.4 Modeling

2.4.1. STEP 1: Methods to quantify space-time patterns of historical burning and projection modeling

2.4.1.1. Quantifying space-time patterns of historical burning

Spatio-temporal methods were used to quantify historical burning in Bihar using the R Project for Statistical Computing (R Core Team, 2022). To quantify the increase in burning over time, total annual fire counts and FRP were examined using the most temporally-resolved active fire product, MODIS, from 2002 to 2020. To examine the expansion of fires across space, the most spatially-resolved active fire product, VIIRS, was used with data from 2012 to 2020 to conduct kernel density estimation (KDE), where each point (i.e., center of a grid cell) consisted of a time and location of a remotely sensed fire event. KDE increased our understanding of where burning hotspots occurred historically, in the expectation that our future emission projection model would represent these hotspots appropriately and spread beyond the hotspots reasonably.

2.4.1.2. Fire projection model development

A grid-based model was developed with four components (rules) to reflect four distinct processes (Text S2). First, the temporal spread of burning was modelled as a social diffusion process by estimating new areas that may adopt the practice in a given year, based on spatial neighborhood characteristics (i.e., proximal burning) in prior years. Second, existing burning was assumed to continue in subsequent years, given the ‘lock-in’ nature of this practice. Third, a probability approach was used to characterize the emergence of burning in areas that are not proximate to burning in previous years, as farmers throughout the state may decide to adopt this practice even if not proximate to farmers who already burn their residues. This captures adoption of the practice in as-yet unaffected areas and is by its nature random from the point of view of the modeler’s knowledge. Lastly, reversals each year out of the potential burning areas, as assessed by the previous steps, are estimated with a separate probability term to reflect year-to-year stochasticity in the use of the practice. These four factors enabled the empirical model to represent spatial dependency, the interannual variability of burning, and a random dimension of burning adoption. Projections were created by repeating these steps each year until 2050.

That is, the final projected 2021 raster was then used to develop the 2022 raster and so forth until 2050 (Figure 2).

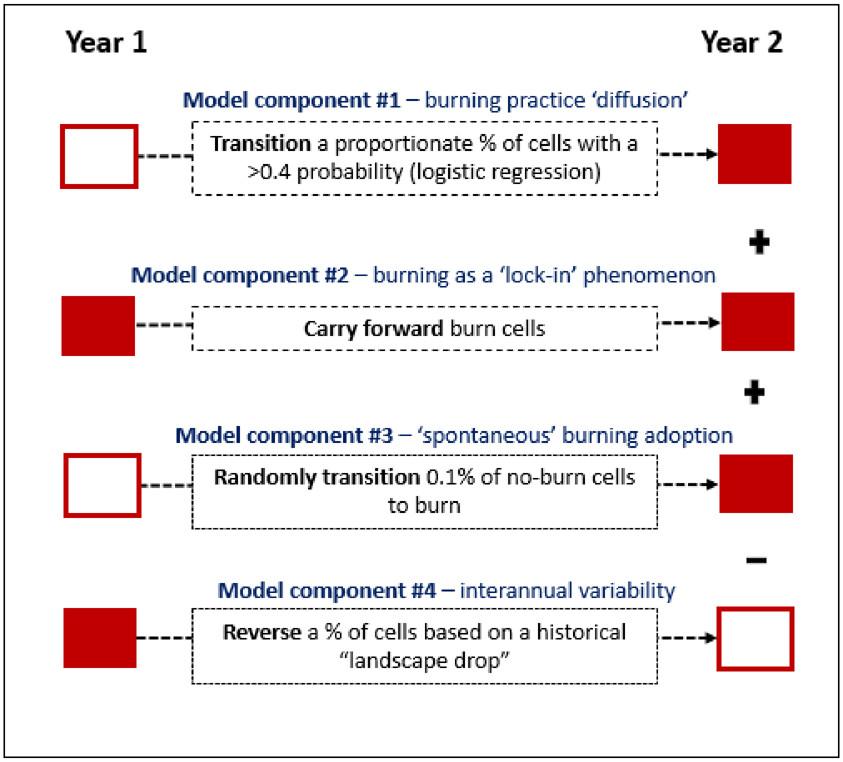

Figure 2. Visual description of the fire projection model development. The future emission model carries forward burning patterns from the prior year and generates a set of gridded projections based on diffusion processes (i.e., those governed by spatial proximity), random occurrences, and expected patterns of interannual variability.

2.4.2. STEP 2: Methods to estimate 2050 air quality impacts with atmospheric transport modeling

2.4.2.1. Scenarios of change

In addition to a present day scenario, six realistic future scenarios were defined to gauge a range of plausible burning outcomes by 2050, including: (1) maintenance of the 'status quo' with fire spatial extent retained at present-day levels (2013-2017) as the counterfactual scenario, (2) rice yield intensification (i.e. more straw biomass production) paired with contemporary fire extent [+75.6% of 2013-2017 fire intensity], (3) area expansion of burning at 'business as usual' rates of increase as estimated from the projection model [+142% of 2013-2017 fire areal extent], (4) rice yield intensification with area expansion of burning at 'business as usual' rates, (5) Northwest IGP analogue assuming that Bihar burning transitions accelerate to resemble contemporary areal extent in Punjab State [+933.7% of 2013-2017 fire areal extent], and (6) rice yield intensification with the Northwest IGP analogue.

Rice yield intensification is expected to result in increased emissions when a field is burned due to the assumed linear relationship between FRP and crop residue biomass (Wooster et al., 2005). As such, the intensification value [+75.6% of 2013-2017 fire intensity] was derived from the percent difference between the 2020 median MODIS FRP and top 25% of the median 2020 MODIS FRP. We acknowledge that FRP is a combined term and varying factors exist, such as the moisture of residue when burned. Yet, this estimation uses the assumption that the yields of most productive rice farmers in our area of interest serve as a suitable yield intensification target by mid-century for this change scenario. The 'business as usual' scenario [+142% of 2013-2017 fire areal extent] was derived from the 2050 projection exercise as the percent change from 2020. The Northwest IGP analogue [+933.7% of 2013-2017 fire areal extent] was derived from the household survey findings of Liu et al. (2020). They found that in the Punjab, 82% of farmers burned their rice residue in 2016 and 53% did so in 2017. Using the average of these values (67.5%), we then used the present cropland mask of Bihar to calculate the equivalent of 67.5% of Bihar rice cropland being burned. All scenarios included future anthropogenic emissions projections as described by SSP585.

2.4.2.2. Estimating 2050 air quality impacts with atmospheric transport modeling

This study used the Community Earth System Model version 2.1 (CESM2.1.0) (Danabasoglu et al., 2020) (see Text S3). Paired simulations were run for each scenario: one with fires from Bihar and one without fires from Bihar. This allows the impact of Bihar fires on pollution levels to be isolated from the difference in each paired simulation scenario. Present day simulations were conducted from 2012 to 2017 inclusive, to account for the interannual variability of the burning phenomenon. Future simulations were simulated using emission projections from 2047 to 2052 inclusive but using meteorology for 2012 to 2017 to isolate impacts of emissions. In all simulations the first year was discarded as spin up and the last five years used for analysis. Future anthropogenic emissions followed the Shared Socioeconomic Pathway (SSP) 585 scenario projections (Gidden et al., 2019). These projections are a set of pathways designed for projecting future emissions in the IPCC (Intergovernmental Panel on Climate Change) framework (O'Neill et al., 2016). To generate these emissions trajectories, Integrated Assessment Models are employed and based on spatial socioeconomic narratives and the chosen level of climate mitigation. In this study, we used the high climate warming scenario SSP585 to estimate future anthropogenic emissions. Under the SSP585 pathway, black carbon emissions are reduced globally by 2050, and relative to other projections, SSP585 represents the median (i.e., not high or low) change (Gidden et al., 2019).

Due to a large uncertainty in how fire emissions will evolve over coming decades and to isolate the impact of future land use management on mid-century Bihar fire emissions, fire emissions outside of Bihar are held at present day levels for all scenarios (i.e., outside Bihar 2012 to 2017 daily fires were used as input to the simulations for 2047 to 2052). As dust and sea salt are prognostic natural emissions that vary as a function of wind speed, their emissions are matched in each scenario. Thus, the difference in atmospheric composition at mid-century compared to present day is a combination of changes to anthropogenic emissions and the projection of land use management for Bihar in each scenario.

2.4.2.3. Model Correction Factor

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We evaluated the model's capability of reproducing daily $PM_{2.5}$ data from ground observations within the same model grid cell as Patna (Table S1). Initial visual evaluation of the time-series revealed that the model significantly underestimated $PM_{2.5}$ during the Bihar crop burning months. With the y-intercept at zero, the coefficients (2.17 and 11.66) of a multiple linear regression model were used as multiplicative correction factors to the emissions without fires (i.e., including all other (non-agricultural burning) anthropogenic emissions sources) and fire emissions only (i.e., excluding all other anthropogenic emissions sources), respectively, in the three months of interest (October to December). We assumed that this bias would propagate through time and thus applied this correction factor to all future Bihar scenario model outputs (Figure S1).

3. Results

3.1 STEP 1: Quantifying space-time patterns of historical burning and projection modeling

The number of post-monsoon crop fires is on the rise in Bihar. From visual evaluation of VIIRS fires in 2012, 2015, 2018 (Figure 3), burning is expanding eastward, as well as becoming more common in the southwest and northwest regions. Also revealed is the rise of 'spontaneous' (i.e., non-diffusion, not spatially-correlated) fire events throughout the eastern part of the state. The naïve nature of this spatial analysis does not provide insights into the underlying drivers of burning diffusion processes nor the emergence of burning in new regions but does provide the basis for empirical projection modeling by assuming future patterns will mirror historical dynamics of change.

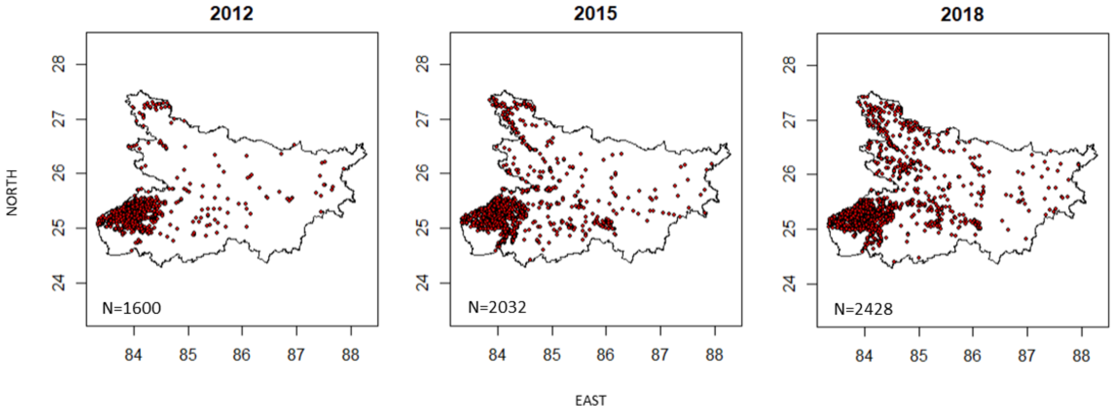

Figure 3. VIIRS active fire observations in 2012, 2015, and 2018 reveal spatially dependent expansion eastwardly across the state, increased density in western areas, and new 'random' burning activities in the east .

Kernel density estimation of fire observations in 2020 showed that the highest contemporary fire density was in the southwest corner of the state (Figure S2). This region of the state is largely characterized by the most intensive rice-wheat cropping systems, the largest farm sizes, and a growing adoption of agricultural mechanization and combine harvesting (Singh et al., 2019). Figures 4 and 5 show the results of the projecting the future emissions across time and space to 2050 under a continuation of 'business as usual' burning pattern. Under this scenario, fires are projected to increase 142% by 2050 (Figure 4). While Bihar had an overall increase in the number of fires from 2002 to 2020, it is important to note the considerable interannual variability. Further research is needed to explore the drivers behind these landscape-scale drops in fires, such as in 2011, 2016, and 2019, as these could be related to environmental, social, or political factors, such as the inability for combines to enter wet fields some years, higher demand for rice straw as a livestock fodder, or increased enforcement of no-burn regulation. This interannual variability with an overarching increasing trend is reflected in the forecasting model from 2021 to 2050.

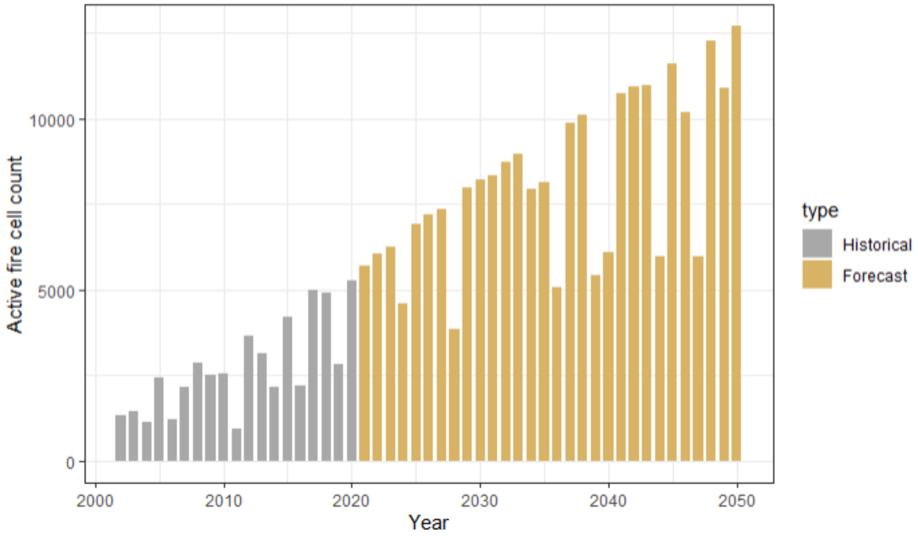

Figure 4. A single realization of the annual active fire count predictions of the 2050 emission projection model.

Figure 5 displays spatial predictions of burning in 2030 and 2050 at maximum potential burning extent (i.e., no landscape-level drops in those realizations of the model). Spatially, the forecasting model shows a ‘burning frontier’ expanding from the southwest area of the state eastward. As the model predictions advance through time, the no-burn areas within the primary southwest hotspot transition to a largely homogeneous burning landscape by 2050. The model shows new, isolated burning hotspots emerging across the state that then expand with time. We cannot be certain where these new areas will be, as this model assumes homogeneity of drivers across the state. The produced maps mirror historical fire dynamics and should be viewed as an approximation of what conditions may evolve if observed change dynamics persist.

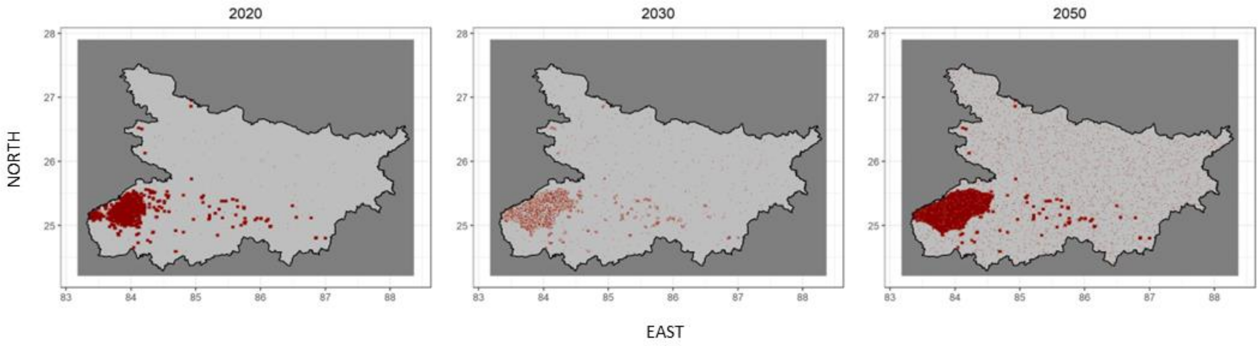

Figure 5. Projected potential burning extent in 2030 and 2050 with 'business as usual' change patterns. Red cells represent an area where rice residue burning is present. The total number of burn cells is increasing over time (see Figure 4) but spatially, the short-term reversals make the 2030 map lighter in color than 2020 and 2050, because the southwest hotspot has a higher fire area density to reverse. By mid-century, the model shows a more homogeneous landscape of burning in the southwest corner.

3.2. STEP 2: Estimating 2050 air quality impacts with atmospheric transport modeling

Step 2 completes Objectives 2 and 3 by describing alternative scenarios of change to 2050 along with associated public health burdens as summarized by daily cumulative PM$_{2.5}$ levels. Table 1 defines the daily average PM$_{2.5}$ exposure from Bihar fires only and all anthropogenic sources, the fraction of total PM$_{2.5}$ exposure derived from Bihar rice residue burning, the October to December cumulative PM$_{2.5}$ exposure, and total exceedance days in Patna due to rice burning only under two different standards.

Table 1. Mid-century PM$_{2.5}$ exposure and exceedance days predictions for Patna.

Future (2050) Scenarios	**Daily average PM$_{2.5}$ exposure from Bihar fires only ($\mu g/m^3$)**	**Daily average PM$_{2.5}$ exposure from all anthropogenic sources ($\mu g/m^3$)**	**Fraction of PM$_{2.5}$ derived from Bihar fires (%)**	**Exceedance days in Patna (out of 92 days in Oct-Dec) due to Bihar rice residue burning**	
				WHO AQG (15 $\mu g/m^3$)	**Indian NAAQS (60 $\mu g/m^3$)**
1- No change	15.4	144.0	10.7	22.2	7.2
2- No change + crop yield intensification	26.8	155.4	17.2	27.2	13.8
3- BAU	36.8	165.4	22.2	30.2	17.0
4- BAU + crop yield intensification	63.5	192.1	33.1	37.6	23.0
5- NW Analogue	155.6	284.2	54.8	44.4	30.4
6- NW Analogue + crop yield intensification	182.3	310.9	58.6	46.2	32.8

3.2.1. Present day air quality burden in Patna

In aggregate, currently rice residue fires contribute a small portion of Patna's total PM$_{2.5}$ emissions compared to other anthropogenic pollution sources, with the present day modeled daily average of 8.1% (October-December; 2013-2017), with 16.2 $\mu g/m^3$ out of 200.3 $\mu g/m^3$ derived from Bihar rice residue fires. However, westwardly winds from the most pervasive burning area in the state make the population of the Patna metropolitan area more vulnerable to acute events when emissions from burning are concentrated and air quality is at its nadir. As such, our results indicate that Bihar-derived rice residue burning can contribute to as much as 62% of the $PM_{2.5}$ exposure on the most extreme day.

3.2.2. 2050 projected air quality burden in Patna

Atmospheric transport model results indicated about a 28% drop in $PM_{2.5}$ emissions mid-century from present day levels in the capital region of Bihar due to cuts in anthropogenic emissions assumed under the SSP585. In addition to examining the results of each scenario in terms of $PM_{2.5}$ derived from Bihar rice burning and total anthropogenic $PM_{2.5}$, we compared the results against two air quality standards for 24-hour $PM_{2.5}$, the Indian NAAQS and the more ambitious WHO AQG, similar to the work of Chowdhury et al. (2019). The Indian NAAQS threshold for 24-hour $PM_{2.5}$ is 60 $\mu g/m^3$ (Central Pollution Control Board, 2020) and the WHO AQG is 15 $\mu g/m^3$ (World Health Organization, 2021).

The first 2050 scenario, with burning remaining at present day levels, resulted in an average daily $PM_{2.5}$ exposure of 144.0 $\mu g/m^3$, but given that burning levels did not change and yet background anthropogenic $PM_{2.5}$ exposure decreased, the fraction of pollution derived from Bihar burning increased from the present day (8.1%) to mid-century (10.7%). However, the number of exceedance days due to burning alone was nearly the same for the first scenario as in the present day, with roughly 7 exceedance days above the NAAQS standard and roughly 22 exceedance days above the WHO standard (five season average). Figure 6 shows the number of days that rice residue burning alone would cause Patna to be over $PM_{2.5}$ air quality thresholds. Using both standards, all future scenarios would expect to exceed the thresholds when considering rice residue burning as the only emission source, with the 'worst case' scenario resulting in 46 days exceedance (annual seasonal average out of 92 days) according to the WHO AQG standard.

In all future scenarios, when all anthropogenic sources of $PM_{2.5}$ were included, each scenario was above the WHO standard for all 92 days in October to December and 84-85 days above the NAAQS standard. It is important to note that all scenarios accounted for future anthropogenic emissions projections, but crop residue fires across the IGP – not including Bihar – were held static due to the available SAGE-IGP fire data. Given the historical rising trend of burning, the 'business as usual' scenario had an expected 142% $PM_{2.5}$ increase due to burning compared to the future no change scenario. The NW analogue and the NW analogue plus intensification had a 910% and 1084% expected increase in $PM_{2.5}$ due to fires only over the future no change scenario.

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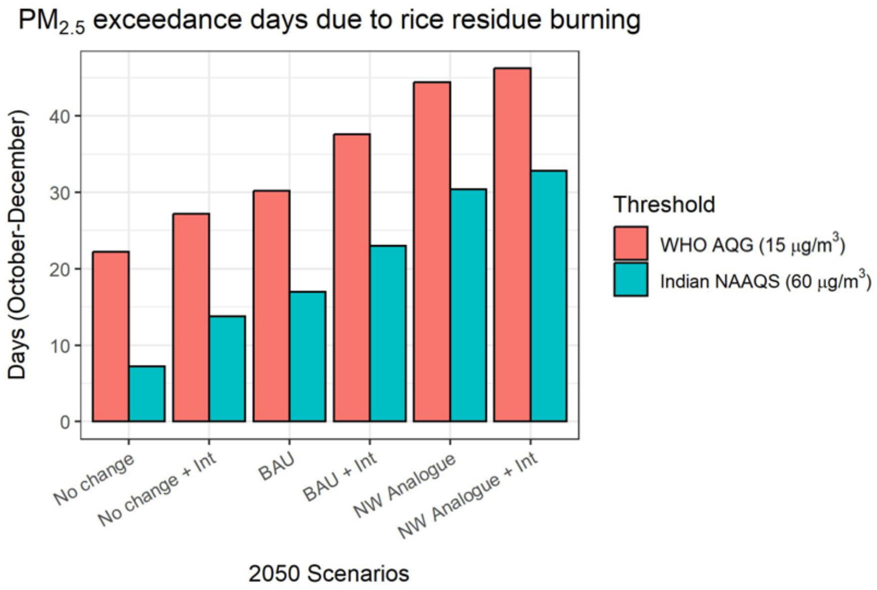

Figure 6: Expected number of seasonal average $PM_{2.5}$ exceedance days in Patna due to Bihar rice burning only in 2050 using the different future emission scenarios.

3. Discussion

While the presence of rice residue burning in Bihar is still far less pervasive than in the Northwest IGP, an examination of nearly two decades of active fire data indicated an alarming increase of burning across space and time in the state. From visual examination of fire count time-series, the past two decades have been characterized by substantial interannual, seasonal and daily variability. Additional research is needed to explore this interannual fluctuation and to characterize the effect of policy changes or technological interventions across several production years.

As with other agricultural burning research findings (Montes et al., 2022), we found strong spatial dependence of fire events between consecutive years. We found that once burning begins in an area, the practice will likely continue to expand in that area. This implies that policies must be put in place to *prevent* farmers from adopting burning practices in the first place since reversing these practices once started has proven extremely difficult in other regions such as the Northwest IGP (Shyamsundar et al., 2019).

The scenario analysis provided a snapshot of plausible mid-century rice burning and associated air quality outcomes given various development trajectories. When considering all current anthropogenic sources, the average fraction of $PM_{2.5}$ as a result of burning is small. However, this study provided clear evidence that residue burning is contributing to these values, and when atmospheric conditions are it is nadir, the contributions of Bihar-based burning to acute air quality events is concerning. Patna is already listed as one of India's non-attainment cities and experiences annual average $PM_{2.5}$ concentration levels as high as or higher than Delhi some years (e.g. 2017) (Nair et al., 2021). There is an urgent need to not only halt the progression of burning but address present day burning, with particular prioritization of the west and southwest areas of Bihar, to achieve current day air quality goals outlined by the National Clean Air Program of the Indian Government.

Future air quality scenarios present a grim picture if burning intensity continues to increase. By 2050, our model assumes a decrease in overall anthropogenic emissions (following SSP585). Unfortunately, continuation of burning will counter some of the projected progress made in other sectors, such as manufacturing and transportation. If the rising ‘business as usual’ trend of the past two decades continues, we forecast higher $PM_{2.5}$ concentration levels resulting in more exceedance days in terms of both WHO and NAAQS standards. In the ‘worse case’ scenario, particularly when coupled with crop intensification, our analysis suggested that a month and a half (i.e., 46 days) of $PM_{2.5}$ exceedance days above the WHO AQG would result due to burning emissions alone. Exceeding WHO AQG and Indian NAAQS thresholds would result in an expansive rise of $PM_{2.5}$ related health concerns including cardiovascular disease, respiratory disease and lung cancer (Chen & Hoek, 2020).

This study has several limitations. Firstly, remote sensing products (i.e., MODIS and VIIRS) have limitations in detecting short-lived agricultural fires, as they are unable to capture fires that occur outside the satellite overpass times. Given that burning in Bihar happens later than in Punjab and Haryana, the resulting pollution, combined with increased cloud cover and fog during the winter months, may hinder satellite detection of Bihar fires. Given that SAGE-IGP heavily relies on satellite detection, this could have led to underestimations in modeled $PM_{2.5}$, which were later corrected using measured $PM_{2.5}$ values. Secondly, in addition to air quality impacts of burning in Bihar, strong westerly winds could exacerbate acute air pollution events in Patna due to $PM_{2.5}$ originating from the Northwest IGP region. However, our study did not quantify the specific impact of Northwest IGP burning on air quality in Patna. Thirdly, our approach to future projections is empirical and reflects past trends at an aggregated state level. District-level trends can vary significantly and are beyond the scope of this paper. Future research should aim to understand the farm-level and landscape drivers of burning that are context-specific to Eastern India ecologies. By incorporating this information, the ability to robustly predict changes in pollutant concentrations at the district level would enhance our understanding of the air quality implications not only in Patna but also in other locations within the state. Finally, future studies could explore how increasing agricultural emissions from Bihar may impact other pollutants, such as tropospheric ozone concentrations, which are also influenced by fire aerosol and gas emissions.

4. **Conclusions**

In the context of systems agronomy for global development, there have been limited examples of *ex ante* research which seeks to understand and address a problem before it fully materializes. This work represents the first comprehensive effort to characterize current rice residue burning trends in the Eastern IGP and to anticipate different development trajectories. Through a naïve point pattern forecasting approach coupled with the scenario outputs derived from the Community Earth System Model version 2.1 (CESM2.1.0), we characterize the spatial nature of the phenomenon, the current trends across historical time starting in 2002, and the air quality implications mid-century if the progression of burning is not stopped. The air quality impact of burning at present levels can be easily overlooked, yet the growing trend and the peak damage potential should be at the forefront of policy conversations at the agriculture and public health nexus. Without creative and urgent interventions to stop burning, the mid-century reality could result in an extensive winter air quality crisis, particularly for the residents of Patna.

Declaration of Competing Interest

The authors report no declarations of interest.

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Data availability

SAGE-IGP data are available from Harvard Dataverse at https://doi.org/10.7910/DVN/JUMXOL.

Daily averaged atmospheric concentrations of $PM_{2.5}$ data are available at https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/data.

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