Economic Cost of Crop Open Field Burning

By

Qurrat-ul-Ain

Registration No. **00000318470**

Supervisor

Dr. Muhammad Fahim Khokhar

Institute of Environmental Sciences and Engineering (IESE)

School of Civil and Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST)

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Approval Certificate

Certified that the contents and form of the thesis are entitled.

"Economic cost of crop open field burning".

Submitted by

Ms. Qurrat-ul-Ain

Has been found satisfactory for partial fulfillment of the requirements of the degree of Master of Science in Environmental Sciences

Supervisor: ……………………………………

Dr. M Fahim Khokhar

Professor (Tenured)

SCEE (IESE) NUST

Dr. Muhammad Fahim Khokhar
Tenured Professor
Environmental Sciences
IESE (SCEE) NUST Islamabad

GEC Member: ……………………………………

Dr. Zeeshan Ali Khan

Associate Professor

SCEE (IESE) NUST

GEC Member: ……………………………………

Dr. Hassan Anwar

Assistant Professor

SCEE (IESE) NUST

30-08-23

Dr. Hassan Anwer
Assistant Professor
IESE (SCEE) NUST Islamabad

Acceptance Certificate

It is certified that the final copy of MS/ MPhill Thesis written by Ms. Qurrat-ul-Ain (Registration No: 00000318470) of IESE (SCEE) has been vetted by the undersigned, found complete in all respects as per NUST Statues/ Regulations, is free of plagiarism, errors, and mistakes, and is accepted as partial fulfillment for the award of MS/Mphil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Supervisor: ……………………………

Prof. Dr. M. Fahim Khokhar

Dr. Muhammad Fahim Khokhar
Tenured Professor
Environmental Sciences
IESE (SCEE) NUST Islamabad

Dated: 30/08/2023

Head of Department: ……………………………

Dr. Zeshan
Tenured Assoc Prof
HoD Environmental Sciences
IESE (SCEE) NUST Islamabad

Dated: 30/08/2023

Associate Dean: ……………………………

Prof. Dr. Imran Hashmi
Associate Dean
IESE (SCEE) NUST Islamabad

Dated: 30-08-2023

Principal and Dean SCEE: ……………………………

PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

Dated: 30 AUG 2023

Declaration Certificate

I declare that this research work titled "**Economic cost of crop open field burning**" is my work. The work has not been presented elsewhere for assessment. The material that has been used from other sources has been properly acknowledged/referred.

Student Signature: ……………………
Student Name: ..Qurrat-ul-Ain
Date: …29-08-2023……

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This thesis has been checked for plagiarism. Turnitin endorsed by the supervisor is attached.

Signature of Student: ……………………

Signature of Supervisor: ……………………

Dr. Muhammad Fahim Khokhar
Tenured Professor
Environmental Sciences
IESE (SCEE) NUST Islamabad

DEDICATION

This thesis is dedicated to my parents whose continuous support and prayers are always with me whenever and wherever required.

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LIST OF ABBREVIATIONS

WHO	World Health Organization
GHG’s	Green House Gases
CO_2	Carbon Dioxide
CO	Carbon Monoxide
CH_4	Methane
NMVOC’s	Non-Metallic Volatile Organic Compounds
NOx	Oxides of Nitrogen
SO_2	Sulfur Dioxide
OC	Organic Carbon
BC	Black Carbon
EC	Electrical Conductivity
FAO	Food and Agriculture Organization
PCAP	Pakistan Clean Air Program
AQI	Air Quality Index
IPCC	Government Panel for Climate Change
AQMS’s	Air Quality Monitoring Stations
ABC’s	Atmospheric Brown Clouds

FRP	Fire Radiative Power
GDP	Gross Domestic Product
LPDAAC	Land Process Distributed Active Archive Centre
PBS	Pakistan Bureau of Statistics
USD	US Dollars
HEC	Higher Education Commission
Sq.Km	Square Kilometer
Mha	Million Hactors
KPK	Khyber Pakhtunkhwa
ETS	Emission Trading Systems
NDC’s	Nationally Determined Contribution
(CERs)	Certified Emission Reductions
AMIS	Agriculture Market Information System
UNFCCC	United Nations Framework Convention on Climate Change

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ABSTRACT

Over recent years, crop residue burning has become a regular agricultural activity in developing countries due to varying economic and social reasons. The burning of crop residue in the open field has become a significant concern for both air pollution and climate change mitigation efforts worldwide. To estimate air pollution caused by crop residue burning in Pakistan, an emission inventory was developed based on district-level crop production data during the period 2001-2020. Spatial distribution of quantified emissions was achieved by using MODIS Active Fire Data (MOD/MYD14A1) at 1-day temporal and 1×1 km^2 spatial resolutions in this study. Two major crop residues, i.e. wheat straw and rice straw, were considered. Total annual emissions of CO_2, CO, CH_4, NMVOCS, N_2O, NH_3, SO_2, NOx, $PM_{2.5}$, PM_{10}, OC and BC in 2020 were 0.12, 0.009, 0.0007, 0.0006, $2.13E^{-05}$, 0.0002, $5.09E^{-05}$, 0.0003, 0.001, 0.0004, 0.0009, and $7.28E^{-05}$ Tg respectively. Spatially, throughout the study period 2001-2020, Dadu, Larkana and Layyah districts exhibited the highest emissions as compared to other districts of Pakistan. Temporally crop residue burning was dependent on the harvesting seasons with highest concentration in May followed by February, November, and December month. There was a significant increase in pollutant emissions over 20 years ranging from 18% for N_2O to 26% for NH_3. The environmental cost of Kharif was highest in 2019 for Sindh and 2020 for Punjab with the values $1.79E^{+09}$ and $8.32E^{+08}$ respectively. While the economic cost of rabi crops was highest in 2013 with a value of $2.22E^{+08}$ In Sindh. The observed trend suggested that emissions from crop residue burning will continue to rise in the future due to the absence of policy intervention and strict action.

CHAPTER 1

Introduction

1.1. Background

Following the industrial revolution in the 1970s, rising anthropogenic emissions not only worsened air quality but also had a negative impact on people's health. These rising anthropogenic emissions come from a variety of sources, such as industrial processes, the burning of biomass, and vehicle emissions. In comparison to North America and Europe, Asia is the largest contributor and has a tendency to accelerate the growth of these emissions (Akimoto, 2003).

Biomass burning, one of the oldest anthropogenic sources, was initially acknowledged and its significance in atmospheric chemistry was suitably underlined by Crutzen et al. in the late 1970s. Due to its long-distance travel, it is one of the main sources of aerosol pollutants and trace gases in local, regional, and global atmospheres (Andreae, 2001; Permadi and Kim Oanh, 2013; Li et al., 2016). Savanna, woodland, and peat land fires, open burning of crop leftovers, and burning of biofuels are all examples of biomass burning (Van Der Werf et al., 2010; Akagi et al., 2011). (Streets et al., 2003 b) came to the conclusion that agricultural burning accounts for 34% of all biomass burned in Asia. Table 1.1 provides statistical information on biomass burning in Asia in 2003. Significant variation was seen, with crop residue burning contributing more in South Asia's China and India.

Common agricultural burning practices include weed and insect management, clearing land for shifting cultivation, maintaining pastures, agroforestry, and removing waste after harvesting crops (Jenkins et al., 1996; Dennis et al., 2002). According to Anderson, Chen, Van Der Werf, Rogers, and Morton (2012), minor fires are thought to have contributed to the rise in burned area proportion from 345Mha/yr in 2000 to 464Mha/yr in 2010.

Table 1.1 Annual Amount of Biomass Burned in Asia in 2003

Country	Grassland	Forest	Crop Residue	Total
Bangladesh	0	8.5	11	20
India	8.6	37	84	130
Pakistan	2.9	0.9	10	14
China	52	25	110	80

Farmers are compelled to intensify agriculture operations in order to preserve yields and earnings due to the rising urbanization. Because farmers would plant more cash crops, use of mechanized harvesting techniques, and on-field residue would grow, this intensification would result in an increase in agricultural burning. Since climate change is a significant effect, it will also affect the distribution of croplands by shifting the growing season and creating microclimates that are drier and less productive. According to Shakoor et al. (2017), global warming will cause a 6% decline in maize yield and a decrease in precipitation through the year 2030. Quantifying GHGs and other emissions from burning biomass is now required at the national and international levels, including agricultural burning.

1.2. Burning of Agricultural Residues and Air Quality

Burning crop residue can worsen local, regional, and international air quality issues. Although dominance in these processes and the subsequent gaseous emission vary on the material being burned, crop residue burning emissions are mostly reliant on the stage of combustion used during a burning episode (Andreae, 2001; Yokelson et al., 2008). For instance, crop residue burning typically has a longer smoldering phase and less flame due to the high temperature, with NOx emissions dominating the flaming period (Saud et al., 2011).

Crop residue burning is episodic in nature and only happens during specific months, which causes an increase in PM concentrations during those months (P. J. Crutzen & Andreae, 1990). These high PM concentrations not only cause the air quality to worsen, but they also have a negative impact on a number of physiological factors, including a person's ability to breathe (Dvonch et al., 2009; Samet et al., 2009; Li et al., 2013). According to research from the WHO, it caused 3.7 million premature deaths in 2010 and is a source of cardiopulmonary morbidity, which has a mortality rate of 6.4 million individuals (WHO, 2003). According to Jenkins et al. (1996) and Zhang et al. (2008), burning crop residue emits carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), non-methane volatile organic compounds (NMVOCs), oxides of nitrogen (NOx), sulfur dioxide (SO_2), organic and black carbon (OC and BC), and particulate matter (PM). The carbon cycle is significantly impacted by CO_2 released during the widespread burning of crop residues (IPCC, 2007; Wiedinmyer et al., 2011). Due to their downwind travel from the site of the fire, gaseous pollutants like CO, SO_2, and NOx behave as a precursor in the production of tropospheric ozone. The vulnerability of photochemical smog, which damages the lungs and visibility, is brought on by an increase in tropospheric ozone concentration (Chen & Watson, 2017).

The burning of agricultural residues must be recognized on a local, national, and international level as a problem for government, the environment, and human health. According to an FAO research, Pakistan produces close to 69 million tons of crop residue each year, which is burned in open fields. The federal and provincial governments have taken an interest in the rising number of SMOG occurrences that have occurred over the past few years in Northern India and Northeastern Punjab during the dry winter months of October to mid-November. Climate change is a result of this transboundary pollution for Pakistan. These incidents generally happened as a result of open rice straw burning in India (Tariq & Ali, 2015). The Pakistan Clean Air Program (PCAP), which offered both short- and long-term strategies with their relevant agencies, was designed by the Climate Change Division to lessen these effects. According to these intentions, the SMOG policy 2017 was created, which forbade the open burning of rice stubble altogether and required the provincial environmental agencies to inform farmers about other ways to use crop leftovers. Six criterion pollutants were used to create an AQI, and their concentrations were determined by Air Quality Monitoring Stations (AQMSs) using average concentrations over 8 and 24 hours. The developed AQI is displayed in Table 1.2 along with an overview of the air quality.

Table 1.2 AQI developed as per smog policy (SMOG Policy, 2017)

PM$_{10}$	**PM$_{2.5}$**	**SO$_2$**	**NO$_2$**	**O$_3$**	**CO**	**AQI**	**Indicator Colour**	**Overall Description**
0-150	0-35	0-120	0-80	0-130	0-5	0-100	Green	Good
151-200	36-70	121-240	80-160	131-260	45204	101-200	Green	Satisfactory
201-250	71-105	241-360	161-320	261-450	45962	200-300	Yellow	Moderately Polluted
PM10	PM2.5	SO2	NO2	O3	CO	AQI	Indicator Colour	Overall Description
251-350	106-140	361-700	321-560	451-550	26-40	301-400	Orange	Poor
351-430	141-300	701-1600	61-800	551-1900	41-50	401-500	Red	Very Poor
430+	300+	1600+	800+	1900+	50+	500+	Maroon	Severe

1.3. Impact of Biomass Burning

By altering the equilibrium of radiation systems in the Earth's atmosphere, biomass burning contributes to the chemical composition of the atmosphere. Numerous forums have detailed analyses of the system's response to these modifications. Biomass burning was identified as a significant source of greenhouse gases by the IPCC in its fourth assessment report. These emissions also have an effect on the climate by altering the chemistry of the atmosphere and the radiation budget (Andreae, 2001; IPCC, 2007). The main cause of the atmospheric brown clouds (ABCs) over South Asia is biomass burning. According to Ramanathan et al. (2005), these clouds have a significant impact on how solar radiation is scattered and absorbed.

When biomass is burned vigorously, visible light is absorbed, which causes an increase in the amount of energy retained in the atmosphere. In contrast, when OC is released, light is scattered, causing a cooling of the surface. Arola et al. (2007) investigated the effects of biomass burning on the optical and physical characteristics of aerosols across the European region. In particular days in October, Tariq and Ali (2015) found that fine mode aerosols produced by burning crop residue contributed more to the overall aerosol burden than coarse mode aerosols, and that these aerosols were transported from the northwest and southeast by backward trajectories.

In contrast to being a local nuisance, fine particles produced from burning crop residue are carried over greater distances by high-speed winds (Badarinath et al., 2009a; Badarinath et al., 2009b). Although not a frequent occurrence in most areas owing to biomass burning, increased aerosol loading (AOD > 1.5) is of more concern because to its detrimental effects on respiratory health and decreased visibility (Eck et al., 2003). Due to its effects on human health, changes in monsoon patterns, and repercussions on Himalayan glaciers and snowpacks, ABC, which was created as a result of biomass burning spanning northern Pakistan and India, is causing worry.

1.4. Study Objectives:

1. To estimate the spatiotemporal extent of stubble burning over Punjab and Sindh
2. To estimate the emissions of various gaseous pollutants from stubble burning
3. To estimate the economic cost of stubble burning

1.5. Scope of the study:

A historical emission inventory for the study's period of 2001–2020 would be created. Other parameters like emission factors, product to residue ratio, dry matter content, and combustion efficiency will be taken from the literature. Before creating an inventory, primary data regarding the production of two major crops, including wheat and rice, would be collected for 57 districts from yearly 18 statistical books prepared by the Pakistan Bureau of Statistics and AMIS. The technique we developed for this study's estimation of pollutant emissions was based on recommendations from (HEC-PBAIRP, 2021).

For gridding, the 1x1 km resolution, daily fire occurrence, quantified emissions MODIS Active fire data of MOD/MYD14A1 would be used. The products from the charred area will then be used to remove these fire incidents. Finally, the obtained results will present the current agricultural burning situation in Pakistan and a quick comparison with related research projects undertaken for Pakistan both locally and internationally.

CHAPTER 2

Literature Review:

2.1. Overview:

In undeveloped countries with economies predominately focused on agriculture and rudimentary management skills, post-harvest burning is a common practice. A considerable amount of crop waste is burned outside in the fields each year. These emissions include particulate matter (PM10 and $PM_{2.5}$), gaseous emissions (CO, CO_2, NO_X, NMVOCs, CH_4, SO_2, and NH_3), as well as BC and OC. On-site burning and off-site burning are the two distinct types of residues burning. Crop wastes that are burned intentionally fall under the category of on-site burning, which can occur both on-site and in an open field.

On the other hand, off-site burning describes the burning of waste materials that have been transported away from their original location and used as a source of energy, like the burning of biofuel in homes or the creation of electricity.

This chapter gives a summary of earlier studies that were done in order to create an emissions database for burning in agriculture. These studies examined the advantages and drawbacks of both top-down and bottom-up approaches to inventory development. This chapter will also give a quick overview of Pakistan and the methodology used to create Pakistan's inventory from agricultural residue burning.

2.2. Approaches for emission estimation:

Emissions estimation methods There have been numerous global efforts since 1979 (Paul J. Crutzen et al., 1979) to establish emission estimates from agricultural burning. With the idea that the emissions across a specific area and period should be properly specified, these estimates are often created on a variety of geographical and temporal resolutions. The methods used to estimate emissions, such as employing statistical data or the volume of satellite data for quantification, vary between the 20 prior emission inventories. Emission databases, including information on the species involved and information about the spatial and temporal resolution, are provided by EI created worldwide, regionally, or on a country basis.

Globally developed emission inventories (Seiler and Crutzen, 1980; Hao and Liu, 1994; Streets et al., 2003a) use pooled datasets of crop residue exposed to open burning in both developed and developing nations to offer historical information from crop residue burning. Two of the methods utilized for increasing emotional intelligence are covered in full below.

2.3. Emission Estimates Using Top-Down Approach

Due to satellite observations of burned areas and active fires (Roy et al., 2008; Huang et al., 2012; J. Li et al., 2016), quantitative estimates for crop residue burning have improved. Therefore, a top-down strategy employs satellite products to determine the burned area and then uses that information to determine emissions. Typically, these estimations are based on a fundamental connection of the following form (Huang et al., 2012).

$\boldsymbol{E} = \boldsymbol{EF} \times \boldsymbol{C} \times \boldsymbol{B} \times \boldsymbol{M}$ (1)

Where, according to Seiler and Crutzen (1980), E stands for crop residue burning emissions, EF for emission factor (g/kg) and C for combustion efficiency (%), B for above-ground biomass burning density in fields (kg dry matter/m2), and M for burned area (km2). Usually, all of the aforementioned factors contribute to uncertainty in emission estimates. This is mostly due to the fact that agricultural fires typically have small burned areas, making it challenging to detect them using satellites (Roy et al., 2008). Additionally, geographical variations exist in combustion efficiency and above-ground biomass density (Hoelzemann et al., 2004; Liu et al., 2015).

Due to active fire products including AVHRR, MODIS active fire satellite product, and VIRS fire count data, better spatial and temporal distribution was achieved (Cooke et al., 1996; Ito et al., 2007). burnt area products including the GBA 2000 product, MODIS burnt area products, and GFED helped with burned area detection (Korontzi et al., 2006; Randerson et al., 2012). However, there are limitations to these satellite observations when it comes to calculating emissions from burning fires (Duncan, Martin, Staudt, Yevich, & Logan, 2003). Ignore minor burn scars that are below detection thresholds because burned area products only offer limited spatial resolution up to 1 km and temporal resolution up to one month.

As a result, little is known about how minor agricultural fires affect overall burned areas and associated fire emissions (Jessica L. McCarty, Korontzi, Justice, & Loboda, 2009). Due to the limited overhead times of satellites, active fire products that provide information on tiny fires help to reduce the uncertainty in fire detection (Streets et al., 2003a; Giglio et al., 2006; Qiu et al., 2016). (Wiedinmyer et al., 2011) used burned area and active fires to estimate the emissions from agricultural burning. Table 2.1 lists these inventories, along with the results and drawbacks of employing these methods.

Table 2.1 Emission inventories developed using Top-Down approach.

Inventories with their findings+A1:B4	**Research Gaps**
Wu et al. (2018) evaluated emissions from four open biomass burning sources, including forests, shrub lands, grasslands, and agricultural straw. They found that these emissions increased between 2003 and 2015, underscoring the necessity of managing these emissions. In terms of total emissions during the years, the four sources produced 9.39 105, 4.59 104, 4.13 102, 3.05 103, 6.4 103, 4.67 103, 1.82 102, 2.12 102, 3.64 103, and 2.87 102 Gg of CO_2, CO, CH_4, NMVOCs, NH_3, NO_x, SO_2, $PM_{2.5}$, OC, and EC, respectively. During the planting and harvesting seasons, emissions from burning crop straw predominate, whereas in other months, emissions from shrublands and woods, which are unaffected by changing environmental circumstances, predominate.	satellite data uncertainty in cr residue burning emissi calculations.
In order to quantify agriculture and eliminate ignorance of small-scale agricultural areas, Liu et al. (2015) analysed	While employing a geostationary satellite can aid

emission from agricultural fires using fire radiative power (FRP) collected from MODIS Terra and Aqua satellites. Fire emissions increased between 2005 and 2007 and in 2012. Comparatively speaking, emission estimations were lower than actual emissions as measured by statistical data.	in a better estimate of the diurnal cycle of FRP, there is still a need for additional research using these estimations, which are somewhat better.
To better quantify biomass burning from minor fires, Randerson et al. (2012) merged burned area with MODIS active fire data. The burned area increased by 35% globally, from 345 Mha to 464 Mha every year. From 1.9 Pg C/year to 2.5 Pg C/year, GFED emissions increased.	Emission was underestimated as a result of satellite data errors because most agriculture fires were overlooked due to their small size.
With 0.5 0.5 spatial and 1 month temporal resolution, Werf et al. (2010) created GFED Version 3 with worldwide fire emissions up to 2.0 Pg C/year from 1997-2009. The main sources of carbon emissions between 2001 and 2009 were fires in grasslands and savannahs, with agricultural fires contributing the least.	Emissions from agricultural fires were understated because relatively minor fires could not be detected by the method used to calculate burned area.
Chang and Song (2010) used burned area products to quantify the emissions from burning biomass over tropical Asia. There were 122, 9.3,0.63, 0.54, 1.1,0.043, 0.11, 3, 3.3,0.39, and 0.033 Tg/year of CO_2, CO, CH_4, NH_3, NMHCs, SO_2, NO_x, $PM_{2.5}$, PM_{10}, OC, and BC, respectively. The burning of agricultural products is the second major source of these	Due to the comparatively modest quantity of agricultural land, emissions from burning crop residue were projected to be lower.

emissions.	
To quantify farmland burning emissions, McCarty et al. (2009) used MODIS active fire data with Normalized burn ratio. In a typical year, the US Forest Service reports that over 1,239,000 ha of cropland is burned, which is equal to 43% of the yearly average area of wild land fires.	Even if active fire occurrences were detected nearby, the detection of burned regions has diminished due to the tiling of agricultural lands following burning.

2.4. Calculating Emissions Using Bottom-Up Approach

The Bottom-Up strategy is another method that can be used to estimate emissions. In a bottom-up method, the Seiler and Crutzen (1980) equation for computing emissions using statistical data prepared by the governments is used. Various emission estimates for burning agricultural residue have been generated using this method, which makes use of information on the burning activity and crop types of certain nations and locations. According to Cao, Zhang, Wang, and Zheng (2008), agricultural burning emissions (Em) are essentially estimated by mulitplying region-specific emission factors (EF) and the actual amount of biomass burned (M)

$$\boldsymbol{Em} = \boldsymbol{M} \times \boldsymbol{EF} \quad (1)$$

Utilizing activity data, such as knowledge of the crop harvesting area and crop yield, one can determine the actual amount of biomass burned (M). Using either crop production or crop harvesting area, Streets et al. (2003) established two equations to determine the actual amount of crop residue burned. The following equation can be used to estimate emissions using information on crop production:

$$\boldsymbol{Mk} = \boldsymbol{Pk} \times \boldsymbol{Sk} \times \boldsymbol{Dk} \times \boldsymbol{Bk} \times \boldsymbol{\sigma k} \qquad (2)$$

Where Pk denotes crop production in kilograms per year, Sk denotes the crop to residue ratio, Dk denotes dry matter content, Bk denotes dry matter residue burned in the field, and k denotes combustion efficiency. Another method created for using crop harvesting area to calculate emissions is as follows:

$$\boldsymbol{Mk} = \boldsymbol{Yk} \times \boldsymbol{Sk} \times \boldsymbol{Dk} \times \boldsymbol{Bk} \times \boldsymbol{Ak} \times \boldsymbol{\sigma k}(3)$$

Where Yk stands for annual yield (kg/ha) and Ak for harvested crop area (ha/yr).

Several criteria, including the grain to straw ratio, combustion efficiency, dry matter content, and fraction burned from agricultural waste, are taken into account when calculating the proportion burned on fields. When utilizing this method to create emission inventories, this parameter reliability is crucial. Significant uncertainty in emission estimates arises from the accumulation of errors caused by these parameters. According to Gadde, Bonnet, Menke, and Garivait (2009), the re-allocation of the emissions determined at the province level using this data, either using land cover data or by equal distribution, results in substantial levels of uncertainty in the EI.

Table 2.2 enlist the inventories developed using this approach and also provides details regarding uncertainties associated with these estimates.

Table 2.2 Emission estimates using the Bottom-Up Approach

Inventories with their findings	**Research Gaps**
A thorough biomass-burning EI was created by Zhou et al. (2017) and the includes GHGs, air pollution precursors (SO_2, NO_x, OC, BC, and $PM_{2.5}$), and heavy metals emitted during residential burning, open burning of agricultural residue, forest fires, and grassland fires. Crop residue emits primarily NO_x.	The degree of uncertainty in emission estimates was lowered through the use of country-specific data.
Li et al. (2016) used MOD/MYD14A1 Active fire data to assign these emissions regionally and temporally and quantified the emissions from agricultural burning from 1990 to 2013. Emissions range from 1.06 Tg to 7.07 Tg,	Better estimation of emissions over China was achieved by using locally determined emission factors, combustion efficiency, and

with an average annual rise of 24%. Regions with the highest emissions increased over time.	product to residue ratio.
Irfan et al. (2015) did a study in Pakistan and created a district-level emission inventory for Punjab and Sindh with a total estimate of 16.08 Tg for the years 2006–2007. a calculated percentage of the emissions of CO_2, CO, SO_2, NO_x, NH_3, CH_4, OC, and EC from wheat straw, rice straw, cotton straw, and bagasse. Emissions are distributed geographically based on districts.	Farmers' local practices are not taken into account in the fraction of biomass burned. It was not discussed how Khyber Pakhtunkhwa and Baluchistan contributed to agricultural burning. Seasonal and annual differences were not taken into account.
Emission inventory from Crop residue burning at state level was prepared by Jain et al., (2014) for India with2008-2009 as base year. Residue generated in 2008–09 was 620 Mt out of which 15.9% residue was burned on farm. Rice straw contributed 40% of the total residue burned followed by wheat straw (22%) and sugarcane trash (20%).	Emission estimates requires experimental validation and uncertainty assessment.
Huang et al. (2012) used provincial statistics data to calculate emissions in China for the base year 2006, and MODIS Thermal Anomalies (MOD/MYD14A1) with a temporal resolution of 1 day enabled a spatial distribution of 1 km. The amount of CO_2, CH_4, CO, NH_3, SO_2, NO_x, OC, BC, and $PM_{2.5}$ emissions each year was calculated. Due to the harvesting and sowing of	Estimates that are somewhat more accurate because of the use of locally derived emission factors and the percentage of agricultural residue burned on the field.

maize and wheat, crop residue burning predominated in the North China Plain, whilst South and Northeast China saw a temporal variance in fire occurrences.	
The amount of rice straw burned in open fields in India, Thailand, and the Philippines was determined by Gadde et al. (2009), who also created pollutant-specific emissions factors from rice straw burning. measured the resulting emissions of air pollutants.	Using emission factors particular to each region and each pollutant, uncertainty in a number of parameters was decreased.
Yevich and Logan (2003) estimated that 400 Tg of crop residue was burned on fields in the developing world in 1985, with a significant contribution coming from the Middle East and India. They did this using government statistics and World Bank data. When compared to the CO_2 emissions from burning fossil fuels, the 0.9 Pg C (CO_2) emissions from burning field waste and biofuels cannot be ignored while being very minor.	The amount of emissions was underestimated since there were no statistical data or emission factors particular to the location.

2.5. Data on Activity Levels

Diverse emission inventories of biomass burning were constructed for industrialized countries (Ito & Penner, 2004; Werf et al., 2006) taking into account prior findings by Seiler & Crutzen, (1980). Pakistani scientists began their research on creating such inventories rather late in comparison to scientists in developed nations. Irfan et al. (2015) developed an emission inventory for burning crop residue in certain regions and with specific crops based on local emission characteristics. Streets et al. (2003) created an inventory of biomass burning on a national scale for developing nations without distinguishing distinct crop varieties. As a result, the scant research done for Pakistan has a number of flaws.

First of all, the paucity of statistical data at the district level for all provinces forced the development of all these inventories in recent years. Second, using a multi-year temporal trend analysis, it is necessary to include locally developed or region-specific emission components in emission calculation for the most recent years. In order to assess the current situation at the district level in different provinces, it is necessary to examine the percentage of straw that is burned on fields. When created utilizing GIS technology, activity data with a coarser resolution may result in extremely high uncertainty (Zhou et al., 2017). Therefore, it is crucial to create an emission inventory of agricultural residue burning with high temporal and spatial precision.

The following sections provide more information on the various components that were obtained from earlier pertinent work done for Pakistan before calculating the emissions. These parameters were needed for calculation using a bottom-up technique.

CHAPTER 3

Methodology:

3.1. Study Area:

With an area of 881,913 square kilometers (340,509 square miles), Pakistan is the second-largest nation in South Asia and the world's 33rd-largest overall. It is surrounded by India to the east, Afghanistan to the west, Iran to the southwest, and China to the northeast. It has a 1,046-kilometer (650-mile) coastline along the Arabian Sea and Gulf of Oman in the south. It shares a sea border with Oman and is just barely separated from Tajikistan in the north by Afghanistan's Wakhan Corridor. With a population of nearly 249.5 million and an average annual growth rate of 2.4%, it is the fifth most populated country in the world (Population Census, 2017).

Pakistan is divided into five administratively separate provinces: Punjab, Sindh, Khyber Pakhtunkhwa (KPK), Baluchistan, and Gilgit-Baltistan. Each province has divisions that are further divided into districts and tehsils (sub-districts), and each division is further divided into districts.

Nearly 70% of Pakistan's population relies on agriculture for a living, making it the foundation of the country's economy. Two provinces and their corresponding districts are included in this study. As compared to other Pakistani provinces, Punjab and Sindh are the most active in terms of agriculture. The study covers twenty-three districts in Sindh and thirty-four in Punjab. Figure 3.1 depicts Pakistan with each district considered for this study.

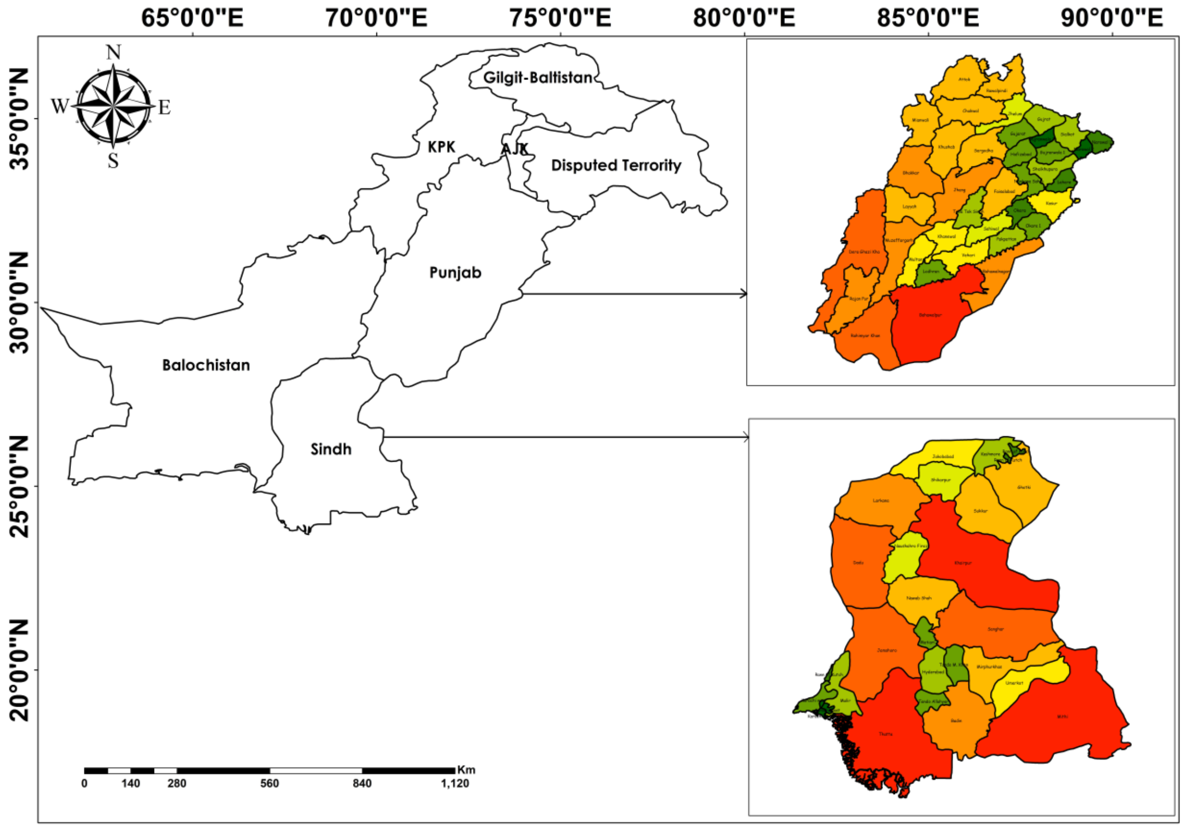


Figure 3.1. Map including different districts of Pakistan.

Pakistan has two crop seasons, the first of which is known as "Kharif" and lasts from April to June before being harvested in October and December. "Kharif" crops include rice, sugarcane, cotton, maize, moong, mash, bajra, and jowar. The second sowing season, "Rabi," runs from October through December and ends with harvest in April or May. The "Rabi" crops are wheat, gram, lentil (masoor), tobacco, rapeseed, barley, and mustard. Water for irrigation has a significant impact on Pakistan's agricultural output.

The most typical materials used to simulate open burning of crop leftovers are wheat straw, rice straw, sugarcane leaves, and maize straw. The main crop, wheat, provides about 45% of the daily calorie intake of the population. Wheat agriculture accounts for 66% of all agricultural land in the country, with an annual average area of 8.3 Mha. Nearly 70% of the nation's wheat is produced in Punjab province's districts, with the majority of the crop being cultivated under irrigation. While the actual planning date may change depending on numerous factors like weather conditions, wheat type, and water supplies, the wheat planting season begins in October and concludes in early December. Two thirds of the total wheat growing area in Pakistan is covered by the rice-wheat and cotton-wheat crop rotation systems.

Another important food grain is rice, which is only grown on 10% of Pakistan's total land area but contributes between 1.3 and 1.6% of the country's GDP. They are cultivated in different patterns due to the dominance of rice and wheat cultivation. Wheat is sown in the early winter, whereas rice, a Kharif crop, is grown in the monsoon months and requires ample water. According to the province, Punjab's Lahore, Gujranwala, Sheikhupura, Sargodha, Multan, and Bahawalpur districts contribute the most to the production of rice, followed by Sindh's Larkana, Khairpur, Sukkur, Nawab shah, and Hyderabad districts. Fall sowing occurs in Punjab and Sindh between September and October, and spring sowing starts in Punjab and Sindh around the middle of February and lasts until the end of March.

3.2. Data Collection:

3.2.1. Crop Production Data

The Agricultural Statistics of Pakistan (2001-2020) is where the statistical information on the output of wheat and rice crops is collected from. The data from 2001 to 2007 were gathered from the Pakistan Bureau of Statistics (PBS), while the data from 2007 onwards were gathered from the agricultural marketing wings of Sindh and Punjab, which provide annual production and per hectare area of major and minor crops at the district level, respectively.

3.2.2. Dry Mass Ratio

According to earlier research based on measurements made in the field, crop residue has a moisture content that ranges from 80 to 90% (Y. Zhang et al., 2013). Farmers typically burn crop debris before it has dried completely. The information in Table on the dry matter composition of garbage made of wheat and rice was gathered from well-respected studies.

3.2.3. Burning Efficiency

As it describes the extent to which different crop leftovers are burned, this component affects the rate at which emissions are produced. Therefore, the combustion efficiency is chosen based on the moisture content of the crops taken into account in the study.

Table 3.1 Combustion efficiency of crops

Crops	Combustion efficiency	Dry matter content
Wheat straw	0.86[b]	0.83[d, e]
Rice straw	0.89[a]	0.85d, e, g
(Turn et al., 1997) [a], (Streets, Yarber, et al., 2003a) [b], (Streets, Yarber, et al., 2003b) [c], (Iqbal & Goheer, 2008)[d], (Gadde et al., 2009) [e], (Kanabkaew & Oanh, 2011) [f], (Irfan et al., 2015) [g]		

3.2.4. Emission Factors

According to the US EPA (1995), Turnet al. (1997), and Hayset al. (2005), the types of crops and the burning technique have a significant impact on the gas and particle emissions that result from open burning. However, in accordance with Gaddeet al. Additionally, the gaseous emissions from the open field burning of rice straw in India, Thailand, and the Philippines were calculated using emissions factors for each gas species that were taken from several articles.

Table 3.2 Emission Factors of different crops

Crops	CO_2	CO	CH_4	NMVOCs	N_2O	NH_3	SO_2	NOx	$PM_{2.5}$	PM_{10}	OC	BC
Rice Straw	1105.2[a]	53.2[c, a]	5.82[b]	6.05[a]	0.07[g]	2.2[b]	0.38[e]	3.16 d, e, f	12.1[a]	3.7[d]	10.53[a]	0.49[a]
Wheat Straw	1557.9[c]	141.2[c]	3.55[i]	7.5[h]	0.07[h]	0.37[h]	0.85[h]	1.12[c]	7.58[h]	5.74[k]	3.46[j]	0.42[j]

(Y. Zhang et al., 2013)[a], (J. Li et al., 2016)[b], (H. Zhang et al., 2008)[c], (Kadam, Forrest, & Jacobson, 2000)[d], (Irfan et al., 2014)[e], (Gadde et al., 2009)[f], (Andreae, 2001)[g], (Sahai et al., 2007)[h], (Sahai et al., 2007)[i], (CAO, ZHANG, GONG, & ZHENG, 2008) j, (Turn et al., 1997) k, (Dennis et al., 2002) l, (Kanabkaew & Oanh, 2011) m

3.2.5. Satellite Data:

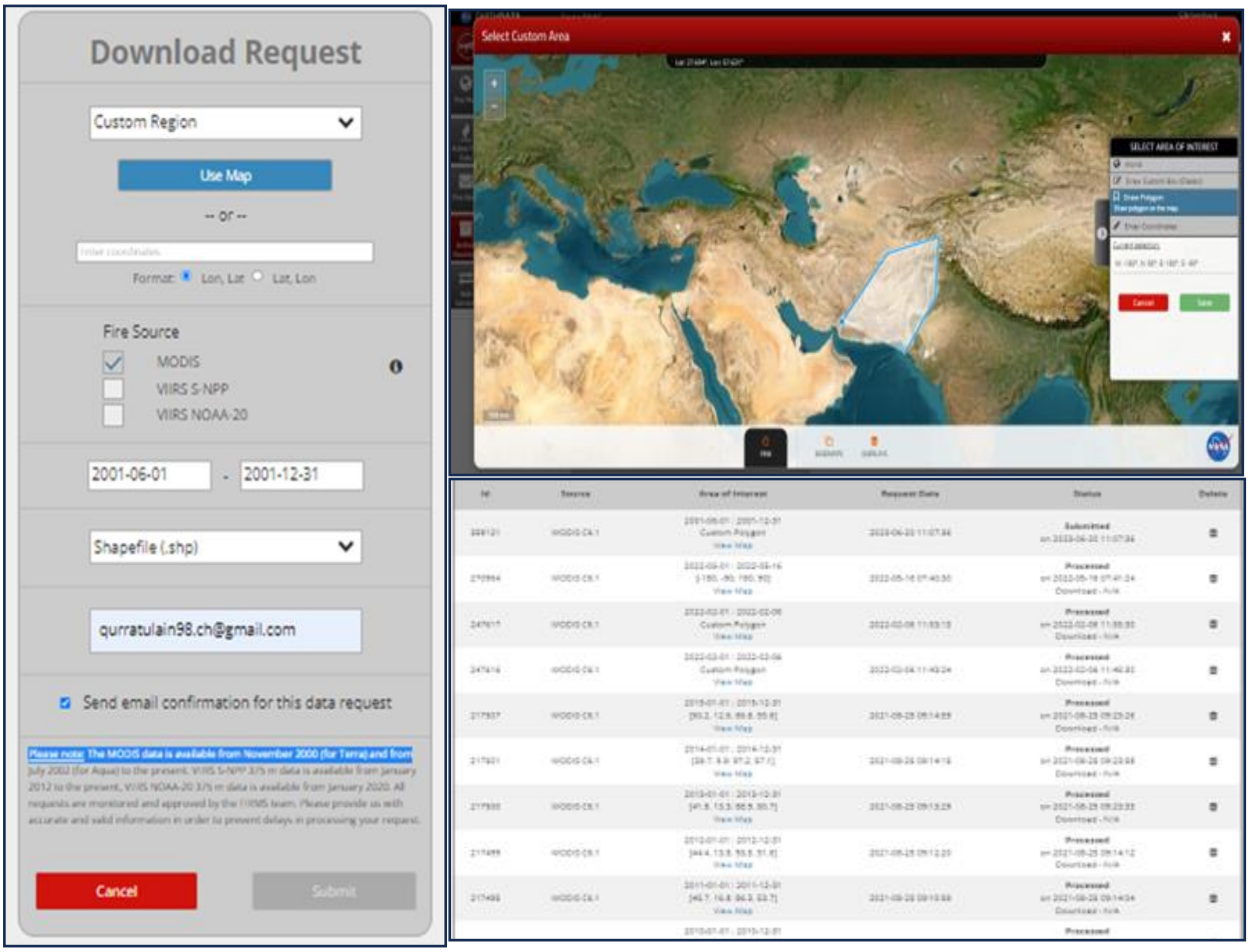
For the purpose of allocating quantified emissions over space and time, the study is based on the use of active fire data. Therefore, active fire data and photographs of the land cover from several sensors with varied resolutions were collected for this purpose. Since the study spans 20 years, photographs for the entire year—that is, from January 1 to December 31—were obtained. Cropland classification is done using data from MODIS Thermal Anomalies/Daily Fire L3, Version 006 for active fires and ESA CCI-LC Maps, which have a spatial resolution of 1 km and 300 meters, respectively.

1. **MODIS Collection 6 Active Fires Data**

It was necessary to obtain the two datasets with the same dates since the study proposes to use fire pixels taken from agricultural land for the distribution of emissions at the district level. Downloads of MODIS Active fire data in HDF format were made through the LPDAAC (Land Process Distributed Active Archive Centre) data connection for the AQUA (MYD14A1) and TERRA (MOD14A1) satellites. The data collected includes daily data in an 8-day composite with a spatial resolution of 1 km for the location of the fire.

The figure below illustrates how the obtained MODIS data was projected from a sinusoidal grid to the WGS 84 geographic coordinate system for further processing and mosaicked for tiles covering Pakistan using the MODIS Re-projection tool. The fire pixels were described using a higher confidence value.

Figure 3.2 showing that MODIS data attained was projected from sinusoidal grid to WGS84-Geographic coordinate system for further processing and mosaicked for tiles covering Pakistan using MODIS Re-projection tool. A higher confidence value was used for the characterization of



Custom Region

Format: ● Lon, Lat ○ Lat, Lon

☑ MODIS
☐ VIIRS S-NPP
☐ VIIRS NOAA-20

2001-06-01 - 2001-12-31

Shapefile (.shp)

qurratulain98.ch@gmail.com

☑ Send email confirmation for this data request

Please note: The MODIS data is available from November 2000 (for Terra) and from July 2002 (for Aqua) to the present. VIIRS S-NPP 375 m data is available from January 2012 to the present, VIIRS NOAA-20 375 m data is available from January 2020. All requests are monitored and approved by the FIRMS team. Please provide us with accurate and valid information in order to prevent delays in processing your request.

Figure 3.2 MODIS Active Fire Data

2. **MODIS Burned Area Product**

3.2.6. Estimation of the burned area from satellite observations

MODIS (MDC64A1), a satellite product, was downloaded from the NASA website at http://ladsweb.modaps.eosdis.nasa.gov. ArcMap was used to process the product. The raster files were changed from the 'hdf' format to the 'tiff' format. A single file was created by mosaicking the monthly readable files. The mosaics were taken from the Punjabi areas that made up the study region. Using the pixel counts, the burned area was computed for each Punjabi district.

3.3. Data Analysis:

The Punjab Agricultural Department provided information on agricultural production at the district level. Each district in Punjab had its rice production per hectare calculated. Each crop has a unique dry mass content and rate of combustion. Both values for rice were taken from the literature research. The following formula was created for the purpose of calculating pollutant emissions in this study using instructions from (HEC Report, 2021).

The calculation below was used to determine the total dry mass that had been burned.

$M = Ph \times A \times m \times e$

A = total burned area in the district, M = dry mass ratio of rice paddies, e = burning efficiency of rice paddies, Ph = rice production per hectare, and A = total dry mass burned.

Pollutant masses such CO_2, CO, CH_4, N_2O, SO_2, NO_x, $PM_{2.5}$, PM_{10}, OC, and BC were computed from the burned dry mass.

$X = M \times f$

Where f is the pollutant's emission factor, M is the total amount of dry mass burned, and X is the pollutant's mass in tons.

Further, using the carbon pricing from the World Bank, the economic/damage cost of the CO_2 emissions was estimated. The following calculations were made to determine the losses brought on by the CO_2 emission from the total dry mass burned;

$C = Ce \times \$$

Where C is the cost of CO_2 emissions, Ce is the amount of CO_2 emissions in tons, and $ is the cost in USD for each ton of CO_2 emissions, as obtained from (Wu et al., 2010).

The World Bank dashboard's "https://carbonpricingdashboard.worldbank.org/map data" was used to gather the values for carbon pricing for each year.

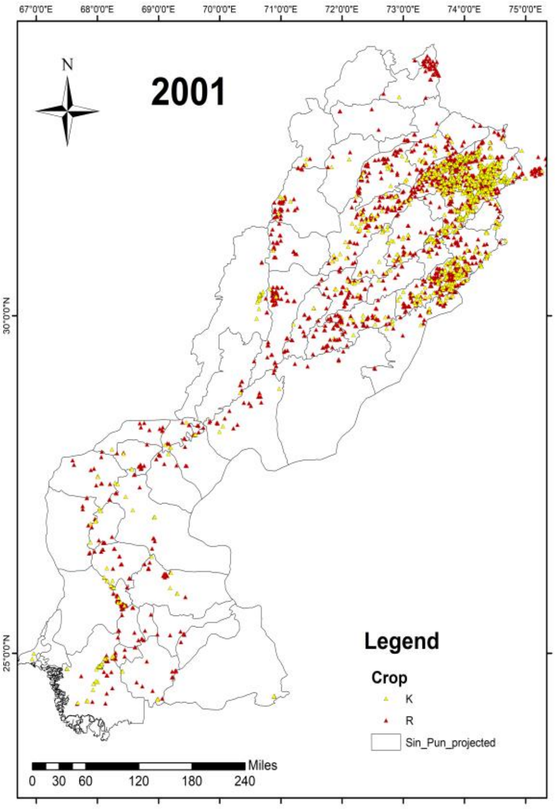
CHAPTER 4

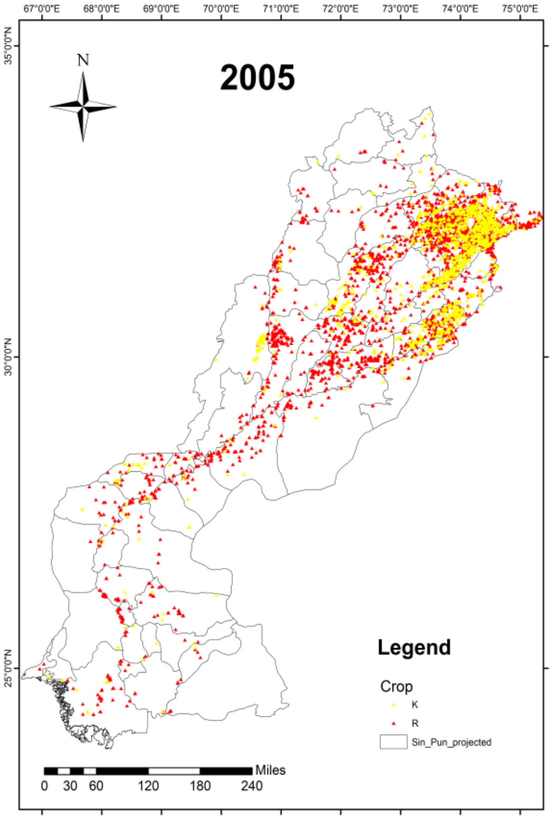
Results and Discussion

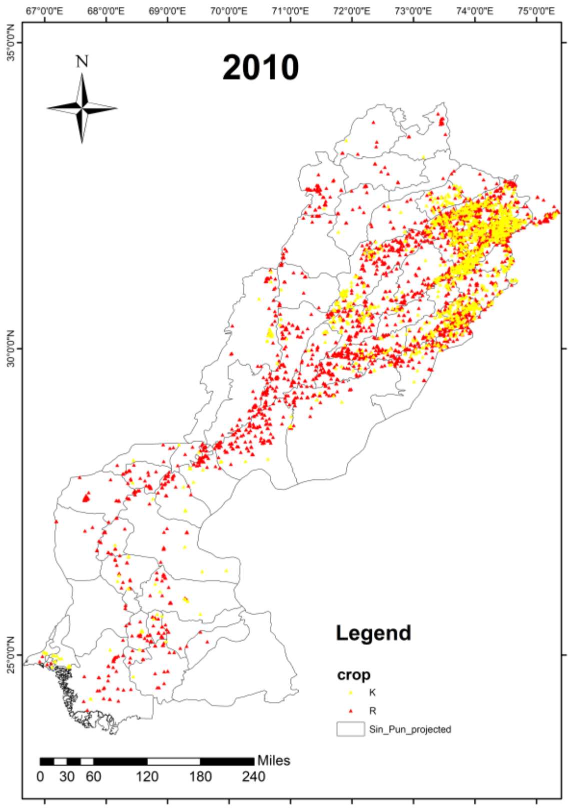
Fire counts:

Several socio-economic drivers and conditions lead to extensive open burning of solid and agricultural waste in developing countries like Pakistan. This practice of open biomass burning is a leading source of major air pollutants. Apart from the major air pollutants, open burning also releases atmospheric-warming agents like black carbon, organic carbon, and several greenhouse gases. The health and climate risks will greatly decrease because of a reduction in open burnings.

The spatial and temporal extent of fire counts across the province of Sindh and Punjab during 2001-2020 has been shown as below.



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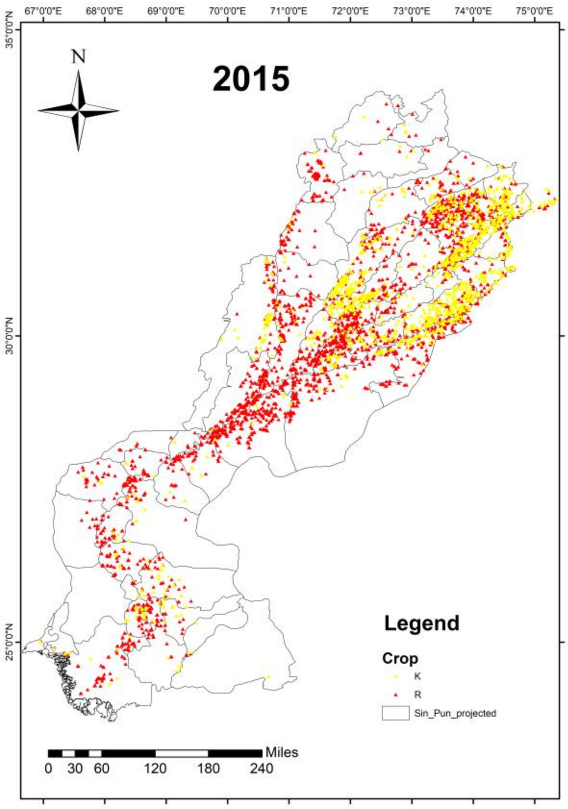
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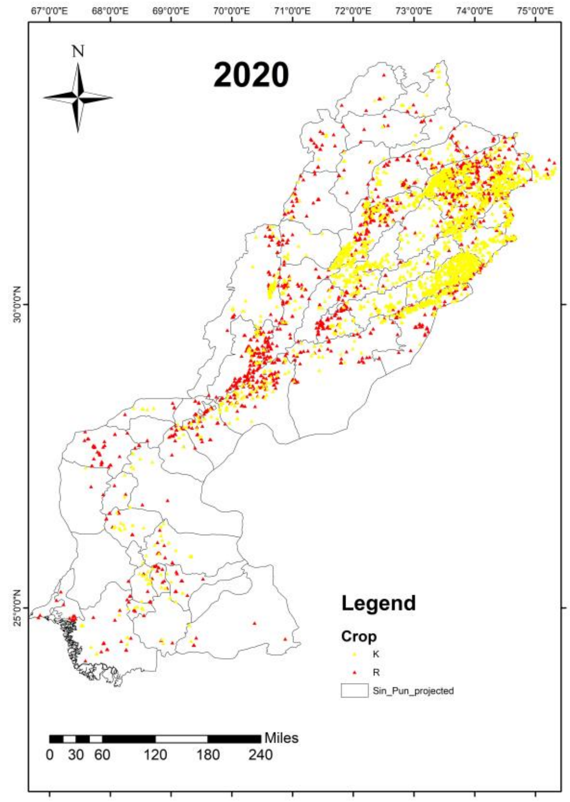

Figure 4.1 Spatial changes of Fire counts over the period of 20 years

4.1. Burned Area:

According to a recent study (Irfan et al., 2014), rice straw and bagasse, two major burning commodities, contributed more than 90% of the total gaseous pollutants emitted in Pakistan. The crop residue burning of rice husk, rice straw, corncobs, and bagasse emits 80 Gt, 5632 Gt, 3 Gt, 8.19 Gt, 15.70 Gt, and 1.42 Gt of CO, CO_2, NO_2, NO, NO_X, and SO_2, respectively. A dramatic increase of 40% CO is observed from the agriculture sector while other gaseous pollutants like CO_2, CH_4, N_2O, NH_3, NO_x, $PM_{2.5}$, OC, BC, and NMVOCs have increased between 37-63% from 2000-2015 (Azhar et al., 2019). These emissions were more prominent in the agricultural districts of Punjab and Sindh, probably due to their intensive vegetation cover.

The impacts of open solid waste burning on the air quality of Pakistan cannot be understated even though agricultural residue burnings contribute more to air pollution in Pakistan. The common practice of solid waste disposal in Pakistan involves solid waste being collected in communal bins, which are mostly set on fire for volume reduction, resulting in a huge amount of air pollution

(Nisar et al., 2008). The burning of solid waste usually results in emissions of hazardous compounds, although, emissions vary depending upon the type and nature of solid waste and the quantity of organic and inorganic fractions in it. These compounds include particulate matter, greenhouse gases like CO_2, CH_4, and N_2O, black carbon, persistent organic pollutants like dioxins, furans, and polycyclic aromatic hydrocarbons, and solid residues like bottom and fly ash with severe documented health impacts (Cogut, 2016).

Table 4.1: Burned area in Sq.km for Punjab and Sidh for both Rabi and Kharif seasons (2001-2020).

Table 4.1 Burned Area of Kharif and Rabi crops

Years	**Kharif (Sq.Km)**			**Rabi (Sq.Km)**		
	Punjab	**Sindh**	**Total**	**Punjab**	**Sindh**	**Total**
2001	106.5	924.75	1031.25	7655	3884	11539
2002	117.25	3625	3742.25	6573.75	2731.25	9305
2003	550	3073.75	3623.75	5721.25	1504.25	7225.5
2004	632	3537.25	4169.25	5116.5	2126	7242.5
2005	738	4362.5	5100.5	4711.5	1890.5	6602
2006	381	3111	3492	3675.5	1448.5	5124
2007	324.25	1006.25	1330.5	3542.25	566.75	4109
2008	410	3231.75	3641.75	4582.75	1187	5769.75
2009	726.75	4114	4840.75	3730.75	888.5	4619.25
2010	633.5	3764.5	4398	3974.875	1075.75	5050.625

2011	404.25	4285.75	4690	4910.375	1536.5	6446.875
2012	547.875	3724	4271.875	4755.25	1425.75	6181
2013	719	3997.75	4716.75	3889	1359.125	5248.125
2014	616.75	3049.25	3666	4063.25	682.75	4746
2015	677.5	3847	4524.5	3498.5	1074	4572.5
2016	759.375	4004.5	4763.875	4155.5	1030.25	5185.75
2017	810.25	4001.5	4811.75	4218.75	1586.5	5805.25
2018	813.25	3996.25	4809.5	4681.25	1488.5	6169.75
2019	717.75	4118.5	4836.25	3969.5	897.75	4867.25
2020	599.745	3841	4440.745	3471.5	1136.5	4608

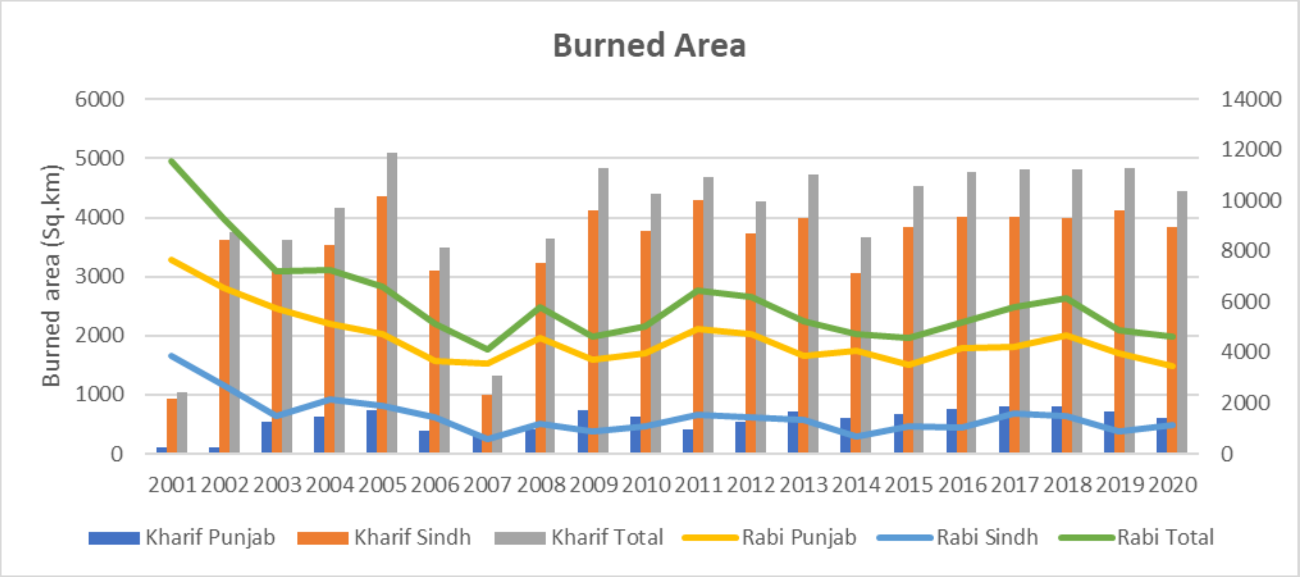

Figure 4.1 A burned area for both the Kharif and Rabi crops

In 2001, the burned area in Punjab was recorded as 106.5 Sq.Km, while in Sindh, it was 924.75 Sq.Km, resulting in a total burned area of 1031.25 Sq.Km. The year 2002 witnessed a significant increase in the burned area. Punjab reported 117.25 Sq.Km, whereas Sindh reported a much higher value of 3625 Sq.Km. The combined burned area for both provinces reached 3742.25 Sq.Km. Moving to 2003, Punjab experienced a burned area of 550 Sq.Km, while Sindh reported 3073.75 Sq.Km. The total burned area for the year was 3623.75 Sq.Km. In 2004, Punjab's burned area increased to 632 Sq.Km, and Sindh reported 3537.25 Sq.Km. The combined burned area for both provinces reached 4169.25 Sq.Km. The year 2005 saw a further increase in the burned area. Punjab reported 738 Sq.Km, and Sindh reported 4362.5 Sq.Km. The total burned area amounted to 5100.5 Sq.Km.

In 2006, Punjab recorded a burned area of 381 Sq.Km, and Sindh reported 3111 Sq.Km. The combined burned area for both provinces reached 3492 Sq.Km. Moving to 2007, Punjab reported 324.25 Sq.Km of burned area, while Sindh reported 1006.25 Sq.Km. The total burned area for the year was 1330.5 Sq.Km. In 2008, Punjab experienced a burned area of 410 Sq.Km, and Sindh reported 3231.75 Sq.Km. The combined burned area for both provinces reached 3641.75 Sq.Km. The year 2009 witnessed a higher burned area in both provinces. Punjab reported 726.75 Sq.Km, and Sindh reported 4114 Sq.Km. The total burned area for the year was 4840.75 Sq.Km. In 2010, Punjab recorded 633.5 Sq.Km of burned area, while Sindh reported 3764.5 Sq.Km. The combined burned area for both provinces reached 4398 Sq.Km.

Moving to 2011, Punjab reported 404.25 Sq.Km of burned area, and Sindh reported 4285.75 Sq.Km. The total burned area for the year was 4690 Sq.Km. In 2012, Punjab experienced a burned area of 547.875 Sq.Km, while Sindh reported 3724 Sq.Km. The combined burned area for both provinces reached 4271.875 Sq.Km. The year 2013 witnessed Punjab reporting 719 Sq.Km of burned area, and Sindh reported 3997.75 Sq.Km. The total burned area for the year was 4716.75 Sq.Km. In 2014, Punjab recorded 616.75 Sq.Km of burned area, while Sindh reported 3049.25 Sq.Km. The combined burned area for both provinces reached 3666 Sq.Km. Moving to 2015, Punjab reported 677.5 Sq.Km of burned area, and Sindh reported 3847 Sq.Km. The total burned area for the year was 4524.5 Sq.Km. In 2016, Punjab experienced a burned area of 759.375 Sq.Km, while Sindh reported 4004.5 Sq.Km. The combined burned area for both provinces reached 4763.875 Sq.Km.

The year 2017 witnessed Punjab reporting 810.25 Sq.Km of burned area, and Sindh reported. Moving to 2018, Punjab experienced a burned area of 813.25 Sq.Km, and Sindh reported 3996.25 Sq.Km. The combined burned area for both provinces reached 4809.5 Sq.Km. In 2019, Punjab recorded 717.75 Sq.Km of burned area, while Sindh reported 4118.5 Sq.Km. The total burned area for the year was 4836.25 Sq.Km. As for 2020, Punjab reported a burned area of 599.745 Sq.Km, and Sindh reported 3841 Sq.Km. The combined burned area for both provinces reached 4440.745 Sq.Km.

4.2. Crop Production

District-wise crop production data were not available for all the years, for Punjab province data was available but for the Sindh province, the production data of wheat crops was not available from 2013 onward.

Table 4.2 The crop production data for Wheat (Rabi) and Rice (Kharif) in Punjab and Sindh from 2001 to 2020 reveals the following key findings.

Years	Kharif (Kg/Sq.Km)			Rabi (Kg/Sq.Km)		
	Punjab	Sindh	Total	Pun	Sin	Total
2001	21514	11584	33098	82717	18568	101285
2002	24471	12994	37465	90127	18734	108861
2003	27285	14314	41599	103176	19576	122752
2004	28378	14993	43371	100221	22857	123078
2005	26896	17202	44098	104120	25169	129289

2006	29395	14560	43955	134995	30130	165125
2007	31259	14672	45931	102523	69728	172251
2008	34799	19776	54575	103839	95096	198935
2009	34799	19776	54575	104150	88980.5	193130.5
2010	31820	11128	42948	104461	82865	187326
2011	30726	19464	50190	105249	66074	171323
2012	32642	15655	48297	119199	70691	189890
2013	28921	26275	55196	95326	85411	180737
2014	34463.2	26173	60636.2	115902.1	NA	115902.1
2015	33121.8	26183	59304.8	118370.5	NA	118370.5
2016	32922.2	26193	59115.2	126770.9	NA	126770.9
2017	183851.4	26203	210054.4	127357.1	NA	127357.1
2018	43663.3	26213	69876.3	126473.9	NA	126473.9
2019	39061.8	26223	65284.8	138966.7	NA	138966.7
2020	49935	26233	76168	122753.1	NA	122753.1

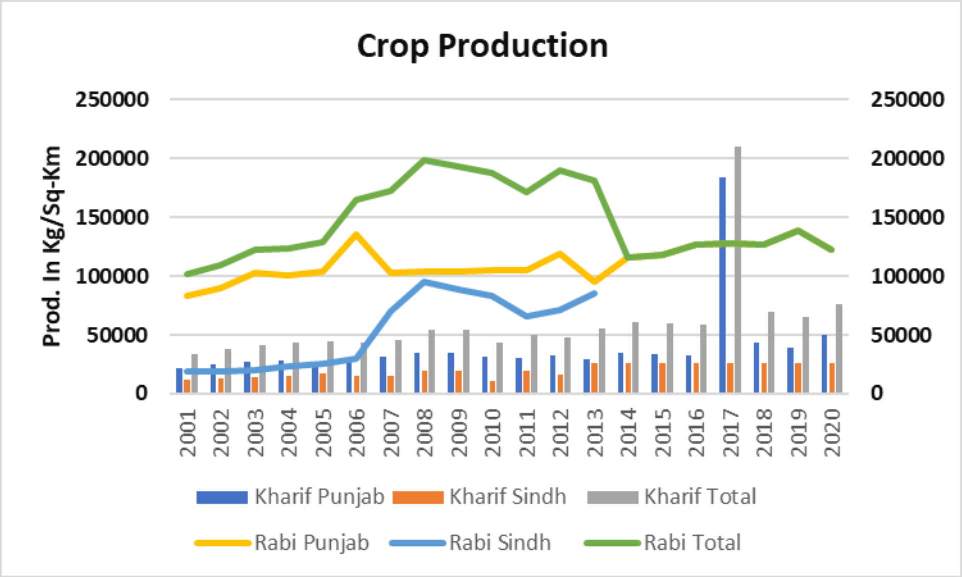

Figure 4.2 Crop production for Punjab and Sindh province in Kg/Sq-Km (2001-2020)

4.2.1. Wheat Production (Rabi Crop Season):

Punjab's Wheat production varied from 82,717 Kg/Sq.Km in 2001 to 138,966.7 Kg/Sq.Km in 2019, with an overall increasing trend. The highest production was recorded in 2019.

Sindh's Wheat production ranged from 18,568 Kg/Sq.Km in 2001 to 26,233 Kg/Sq.Km in 2020, with fluctuations over the years. The highest production was observed in 2020.

4.2.2. Rice Production (Kharif Crop Season):

Punjab's Rice production ranged from 21,514 Kg/Sq.Km in 2001 to 49,935 Kg/Sq.Km in 2020, with fluctuations over the years. The highest production was recorded in 2020.

Sindh's Rice production varied from 11,584 Kg/Sq.Km in 2001 to 26,233 Kg/Sq.Km in 2020, with fluctuations over the years. The highest production was observed in 2020.

The crop production data highlights several factors that may have influenced the trends and variations in Wheat and Rice production in Punjab and Sindh from 2001 to 2020.

4.3. Emission inventory

Table 4.3 Emission inventory of Kharif

The emissions of all the gases were calculated in tons/Sq.Km.

Years	CO_2	CO	CH_4	NMVOCs	N_2O	NH_3	SO_2	NO_x	$PM_{2.5}$	PM_{10}	OC	BC

2001	822453.1	39589.67	4331.051	4502.209	52.09167	1637.167	282.7834	2351.567	9004.418	2753.417	7836.076	364.6417
2002	2974867	143198.4	15665.69	16284.78	188.419	5921.74	1022.846	8505.771	32569.57	9959.289	28343.6	1318.933
2003	2629467	126572.3	13846.81	14394.03	166.5424	5234.191	904.0875	7518.202	28788.05	8802.958	25052.74	1165.797
2004	1003365	48298.05	5283.734	5492.542	63.55007	1997.288	344.9861	2868.832	10985.08	3359.075	9559.746	444.8505
2005	4372576	210478.7	23026.05	23936.01	276.9456	8704.005	1503.419	12502.12	47872.03	14638.55	41660.53	1938.619
2006	3504459	168690.9	18454.53	19183.84	221.9617	6975.94	1204.935	10019.99	38367.67	11732.26	33389.39	1553.732
2007	876578.1	42195.03	4616.073	4798.496	55.51978	1744.907	301.3931	2506.322	9596.991	2934.617	8351.762	388.6385
2008	4899819	235858.1	25802.52	26822.21	310.3396	9753.53	1684.701	14009.62	53644.42	16403.66	46683.94	2172.377
2009	4901535	2132887	117118.1	36811.99	10694.91	9873.682	5460.907	14661.87	59068.42	37172.8	53034.84	20246.67
2010	1716.457	1897029	91315.54	9989.782	10384.57	120.152	3776.206	652.2538	5424.006	20769.14	6350.893	18074.3
2011	7785723	374774.2	40999.73	42620	493.124	15498.18	2676.959	22261.02	85240	26065.12	74179.93	3451.868
2012	6074179	292387.2	31986.72	33250.8	384.72	12091.2	2088.48	17367.36	66501.59	20335.2	57872.88	2693.04
2013	6339769	305171.6	33385.32	34704.67	401.5416	12619.88	2179.797	18126.74	69409.34	21224.34	60403.33	2810.791
2014	89164342	4292022	469540.8	488096.5	5647.398	177489.6	30657.3	254939.7	976193	298505.3	849530	39531.78
2015	84908569	4087166	447129.8	464799.9	5377.85	169018.1	29194.04	242771.5	929599.8	284257.8	808982.3	37644.95
2016	88543778	4262151	466272.9	484699.5	5608.093	176254.4	30443.93	253165.3	969398.9	296427.8	843617.4	39256.65
2017	87719658	4222481	461933.1	480188.1	5555.896	174613.9	30160.58	250809	960376.3	293668.8	835765.5	38891.27
2018	88723910	4270822	467221.5	485685.5	5619.502	176612.9	30505.87	253680.4	971371.1	297030.8	845333.7	39336.51
2019	91286859	4394192	480718	499715.4	5781.831	181714.7	31387.09	261008.4	999430.9	305611.1	869752.6	40472.82
2020	92718383	7083329	614377	521337.6	20216.43	184725.5	37094.5	265995.6	1022570	339083.8	892141.6	66072.26

The provided data presents the emission inventories for several greenhouse gases (GHGs) across different years. Let's analyze the minimum and maximum values recorded for each GHG and discuss their implications.

CO_2: In 2002, the minimum CO_2 emissions were recorded at 269,081.4 tonns/Sq.Km. This sharp decline from the previous year (2001) can be attributed to various factors such as changes in energy consumption patterns, economic fluctuations, or policy interventions. The highest CO_2 emissions were observed in 2018, reaching 22,857,507 tonns/Sq.Km.

CO: In 2002, the lowest CO emissions were recorded at 24,388.15 tonns/Sq.Km. Similar to CO_2, this decline might be associated with changes in industrial processes, energy sources, or emission control measures. The highest CO emissions occurred in 2019, reaching 2,293,958 tonns/Sq.Km.

CH_4: In 2002, the minimum CH_4 emissions were observed at 613.1581 tonns/Sq.Km. The highest CH_4 emissions were recorded in 2020, amounting to 57,673.88 tonns/Sq.Km.

NMVOCs: In 2002, the minimum Non-Methane Volatile Organic Compounds (NMVOCs) emissions were observed at 1,295.404 tonns/Sq.Km. The highest NMVOCs emissions occurred in 2020, reaching 121,846.2 tonns/Sq.Km.

N_2O: In 2002, the lowest N_2O emissions were recorded at 12.09044 tonns/Sq.Km. The highest N_2O emissions were observed in 2018, amounting to 1,137.231 tonns/Sq.Km.

NH_3: The lowest NH_3 emissions were recorded in 2002, amounting to 63.90662 tonns/Sq.Km. The highest NH3 emissions occurred in 2018, reaching 18,195.7 tonns/Sq.Km.

SO_2: In 2002, the minimum SO_2 emissions were observed at 146.8125 tonns/Sq.Km. The highest SO_2 emissions were recorded in 2008, amounting to 12,471.2 tonns/Sq.Km.

NO_x: In 2002, the lowest NOx emissions were observed at 193.4471 tonns/Sq.Km. The highest NO_x emissions occurred in 2018, reaching 16,432.64 tonns/Sq.Km.

$PM_{2.5}$: In 2002, the minimum $PM_{2.5}$ emissions were recorded at 1,309.222 tonns/Sq.Km. The highest $PM_{2.5}$ emissions were observed in 2020, amounting to 123,145.9 tonns/Sq.Km.

PM_{10}: In 2002, the lowest PM_{10} emissions were observed at 991.4162 tonns/Sq.Km. The highest PM_{10} emissions occurred in 2020, reaching 93,252.98 tonns/Sq.Km.

OC (Organic Carbon): In 2002, the minimum OC emissions were recorded at 597.6133 tonns/Sq.Km. The highest OC emissions were observed in 2020, amounting to 56,211.73 tonns/Sq.Km.

BC (Black Carbon): In 2002, the lowest BC emissions were observed at 72.54265 tonns/Sq.Km. The highest BC emissions occurred in 2020, reaching 6,823.389 tonns/Sq.Km.

Overall, the emissions from Rabi crop cultivation showed some variations and changing patterns for different pollutants over the 20-year period. The increase in CO_2 and CO emissions until 2010 highlights the need for mitigation measures to curb greenhouse gas emissions from agricultural activities. The fluctuating trends observed for CH_4, NMVOCs, $PM_{2.5}$, PM_{10}, OC, and BC indicate the complexity and variability of emissions from Rabi crop cultivation. The increasing trend in NH_3 emissions signifies the importance of addressing ammonia release and its potential impact on air quality and ecosystem health.

The decreasing trends observed for SO_2 and NO_x emissions indicate positive developments in emission control strategies, which may have contributed to improved air quality in the region. However, the significant increase in N_2O emissions after 2010 requires further investigation to understand the underlying causes and implement measures to mitigate its impact.

Table 4.4 Emission inventory for Rabi

Years	**CO_2**	**CO**	**CH_4**	**NMVOCs**	**N_2O**	**NH_3**	**SO_2**	**No_x**	**$PM_{2.5}$**	**PM_{10}**	**OC**	**BC**
2001	822453.1	39589.67	4331.051	4502.209	52.09167	1637.167	282.7834	2351.567	9004.418	2753.417	7836.076	364.6417
2002	2974867	143198.4	15665.69	16284.78	188.419	5921.74	1022.846	8505.771	32569.57	9959.289	28343.6	1318.933
2003	2629467	126572.3	13846.81	14394.03	166.5424	5234.191	904.0875	7518.202	28788.05	8802.958	25052.74	1165.797

2004	1003365	48298.05	5283.734	5492.542	63.55007	1997.288	344.9861	2868.832	10985.08	3359.075	9559.746	444.8505
2005	4372576	210478.7	23026.05	23936.01	276.9456	8704.005	1503.419	12502.12	47872.03	14638.55	41660.53	1938.619
2006	3504459	168690.9	18454.53	19183.84	221.9617	6975.94	1204.935	10019.99	38367.67	11732.26	33389.39	1553.732
2007	876578.1	42195.03	4616.073	4798.496	55.51978	1744.907	301.3931	2506.322	9596.991	2934.617	8351.762	388.6385
2008	4899819	235858.1	25802.52	26822.21	310.3396	9753.53	1684.701	14009.62	53644.42	16403.66	46683.94	2172.377
2009	4901535	2132887	117118.1	36811.99	10694.91	9873.682	5460.907	14661.87	59068.42	37172.8	53034.84	20246.67
2010	1716.457	1897029	91315.54	9989.782	10384.57	120.152	3776.206	652.2538	5424.006	20769.14	6350.893	18074.3
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2014	89164342	4292022	469540.8	488096.5	5647.398	177489.6	30657.3	254939.7	976193	298505.3	849530	39531.78
2015	84908569	4087166	447129.8	464799.9	5377.85	169018.1	29194.04	242771.5	929599.8	284257.8	808982.3	37644.95
2016	88543778	4262151	466272.9	484699.5	5608.093	176254.4	30443.93	253165.3	969398.9	296427.8	843617.4	39256.65
2017	87719658	4222481	461933.1	480188.1	5555.896	174613.9	30160.58	250809	960376.3	293668.8	835765.5	38891.27
2018	88723910	4270822	467221.5	485685.5	5619.502	176612.9	30505.87	253680.4	971371.1	297030.8	845333.7	39336.51

2019	91286859	4394192	480718	499715.4	5781.831	181714.7	31387.09	261008.4	999430.9	305611.1	869752.6	40472.82
2020	92718383	7083329	614377	521337.6	20216.43	184725.5	37094.5	265995.6	1022570	339083.8	892141.6	66072.26

CO_2 Emissions: The CO_2 emissions from rice crop cultivation have shown an increasing trend over the 20-year period, from 822,453.13 tonns/Sq.Km in 2001 to 92,718,383.4 tonns/Sq.Km in 2020. This significant rise in CO_2 emissions indicates a growing impact on climate change.

CO Emissions: Carbon monoxide (CO) emissions also increased over the years, with a substantial spike in 2020, reaching 7,083,328.66 tonns/Sq.Km. High CO emissions can have detrimental effects on air quality and human health.

CH_4 Emissions: Methane (CH_4) emissions from rice crop cultivation have fluctuated but generally increased over the 20-year period. From 4,331.05 tonns/Sq.Km in 2001, they reached 614,376.98 tonns/Sq.Km in 2020. Methane is a potent greenhouse gas that contributes to global warming.

NMVOC Emissions: Non-methane volatile organic compounds (NMVOCs) emissions have also shown an increasing trend, reaching 521,337.56 tonns/Sq.Km in 2020. NMVOCs play a significant role in the formation of ground-level ozone and contribute to air pollution.

N_2O Emissions: Nitrous oxide (N_2O) emissions, another potent greenhouse gas, have increased over the years, with a substantial rise observed in 2020 at 20,216.43 tonns/Sq.Km. N_2O emissions contribute to climate change and ozone depletion.

NH_3 Emissions: Ammonia (NH_3) emissions, which can contribute to air pollution and have implications for ecosystem health, have fluctuated over the years but remained relatively high. In 2020, NH_3 emissions were reported at 184,725.53 tonns/Sq.Km.

SO_2 Emissions: Sulfur dioxide (SO_2) emissions, associated with industrial activities and burning fossil fuels, have increased over the 20-year period. In 2020, SO_2 emissions were reported at

37,094.50 tonns/Sq.Km.

NO_x Emissions: Nitrogen oxides (NO_x) emissions, including nitrogen dioxide (NO_2) and nitric oxide (NO), have shown fluctuations but no clear trend over the years. In 2020, NO_x emissions were reported at 265,995.59 tonns/Sq.Km.

$PM_{2.5}$ and PM_{10} Emissions: Particulate matter ($PM_{2.5}$ and PM_{10}) emissions, which have adverse health effects and contribute to air pollution, have increased steadily over the 20-year period. In 2020, $PM_{2.5}$ emissions reached 1,022,569.70 tonns/Sq.Km, and PM_{10} emissions reached 339,083.78 tonns/Sq.Km.

Organic Carbon (OC) and Black Carbon (BC) Emissions: Emissions of organic carbon (OC) and black carbon (BC) have followed a similar pattern to $PM_{2.5}$ and PM_{10} emissions. In 2020, OC emissions were reported at 892,141.59 tonns/Sq.Km, and BC emissions were reported at 66,072.26 tonns/Sq.Km.

4.4 Economic Cost

4.4.1 Economic Cost of Emitted Pollutants

Carbon pricing curbs greenhouse gas emissions by placing a fee on emitting and/or offering an incentive for emitting less. The price signal created shifts in consumption and investment patterns, making economic development compatible with climate protection.

Carbon pricing is advancing rapidly as an approach to spur climate action. By 2020, 25 percent of global emissions are expected to be under some carbon pricing mechanism. A large and growing number of non-Annex I countries under the UNFCCC are pursuing carbon pricing: South Korea, China, Thailand, Singapore, Bangladesh, Kazakhstan, South Africa, Côte d’Ivoire, Colombia, Chile, Argentina, Brazil, Mexico, Panama, Trinidad and Tobago, others. Recently, the V20, a group of 20 developing countries vulnerable to climate change, announced its intention to adopt carbon pricing by 2025.

4.4.3. How Does Carbon Pricing Work?

Carbon pricing works by capturing the external costs of emitting carbon - i.e. the costs that the public pays, such as loss of property due to rising sea levels, the damage to crops caused by changing rainfall patterns, or the health care costs associated with heat waves and droughts - and placing that cost back at its source.

Carbon Pricing effectively shifts the responsibility of paying for the damages of climate change from the public to the GHG emission producers. This gives producers the option of either reducing their emissions to avoid paying a high price or continuing emitting but having to pay for their emissions.

Carbon Pricing also creates a price signal that reduces, or regulates, GHG emissions and at the same time provides a strong financial case for shifting investments away from high-emission fossil-fuels-based technology toward cleaner technology.

4.4.4. Current Status of Carbon Pricing in the World:

Momentum is building around the world for carbon pricing instruments:

- Currently 40 national and 25 sub-national jurisdictions put a price on carbon.
- These carbon pricing initiatives cover 8 gigatons of CO_2e, which is equal to 15% of global GHG emissions.
- Of the 46 carbon pricing initiatives underway or planned for implementation, 23 are ETSs, applied mainly across subnational jurisdictions, and 23 are carbon taxes, primarily implemented on the national level.

Various carbon pricing approaches are being implemented. They tend to fall on the continuum between purely a price signal and purely an ETS. They are designed to benefit from both the predictable pricing of a price signal and the flexibility offered by an ETS. The emerging trend across carbon pricing approaches is a move towards the international linkage of carbon markets.

4.4.5. Carbon Price Signal

In 2008, the Canadian province of British Columbia put in place a carbon tax on fossil fuels burned for transportation, home heating, and electricity. The approach covers 70% of the province's total GHG emissions and is revenue neutral, implying that all the revenue earned via the carbon tax is returned to the citizens of British Columbia in the form of reductions to personal income tax, corporate income tax, and property tax, among others.

4.4.6. Emission Trading System

China is launching a national ETS. Once implemented, it will be the largest ETS in the world, covering approximately 40% of China's GHG emissions. China has also signed a bilateral plan with New Zealand to cooperate on carbon markets and is working on identifying opportunities for collaboration or linking markets with other countries in the Asia-Pacific region.

4.4.7. Mixed Systems

In 2014, Mexico introduced a $3.50/tonne carbon price on fossil fuels and is currently preparing for a national ETS, planned for 2018. The goal is to allow emitters to use certified emission reductions (CERs) from Clean Development Mechanism projects for compliance. Mexico has also signed an MoU with the US State of California to potentially link its ETS with the California cap-and-trade program.

The South African carbon pricing approach allows for the cancellation of offsets to mitigate the tax liability of emitters. In other words, emitters will be able to purchase and cancel offsets to reduce their carbon tax liability up to a certain limit.

4.4.8. Can countries use carbon pricing for achieving their NDCs?

Two-thirds of all submitted Nationally Determined Contributions (NDCs) under the Paris Agreement consider the use of carbon pricing to achieve their emission reduction targets. This means 100 countries are looking into carbon pricing as a way to achieve their NDC through international trading of emissions, offsetting mechanisms, carbon taxes, and other approaches. According to the World Bank, using carbon pricing approaches on a large scale to meet the emission reduction targets set in NDCs could reduce the cost of climate change mitigation by 32% by 2030.

While putting a price on carbon is a low-cost, efficient way to achieve mitigation targets as expressed in NDCs, these approaches must be coupled with complementary energy and environment policies to truly harness the potential that carbon pricing promises.

4.4.9. Paris Agreement and Carbon Pricing:

The Paris Agreement of 2015 marked a turning point for international climate action. For the first time, all nations came together in the common cause of combatting climate change. The Agreement aims to keep global temperature rise to well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further, to 1.5 degrees Celsius. To achieve these ambitious goals the Agreement sets in place provisions for enhanced cooperation among nations on climate change mitigation, including through market-based approaches, such as carbon pricing.

These provisions are elaborated in the following articles of the Paris Agreement:

- **Article 6.2:** Establishes the potential of trading emission reduction credits across borders, between nations or jurisdictions. This can encourage the linking of carbon pricing approaches across countries and jurisdictions resulting in the reduction of emissions by a magnitude greater than what is possible solely domestically or nationally.

- **Article 6.4:** Creates a new international mitigation mechanism to help countries reduce emissions and promote sustainable development. The mitigation engendered under this mechanism can also be used by Parties other than the host Party to fulfil their NDC. In other words, this provision allows for offsetting through the trading of emission reduction credits.

- **Article 6.5:** Puts in place robust accounting measures to avoid double counting of emission reductions and increase transparency, thereby ensuring the integrity of the proposed market-based approaches.

Table 4.5 Economic cost of Rabi and Kharif in US $:

Cities	Kharif (US$)			Rabi (US$)		
	Pun	Sin	Total	Punjab	Sindh	Total
2001	851977.9	13252968	14104946	4.86E^{+08}	62479546	5.48E^{+08}
2002	2500481	48418218	50918699	2.88E^{+08}	73022930	3.61E^{+08}
2003	5211680	40310539	45522219	1.77E^{+08}	44679503	2.22E^{+08}
2004	12318128	6826427	19144555	3.96E^{+08}	48854828	4.44E^{+08}
2005	15002209	61785366	76787575	3.41E+08	54413432	3.95E^{+08}
2006	4512290	50531860	55044151	2.36E^{+08}	65956809	3.02E^{+08}
2007	3068989	68008637	71077625	76759491	55821447	1.33E^{+08}
2008	10981139	67143768	78124907	1.18E^{+08}	1.11E^{+08}	2.29E^{+08}

2009	1.78E^{+08}	1.21E^{+08}	2.99E^{+08}	1.41E^{+08}	99304349	2.4E^{+08}
2010	3.34E^{+08}	1.07E^{+08}	4.41E^{+08}	1.63E^{+08}	87565557	2.51E^{+08}
2011	8565072	50477375	59042447	3.37E^{+08}	1.37E^{+08}	4.74E^{+08}
2012	11501963	37769401	49271365	2.3E+08	1.35E+08	3.64E^{+08}
2013	15912257	38114424	54026680	2465	2.22E^{+08}	2.22E^{+08}
2014	11379260	7.29E^{+08}	7.4E^{+08}	1.34E^{+08}	NA	1.34E^{+08}
2015	6702903	6.92E^{+08}	6.99E^{+08}	2.2E^{+08}	NA	2.2E^{+08}
2016	17357120	1.74E^{+09}	1.76E^{+09}	71001996	NA	71001996
2017	21176.98	1.74E^{+09}	1.74E^{+09}	78944932	NA	78944932
2018	23381058	1.74E^{+09}	1.76E^{+09}	75167634	NA	75167634
2019	20292072	1.79E^{+09}	1.81E^{+09}	47795469	NA	47795469
2020	8.32E^{+08}	1.67E^{+09}	2.5E^{+09}	28839817	NA	28839817

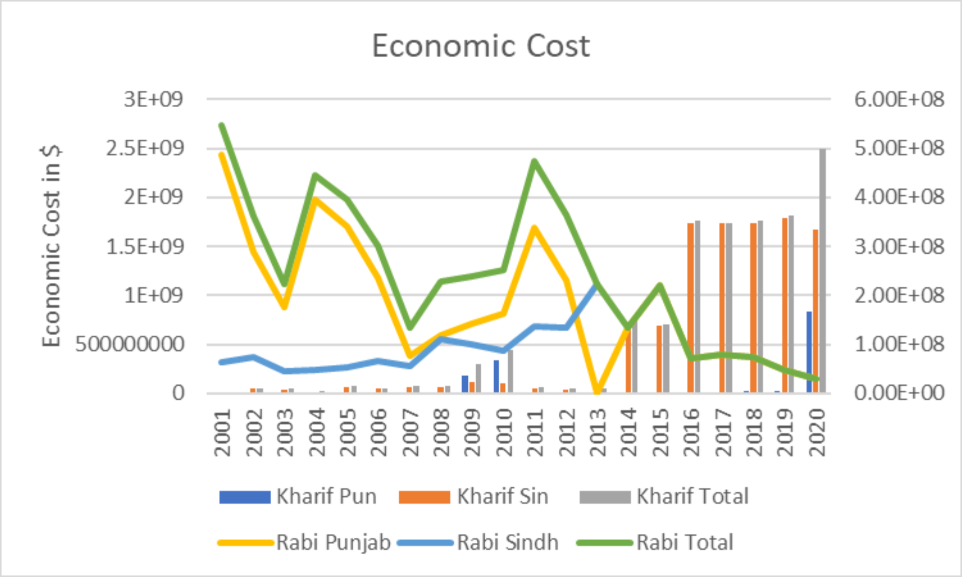

Figure 4.3: Economic Cost of crop residue burning during 2001-2020 in the province of Punjab and Sindh

3.5 Kharif Crop Economic Costs:

The total economic costs of Kharif crops showed an upward trend over the years, with some fluctuations. The highest economic costs for Kharif crops were observed in 2020, reaching $2,501,879,313. This represented a substantial increase compared to previous years. Among the cities, Punjab consistently had higher economic costs for Kharif crops compared to Sindh.

3.6 Rabi Crop Economic Costs:

The economic costs of Rabi crops also exhibited an upward trend with fluctuations over the analyzed period. The highest economic costs for Rabi crops were observed in 2016, totaling $1,755,854,895. Similar to Kharif crops, Punjab consistently had higher economic costs for Rabi crops compared to Sindh.

Regional Disparities:

Punjab consistently had higher economic costs for both Kharif and Rabi crops compared to Sindh. This suggests that Punjab may have had larger cultivation areas, higher agricultural productivity, or different crop preferences compared to Sindh.

Year-to-Year Variations:

Both Kharif and Rabi crops experienced significant year-to-year variations in economic costs. These variations could be influenced by factors such as weather conditions, market prices, government policies, and agricultural practices.

3.7 Overall Economic Costs:

The total economic costs of Kharif and Rabi crops increased over the years, indicating potential growth in production or prices. The economic costs of Kharif crops generally exceeded those of Rabi crops throughout the analysed period.

It is important to note that without further contexts, such as the unit of measurement and specific crop categories, it is challenging to interpret the absolute magnitude of the economic costs. Additionally, a more detailed analysis would require considering other factors, such as inflation and population growth.

CHAPTER 5

Conclusion

Over recent years, crop residue burning has become a widely practiced agricultural activity in developing countries due to varying economic and social reasons. To estimate current pollution generation from crop residue burning in Pakistan, an accurate emission inventory was developed based on district-level crop production data from 2001-2020. Spatial distribution of quantified emissions was achieved by using MODIS Active Fire Data (MOD/MYD14A1) at 1-day temporal and 1×km spatial resolutions. Total annual emissions of CO_2, CO, CH_4, NMVOCS, N_2O, NH_3, SO_2, NO_x, $PM_{2.5}$, PM_{10}, OC and BC in 2020 were 0.12, 0.009, 0.0007, 0.0006, $2.13E^{-05}$, 0.0002, $5.09E^{-05}$, 0.0003, 0.001, 0.0004, 0.0009, and $7.28E^{-05}$Tg respectively. Spatially, throughout the study period 2001-2020, Dadu, Larkana and Layyah had the highest emissions as compared to other areas of Pakistan. Temporally crop residue burning was dependent on the harvesting seasons, with the highest concentration in May followed by February, November and December. There was a significant increase in pollutant emissions over 20 years ranging from 18% for N_2O to 26% for NH_3. The environmental cost of Kharif was highest during 2019 for Sindh and 2020 for Punjab with the values $1.79E^{+09}$ and $8.32E^{+08}$ respectively. While the environmental cost of rabi crops was highest in 2013 with the value $2.22E^{+08}$ In Sindh. Comparison with other studies revealed that the results of this study are more reliable and accurate. The observed trend suggested that emissions will continue to rise in future due to absence of policy intervention.

Recommendations

The study aimed at developing more accurate emission estimates for Pakistan from open burning of crop residues:

- Emission Factor and chemical species considered are the most important parameters in emission estimation, so more localized emission factors for different straw types needs to be developed for better emission estimates.
- High temporal resolution satellite data should be used to provide hourly emission information for developing adequate control policy.
- Fraction of crop residue burned on field plays vital role in calculating the amount of crop residue burned so surveys should be conducted in all districts of Pakistan to understand the local behaviors of farmers i.e. when, where and how farmers burn residues.
- The availability of district-wise crop production data for the Sindh province is limited, which hinders our ability to understand the farmers' interests and discern overall trends over the year, it should be available.
- Governments can implement policies and interventions to promote sustainable agricultural practices and discourage crop residue burning.
- Initiatives such as providing incentives for residue management techniques like mulching, composting, and bioenergy production can be effective.

CHAPTER 6

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