Low-hanging fruit in black carbon mitigation: crop residue burning in South Asia

Abstract

Biomass burning in South Asia is a significant contributor to global emissions of black carbon, the second most important greenhouse agent after carbon dioxide. Emissions from domestic fires are the largest contributor to biomass burning but may be costly to mitigate. Open field burning is the second-largest contributor to black carbon in South Asia. This study uses primary field data to identify the determinants of emissions from open-field burning of crop residue with the aim of analysing possibilities for its regulation. The effectiveness of a new seeding machine that lets farmers plant their crops without having to burn the residue from the previous crop is assessed. A comparison of the new machine with conventional practice shows that the new technology decreases field preparation costs but does not significantly impact crop yield and profits. The use of plot-level data with farmer fixed effects enables reliable identification of the impacts of the technology. Given the considerable adverse effects on mortality and health of pollution from burning, these results imply that this source of black carbon can be mitigated at zero private cost and negative social cost. Since farmers have no strong private incentive to adopt the new technology, extension and subsidies to accelerate adoption would be a high net-benefit policy.

Key Words: Crop Residue Burning, Black Carbon Emissions, Happy Seeder Technology, Asia

JEL CLASSIFICATION CODE: Q15

1 Introduction

Biomass burning in South Asia is a significant contributor to global emissions of black carbon, the second most important greenhouse agent after carbon dioxide. Emissions from domestic fires are the largest contributor to biomass burning but may be costly to mitigate. Open field burning is the second-largest contributor to black carbon in South Asia (Bond et al., 2013). This source contributes about 20% of carbonaceous aerosol emissions in South Asia (Venkataraman et al., 2006). Previous studies have focused on estimating emissions from open burning of agricultural fields or on analysing its impact on climate and public health. Thus, it is widely recognised to be a key environmental problem facing this region. Yet policy makers have done little to solve it as mitigation strategies for dealing with this problem remain unexplored. Consequently, residue burning goes unchecked in Asia. This study attempts to fill this gap. I use primary field data to identify the determinants of emissions from open-field burning of crop residue with the aim of analyzing possibilities for its regulation. Curbing emissions of black carbon has an immediate payoff because black carbon is quickly washed out and can be eliminated from the atmosphere if emissions stop (Bond et al., 2013).

Reductions in emissions of black carbon are warranted from considerations of regional climate change and human health. For example, in the Himalayan region, heating from black carbon at higher elevations has as large an effect on the melting of snow packs and glaciers as heating due to greenhouse gases (Ramanathan and Carmichael, 2008). This not only has implications for the hydrological cycle, it also intensifies warming. As the glaciers melt, darker areas beneath them get exposed that in turn absorb more sunlight.

Black carbon being a component of particulate matter (PM) has a large adverse impact on public health. The Global burden of Disease study (2010) attributes 6% of all deaths in India in 2010 to ambient particulate matter pollution. Preventing black carbon can prevent on average 0.7-4.6 million premature deaths annually from outdoor air pollution world-wide by 2030, particularly in Asia (UNEP, 2011).

Open burning of agricultural residue contributes to the creation of the Atmospheric Brown Cloud, a layer of air pollution that covers large parts of South Asia (Gustafsson et al., 2009). Atmospheric Brown Cloud consists of aerosols such as black carbon, organic carbon, dust, sulfates and nitrates. Ramanathan et al. (2005) attribute the observed decrease in all India averaged monsoon rainfall since 1950's (June-September) to Atmospheric Brown Clouds. Auffhammer et al. (2006) found that joint reductions in brown clouds and green-house gases had complementary, positive impacts on rice harvests in India over the period 1972-1998. Harvest reductions attributed to brown cloud pollution are estimated to have grown from 3.94% during the 1966-84 period to 10.6% during the 1985-1998 period.

The impact of black carbon on regional climate, in conjunction with its health impacts provides a strong rationale for reducing black carbon emissions in developing countries like India where they have been rising overtime. Between 1996 and 2010, black carbon emissions increased by 41% in India (Lu et al., 2011). Estimates from (Venkataraman et al., 2006). indicate that farmers in India burnt 116 million metric tonnes of crop residue in 2001, but with a strong regional variation. Open burning of cereal residue was estimated to account for about 14% of black carbon and organic matter, and 10% carbon monoxide emissions, 9% of PM2.5 (particulate mass in particles smaller than 2.5 micron diameter), 6% carbon dioxide emissions, and about 1% of sulphur dioxide emissions in India. Field burning in the major agricultural states of Punjab, Haryana and Western Uttar Pradesh was the largest contributor to these emissions. Yang et al. (2008) estimated the emissions from crop residue burning in the Suqian region of the Jiangsu Province of China. Their results suggest that farmers burnt about 82% of the wheat straw and 32% of the rice straw in the field during the period 2001-2005. Gadde et al. (2009) estimate that farmers annually burn about 10 million tons of rice straw in Thailand and 10 million tons of rice straw in Philippines.

Biomass regulation from open burning of agricultural residue, therefore, becomes both a national and an international priority. Here, I investigate the following questions: what factors explain the open-field burning of rice residue in India and what are the available alternatives to this practice? Understanding why farmers resort to burning is essential for policy makers to arrive at suitable mitigation policies which would reduce rice residue burning in the region.

Burning of rice residue is a part of the 'rice-wheat cropping system' (RWCS) that is the dominant cropping system in the Indo-Gangetic Plains of South Asia. Rice is grown in summer and wheat in winter. Uttar Pradesh, Punjab, Haryana, Bihar, Madhya Pradesh and Himachal Pradesh have the largest areas under this system among the Indian states (Hobbs and Morris, 1996). Rice residue is the biggest contributor to emissions from open-field burning of crop residue in this region (Badarinath et al., 2006). In fact, the Indo-Gangetic plains have been identified as a regional hotspot of Atmospheric Brown Clouds (Ramanathan et al., 2007).[1]

[1] ABC hotspots are defined as regions where the annual mean anthropogenic aerosol optical depth

This is the first study that uses farm-level data to address the possibility of mitigating emissions from open-field burning of rice residue in Punjab, India. Punjab is the largest producer of wheat and the third largest producer of rice among Indian states. Rice and wheat are grown on an agricultural area of more than 2 million hectares and more than 80% of the 24 million tonnes of rice stubble is burnt each year (Tiwana et al., 2007).

My survey of a representative sample of farmers collected information on the method of residue disposal and its determinants for the purpose of identifying the factors that explain open-field burning of rice residue. I find that the use of coarse (as opposed to higher-priced Basmati) varieties of rice increases the likelihood of farmers harvesting rice using the combine-harvester, which in turn scatters residue and therefore makes the burning of biomass almost certain.

A second survey examined a new seeding machine called the Happy Seeder, which obviates the need to burn rice residue. I conclude that it has the potential to reduce emissions from residue burning in Punjab. The Happy Seeder is a tractor-mounted machine that cuts and lifts the rice straw, sows wheat into the bare soil, and deposits the straw over the sown area as mulch.[2] Farmers can therefore sow wheat immediately after the rice harvest, without having to burn the rice residue.

A comparison of the Happy Seeder with conventional practice shows that that the new technology decreases field preparation costs but does not significantly impact crop yield and profits. Adoption of the Happy Seeder technology may therefore be slow since it has no strong advantage from the viewpoint of profits. Given the considerable adverse effects on mortality and health of pollution from burning, these results imply that this source of black carbon can be mitigated at zero private cost and negative social cost. Accordingly, there is a strong case for promoting the machine through extension and subsidies in order to reduce residue burning, the costs of which are mostly external to the farmer.

The rest of the paper is organized as follows. The following section describes the sampling design. Section 3 discusses the factors that explain rice residue burning in Punjab. Section 4 analyses the profitability of the Happy Seeder technology and section 5 concludes with policy implications.

(AOD) exceeds 0.3 and the percentage of contribution by absorbing aerosols exceeds 10 percent (absorbing AOD > 0.03).

[2]Mulch refers to a protective cover placed over the soil to retain moisture, reduce erosion, provide nutrients, and suppress weed growth and seed germination.

2 Study Area and Sampling

My study area is the state of Punjab in India. I chose Punjab for the study because, at the time the research was done in 2010, the Happy Seeder technology was available only in that state. The empirical analysis uses two samples, the first, a representative sample of farmers and the second a sample of users of the Happy Seeder machine. The representative sample of farmers was selected from the districts of Amritsar, Ludhiana and Sangrur. These districts were chosen to capture the geographical variation that exists across Punjab. Thirty villages and ten households were surveyed within each village. The data collected includes information on costs incurred by 300 farmers in preparing the field for the wheat crop by conventional tillage.[3]

The second survey gathered information for the assessment of the Happy Seeder machine. Data was collected from all 92 Happy Seeder users spread across the 7 districts of Punjab. Most users experimented with it on only a part of their farms.

The two surveys were conducted between January and April in 2010, with a follow-up via telephone during June 2010 in order to obtain data on the yield of the wheat crop for all respondents.

3 Determinants of Rice Residue Burning

Presently, four options are available to the farmers for the disposal of residue, namely, the complete burning of residue, the partial burning of residue, the incorporation of residue into the soil and removal of the residue from the field.

The mode of harvesting strongly influenced the choice of crop residue disposal. Farmers burnt 1% of the area that they manually harvested while they burnt 90% of the area that was harvested by the combine-harvester (see Table 1). This is because manual harvesting allows for easy retrieval of the rice residue since the rice plant is cut close to ground level and collected into bundles for subsequent threshing. The

[3] Since there would be people who did not engage in any farming activity in each village, forty households were randomly selected from each voter list. If the first household among the forty households was a farm household, I included it in the survey. If that was not the case, I dropped it and contacted the second household. This procedure was followed until the enumerator was able to complete nine interviews. In order to find out if farmers with large landholdings behaved differently from farmers with small land- holdings, I included one farmer with a large landholding from each village in the sample. This was accomplished by asking the respondents to provide the names of the five largest landowners in their village. I randomly selected one farmer from this list for the interview.

recovery of stalks and stubble after harvesting by a combine-harvester, on the other hand, is more problematic since the cut residue (loose residue) is scattered all over the harvested fields. So additional labour is required to collect the loose residue.

Table 1 also shows that the rice variety grown by the farmer, whether coarse or Basmati (fine grain) varieties[4], in turn drives the choice of the mode of harvesting. I observed that farmers were more likely to harvest Basmati varieties manually. Two factors explain this observed difference, the most striking being the price differential between Basmati and coarse varieties with the former fetching between two and three and a half times the price of the latter.

Given that the use of the combine-harvester results in a loss of grain and given that the price of Basmati rice far exceeds the price of coarse rice, farmers prefer to opt for manual harvesting of Basmati varieties in order to minimize this loss. On the other hand, it is also much cheaper and quicker to use combine-harvesters than to employ labor. These time savings are dear to the farmers as there is only a short time period between rice harvesting (mid October-early December) and the sowing of wheat, which takes place between November and early December. Any delay in planting reduces the productivity of the wheat crop (Gupta et al., 2004). Consequently, combine-harvesters are popular with farmers for coarse varieties.

The above findings are confirmed by a recursive bivariate probit model with the methods of harvesting and residue burning as the two dependent variables with the method of harvesting being an explanatory variable in the residue burning equation. Absence of a market for rice residue in the surveyed districts suggests that the method of residue disposal does not influence the choice of the method of harvesting. Thus, in terms of profits, the residue disposal decision is not as important as the choice of the mode of harvest. Hence, I do not control for the method of residue disposal in the equation on the mode of harvesting.

The control variables used in this study to explain the choice of the method of residue disposal and the mode of harvesting come out of the profit maximizing exercise of the farmer. Even though profits are not modeled explicitly, the preceding discussion seeks to identify which heterogeneous characteristics of farmers and their growing conditions influence their choice of harvesting and residue disposal. This discussion implies that the mode of harvesting, proxies of scale of operation and technical ability of the farmer, family size, age of the farmer and farm location explain the choice of the method of residue disposal. Farm location enters this equa-

[4]The districts of Amritsar, Tarn Taran, and Gurdaspur, comprise the Basmati belt of Punjab. This is because the agro-climatic conditions of this region are conducive to growing Basmati varieies

tion owing to the enforcement of a ban on burning rice residue in Amritsar prior to the rice-harvesting season. The punishment meted out to violators of the ban was the permanent disconnection of the power supply by the Punjab State Electricity Board.

Introducing a dummy variable that equals 1 if the farmer used a combine-harvester to harvest the rice crop on a plot and 0 otherwise captures the mode of harvesting. Farm size indicates the effect of scale of operation while family size is proxied by the number of family members equal to or above 15 years of age in the household per hectare of farm area sown to rice. Years of education of the farmer, viewership of a television program related to farming, contact with extension services, and whether a farmer reads agricultural magazines are proxies for the technical ability of the farmer.[5] The dummy variable Amritsar represents location, which equals 1 if the plot is located in Amritsar and 0 otherwise.

Turning to the explanatory variables in the equation on the mode of harvesting, these are, the rice variety farmers sow on a plot, ownership of livestock, farm size, family size, rental rate of a combine-harvester in the village, rental rate of contract labor in the village, age and education of the farmer, proxies of technical ability of the farmer and farm location. The rice variety that farmers sow has direct implications for the mode of harvesting (manual or combine). Small-scale farmers may be more inclined to use their own labor or employ labor to harvest Basmati varieties. Farmers who own livestock are more likely to harvest the crop manually. However, I allowed for this effect to vary with the rice variety that farmers sow since they prefer the residue of the Basmati variety for the purpose of feeding livestock. The location of the farm may influence the mode of harvesting even after controlling for the rice variety that farmers grow. This is because farmers in Amritsar plant high quality Basmati varieties that are more likely to be harvested manually.

The binary variable Coarse identifies the rice variety that farmers sow on a plot equaling 1 if the variety of rice that farmers sow on a plot is coarse and 0 otherwise. The number of family members equal to or above 15 years of age in the household per hectare of farm area sown to rice is a proxy for family size. The number of livestock owned per hectare of farm area reflects ownership of livestock. The descriptive statistics of the variables are shown in Table 2 and the results are shown in Table 3 and Table 4.

As expected, the use of a combine-harvester exerted the most substantial ef-

[5] If there were more than two active farmers in the same household, I used the information on the oldest farmer as a measure of the technical ability of that farming household.

fect, on average, on the probability that farmers will burn residue on a plot whereas choice of the mode of harvesting was driven by the variety of rice that the farmer sold. Plots located in Amritsar on average were less likely to get burnt than plots situated in Ludhiana and Sangrur due to the ban on burning rice residue in this region. Farmers in this area were also significantly less likely to use a combine-harvester opting for manual harvesting of the high quality Basmati varieties. These findings are consistent with the results obtained from the models that include farmer-fixed effects and village-fixed effects (see columns 2-3 of Table 3 and Table 4).

4 *Examination of an Available Alternative to the Problem of Burning: The Happy Seeder Technology*

The results imply that the most important determinant of the decision to burn rice residue is the use of a combine-harvester. Its prevalence is not amenable to policy intervention because the advantages that combine-harvesters offer in terms of savings in money and time as well as reduced supervision of labor have made them immensely popular with farmers. At present farmers use combine-harvesters mainly to harvest coarse varieties of rice in Punjab. However, farmers who face a labor shortage may resort to mechanical harvesting even in the case of the Basmati varieties. Labor scarcity will therefore lead to an increase in the use of combine-harvesters among farmers. Although a strict ban on burning rice-residue may make the problem of residue burning less severe, in the absence of any economically viable alternative to burning, the ban will not succeed in eradicating emissions from the open burning of rice fields.

It is possible to make a modification to the combine-harvester enabling the residue to be collected separately. However, this raises questions about the utilization of residue. Given that rice residue is of limited value to the farmers, whether as livestock feed or non- feed use, it remains to be seen whether uses can be found for rice residue outside the agricultural sector. The Government has introduced balers in the district of Amritsar. In addition, a sugar mill in the district is also using the baled residue to generate electricity in this district. However, the baling of residue may not be a viable mitigation strategy as the supply of baled residue may outweigh its demand.

Another viable alternative is to develop machines that allow farmers to plant wheat into the loose residue. The Happy Seeder technology performs this function in the context of rice residue. Engineers of CSIRO Griffith at Punjab Agricultural University developed the first prototype of the Happy Seeder in July 2001. At the time of the field survey, a manufacturer at Ramdass in the district of Amritsar in Punjab was manufacturing the Happy Seeder which had been first sold to a farmer in the district in 2007. The Happy Seeder technology is currently undergoing modifications in its design and engineers continue to test it for its performance.

Thus, an important research question is whether the Happy Seeder technology is a viable alternative to open-field burning of rice residue. I address this question in the next section.

4.1 *Comparison of Profits from the Happy Seeder and conventional technology*

4.1.1 Comparison of Yields

To determine the impact of the Happy Seeder technology on wheat yields in comparison with conventional tillage, I ran regressions of yield on various covariates that included farmer fixed effects. As a robustness check I also estimate regressions with random effects and pooled OLS . Plot level data collected from the users of the Happy Seeder was used to conduct these regressions. The farmer fixed effects eliminate any unobservable factors among farmers that might simultaneously affect yield and the performance of the Happy Seeder technology.

The explanatory variables include a set of plot-level and farmer-level characteristics (the size of the plot, soil type, quantity of fertilizers applied to a plot, age and education of the farmer and variables that measure the technical ability of the farmer such as whether the farmer watched a television program related to farming, etc.), and a dummy variable for the Happy Seeder.

It is not possible to control for the mode of irrigation as all farmers in the sample use a tube-well for irrigation. Since the government gives farmers electricity for free in Punjab, they are unable to provide information on the expenditure incurred on irrigation or the quantity of water used for irrigation. However, the farmer-fixed effect captures the effect of the quantity of water used for irrigation.

For the coefficient on the Happy Seeder variable to have a causal interpretation, any unobserved determinants of yield must remain uncorrelated with the Happy Seeder variable. Since farmer-fixed effects account for any potential confounding farmer-level characteristics, any correlation between yield and the error term must be on account of unobserved plot-level characteristics. If the wheat variety that farmers sow on a plot affects yield and correlates with the Happy Seeder variable, the estimated coefficient on the Happy Seeder variable will be biased. Focus group discussions with farmers suggest that the wheat variety that farmers sow does not significantly affect the yield of wheat. The yields differ at most by a magnitude of 1-2 quintals per acre across varieties. However, to rule out the possibility of correlation between the wheat variety that farmers sow and the Happy Seeder variable, I control for the variety of wheat sown in the yield and the profit regressions. There may also be a plot-specific selection effect as farmers may choose to use the Happy Seeder on plots that they believe are more suited for this technology. I control for the type of soil in a plot to account for this effect. Moreover, Happy Seeder is a new technology so farmers are unlikely to be aware of the plot characteristics that are appropriate for this technology. Hence, I can assume plot selection to be random.

4.1.2 Comparison of Costs

The second question that I investigate in this section is whether the Happy Seeder technology was a low or high cost alternative to conventional field preparation. For this purpose, I estimate regressions taking the cost incurred per hectare in establishing the wheat crop as the dependent variable. The independent variables in these regressions include the controls in the yield regressions, the output of the wheat crop in a plot, and the mean price per kg of fertilizer paid by the farmer.[6]

A prerequisite for using the Happy Seeder is that the loose rice straw left by the combine-harvester should be spread uniformly on the field. Farmers mostly employed labor for spreading this residue as combine-harvesters with a spreader attached to them are not widely available. In addition, farmers incurred expenditure on the purchase and application of weedicide and fertilizers.

Farmers who had utilized their own labor or equipment for field preparation were assigned the prevailing rate of that activity in their village.

The cost per hectare to prepare the field using the Happy Seeder machine comprised the cost of hiring the Happy Seeder, the cost of the diesel to run it and the costs of purchasing and applying weedicide and fertilizers. The cost per hectare of establishing wheat with conventional tillage was calculated in the same manner with the cost of hiring farm equipment replacing the cost of hiring the Happy Seeder

[6]Nine respondents had purchased the Happy Seeder implement and consequently did not incur any expenditure to hire it. They were assigned the average cost of hiring the Happy Seeder that prevailed in their district. If village level rates were not available, district level estimates were used to impute these rates.

machine.

4.1.3 Comparison of Profits

I also ran regressions taking profit per hectare from wheat production as the dependent variable to see whether the Happy Seeder technology is a profitable alternative to conventional tillage. The controls in these regressions are similar to the controls in the cost regression except that I do not control for the yield of the wheat crop. The descriptive statistics of the variables used in the analysis are reported in Table 5.

4.2 *Results*

Table 6 contains estimates of the effect of Happy Seeder on yield per hectare, cost per hectare and profit per hectare of wheat sown. Columns 1 to 3, report the results of the regression model which has yield per hectare as the dependent variable. Column 1 shows the results of the random-effects model. The coefficient on the Happy Seeder variable was negative about -0.5, small compared to the mean of 43 and standard deviation of 5 tonnes/ha, and statistically insignificant. Thus, I do not find any impact on the yield from using the Happy Seeder. The results in column 2 of Table 4 are estimates of the farmer-fixed effects model. I continue to find no effect on the yield of the wheat crop from operating the Happy Seeder. Column 3 presents the results of the pooled least squares estimation. The least squares results also imply that the Happy Seeder technology had no effect on the output of the wheat crop relative to conventional tillage.

Columns 4 to 6 display the results of the equation with the cost incurred per hectare to prepare the field of wheat as the dependent variable. The results from all the models indicate that on average the Happy Seeder technology was a significantly lower-cost alternative compared to conventional tillage. Since the fixed-effects model controls for confounding factors at the farmer level, the result strongly indicates that among farmers who used the Happy Seeder technology, the plots that they cultivated using the Happy Seeder technology, on average, incurred a lower cost than those prepared by conventional tillage. This cost saving amounted to INR 1055 per hectare (USD 23).

Columns 7 to 9, present the results of the model that estimates the effect of Happy Seeder technology on profitability. The results show that on average the

Happy Seeder is a not a more profitable alternative to conventional tillage, a finding that is consistent across specifications.

These findings, of course, are based solely on the existing users of the Happy Seeder technology. The question that is of greater relevance to policy is whether the Happy Seeder technology will work for the general population of farmers. In order to investigate whether the users of the Happy Seeder machine are comparable in farm characteristics to representative farmers, I compared the means of farm characteristics between the two samples.

Table 7 shows the means of plot level characteristics between the users and non- users of the Happy Seeder. The table also reports the t-test statistics for the difference in means across plots in the two samples (see columns 4, 5 and 6). The numbers in Table 7 indicate that the mean output of the wheat crop is similar across the three types of plots, i.e., those that were conventionally tilled and those that were cultivated using Happy Seeder technology. This is a noteworthy feature of the estimates. It means that the general population of farmers is as productive as the Happy Seeder sample.

Table 8 reports the statistics on farmer characteristics across the two samples. The users of the Happy Seeder were more educated and may be more technically able (as measured by indicators such as viewership of television programs on farming and subscription to agricultural magazines) than non-users of the Happy Seeder. They were better connected with the agricultural extension network. This is not surprising as the agricultural adoption literature highlights that a farmer's education and his connectivity with the extension network play a crucial role in his decision to adopt a new technology (Rahm and Huffman, 1984). However, what is important is that the general population of farmers are as productive as the pioneer Happy Seeder users. So I have no reason to think that they will do any worse with the Happy Seeder.

4.3 Benefit Analysis of the Happy Seeder Technology

How large is the social benefit of using Happy Seeder Technology across Punjab? I quantify the benefit of using the Happy Seeder technology by estimating the number of premature deaths that could be avoided if the air pollution associated with rice-residue burning was eliminated. This calculation adopts the methodology prescribed in Ostro et al. (2004). Data derived from satellite images on fine particulate matter (PM 2.5) for 2001-2010 for Punjab was kindly provided by Professor

Sagnik Dey, Department of Atmospheric Sciences, Indian Institute of Technology, Delhi (Dey et al., 2012). According to these estimates the annual average of PM 2.5 for 2001-2010 was 50% higher for the month of October than for September (70 $\mu g/m^3$ compared to 46 $\mu g/m^3$). I attribute this difference to open-field burning of rice residues. This is not an unreasonable assumption.Venkataraman et al. (2006) found that emissions from crop residue burning peaked during the month of May and October in the western Indo-Gangetic plains corresponding with the two major harvesting seasons for rice and wheat.

Ostro et al. (2004) summarize the health burden of short term exposure to PM 10 as follows: a 1 $\mu g/m^3$ increase in particulate matter increases the all-cause mortality risk by 0.008 (central estimate), with a 95% confidence interval of [0.0006-0.0010]. Most of the all-cause mortality resulting from exposure to PM is associated with cardiovascular and pulmonary disease.[7]

The deaths attributable to outdoor air pollution caused by burning of rice-residue are estimated by using the average concentration of PM 10 in the month of September of 92 $\mu g/m^3$ as the baseline value and the the average concentration of PM 10 of 141 $\mu g/m^3$ in the month of October as the current value.

Using these values, the relative risk, (the risk of developing a disease in the exposed group relative to the risk of developing a disease in the unexposed group) was 1.0397. Thus, the percentage of all deaths that can be attributed to short-term outdoor air pollution i.e. the attributable fraction was 3.82%.[8]

The expected total number of cases of premature mortality from short-term exposure to PM10 due to burning of rice residue was calculated by multiplying the

[7] In the absence of a local measurement of the PM2.5/PM10 ratio, Ostro et al. (2004) advocate a value of 0.5 for developing countries.

[8] In general, relative risk is calculated by dividing the incidence rate among those exposed to the pollutant by the incidence rate among those not exposed to the pollutant.

$$\text{Relative Risk} = e^{0.0008}(141.32 - 92.69)$$

$$\text{Attributable Fraction} = \frac{\text{Incidence of disease in exposed} - \text{Incidence of disease in unexposed}}{\text{Incidence of disease in exposed}}$$

= Relative risk -1/ Relative Risk

attributable fraction with the average per person monthly all-cause mortality rate in Punjab and its population. All-cause mortality data were obtained from the Indian Ministry of Health and Family Welfare for 2005-2010. The annual mortality rate is .0684 deaths per person. The Census of India, 2011, estimated a population of 27.70 million for Punjab. In the absence of monthly data on mortality, I assume that the health effects of short-term exposure to air pollution depend on cumulative exposure throughout the year. Thus, an estimate of the expected number of cases of premature mortality from short-term exposure to PM 10 is 606 with a 95% confidence interval of [461-752].

The Value of Statistical Life (VSL) estimates for India from Bhattacharya et al. (2007) were used to determine the value of the benefit from reduced mortality from using the Happy Seeder technology. Bhattacharya et al. (2007) report a preferred VSL estimate of INR 1.93 million (2010 rupees) based on a stated preference study of Delhi residents. Other estimates of VSL for India are 14-29 times higher than this estimate (Shanmugam, 2001; Madheswaran, 2007). Hence, the estimated social benefit of INR 1170 million (USD 25 million) is a lower bound on its value. The 95% confidence interval of the benefit ranges from INR 889- 1451 million (USD 19-31 million).

The social benefit of using this technology is much higher because the other health and climate benefits from stopping the burning of rice residue are expected to be substantial though they have not been quantified here. On the other hand, the social cost of adopting Happy Seeder is zero because profits with Happy Seeder are equal to profits with the conventional technology as shown in section 4.2.

5 Conclusions and Policy Implications

Emissions from domestic fires are the largest contributor to biomass burning but may be costly to mitigate. Open field burning is the second-largest source of black carbon in South Asia. Bans on burning have been instituted to deal with this pollution but in the absence of any economically viable alternative to burning, they have been rendered ineffective. Hitherto, such alternatives were missing. This study highlights a new technology that makes it possible to incorporate rice residues. I conclude that this technology has the potential to reduce emissions from rice residue burning in Punjab, India. My findings imply that this source of black carbon can be mitigated at zero private cost and negative social cost. In fact, it is one of the few mitigation options that are presently available to stop agricultural fires. Since black carbon is a short lived pollutant, fast actions on cutting down its emissions will reap immediate climate and health benefits.

My results indicate that there is a strong link between combine harvesters and biomass burning. Combine-harvesters scatter crop residue as they harvest. As a result, rice residue left behind by a combine-harvester is more likely to be burnt than residue left after a rice crop has been harvested using manual labour. Yang et al. (2008) also attribute the open-field burning of cereal residues in China to the practice of mechanized harvesting of rice crop by a combine-harvester. Farooq et al. (2007) too associate agricultural residue burning with the use of the combine-harvester to harvest crops in the Punjab province of Pakistan. Hence, the Happy Seeder technology may offer a solution to the problem of residue burning in these countries as well.

Another technological innovation that could boost the uptake of Happy Seeder machines is combine-harvesters fitted with a spreader to evenly distribute loose residue. Using these attachments therefore removes one cost element from the use of the Happy Seeder machine. It can also improve wheat crop yields (Singh et al., 2006). However, the decrease in cost may not be large enough to motivate farmers to switch to the Happy Seeder technology. Agricultural research finds that reliance of farmers on weed control measures may decrease with the use of the Happy Seeder as the mulch suppresses weeds (Singh et al., 2006). My study supports this finding because the operators of the Happy Seeder applied lower quantities of fertilizer and weedicide to the wheat crop. It is indisputable that lower quantities of fertilizer and weedicide have desirable external benefits.

The results suggest that the Happy Seeder has no strong advantage from the point of view of the private profitability of the farmer. This means that, on its own, the Happy Seeder technology will spread only slowly since farmers are often resistant to taking on new methods and prefer to stick with the tried-and-tested status quo. However, as the machine offers a viable way to tackle the residue burning problem, it makes good policy sense to promote the machine to secure the pollution control benefits it can bring to society as a whole.

The findings indicate that a two-pronged approach of accelerating the adoption of Happy Seeder and prohibiting the burning of rice residue can prevent the burning of rice residue. The state agricultural department has already been successful in spreading the use of the Rotavator across Punjab. Rotavator is a tractor drawn machine that costs nearly the same as the Happy Seeder (INR. 1,15,000 or USD 2638). A combination of subsidies, recommendations by scientists at the state agricultural university, demonstrations by extension agents helped to accomplish this (personal communication Peter Hobbs). A similar approach may be tried for promoting the Happy Seeder. This will have benefits to society at large and also to the natural environment both of which are affected by the pollution from residue burning with wider applicability elsewhere in Asia.

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Table 1: Variety-wise and Mode of Harvesting-wise disaggregation of the Method of the Residue Disposal in Punjab, 2010

Variety of Rice - Basmati				
	Manually Harvested		Combine Harvested	
	% of the Area	Area in Hectares	% of the Area	Area in Hectares
Fully Burnt	1	2	57	53
Partially Burnt	0	0	16	15
Incorporated	0	0	18	17
Removed	99	175	9	9
Total	100	177	100	94
Variety of Rice - Coarse				
Fully Burnt	–	0	76	657
Partially Burnt	–	0	16	141
Incorporated	–	0	4	33
Removed	–	0	4	38
Total	–	0	100	869

Table 2 : Description of the variables used in the analysis

Variables	Description	Unit of Measurement	Variables	
			Mean	S.D.
Burnt	Indexes the method of residue disposal on a plot. 1= residue is burnt ,0 otherwise	Percent of Plots	0.64	0.48
Combine	Whether or not farmer used a Combine to harvest rice on a plot. 1= Combine machine is used ,0=otherwise	Number of Plots	0.74	0.44
Coarse	Variety of rice sown by the farmer on a plot. 1=coarse,0=Basmati	Number of Plots	0.64	0.48
Farm Size	Size of a farm unit	Hectares	5.03	5.51
Livestock per hectare of farm area		Number	2.46	1.96
Watch	Whether or not farmer watched a television programme on farming. 1=Watches,0=Does not watch	Number of Farmers	0.56	0.50
Contact with Extension	Whether or not an extension agent visited the farmer in the year preceding the survey 1=Yes,0=No	Number of Farmers	0.24	0.43
Reads Magazines	Does the farmer read agricultural magazines. 1=Yes,0=No	Number of Farmers	0.20	0.40
Age of the farmer		Number	51.73	14.21
Education of the farmer		Number	8.16	4.1
Number of persons equal to or above 15 years of age in the household per hectare of farm area sown to rice		Number	2.71	2.91

Variables	Description	Unit of Measurement	Variables	
			Mean	S.D.
Rental rate of combine-harvester in Village		Rupees per Hectare	1889.55 ($16.34)	400.05
Rental rate of Contract Labour in Village		Rupees per Hectare	5882.717 ($50.84)	1460.73
Amritsar	Dummy Variable that equals 1 if a plot is located in Amritsar,0 otherwise	Number of Plots	0.32	0.47
Number of Plots	Number of plots in the sample	Number	604	
Number of Farmers	Number of farmers in the sample	Number	268	

Table 3: Marginal Effect of the Variables on the probability of using a combine-harvester

Variables	Probit Method (Marginal Effect)	Linear Probability Model with: Farmer Fixed Effects (Marginal Effect)	Linear Probability Model with: Village Fixed Effects (Marginal Effect)
Coarse	.6275***	.5036***	.5123***
	(17.98)	(8.38)	(7.42)
Livestock per hectare	-.0254***	–	-0.0535***
	(-2.75)	–	
Livestock per hectare *Coarse	.0710**	.0669***	.0537***
	(2.33)	(3.46)	(3.07)
Farm Size	.0009	–	.00103
	(0.48)	–	(0.55)
Number of Persons Equal to or Above 15 years of Age in the Household	.0226	–	.00009
	(0.42)	–	(0.01)
Rental rate of Contract Labour in village	-.00003***	–	–
	(-3.42)	–	–
Rental rate of combine-harvester in Village	-.00004	–	–
	(-1.44)	–	–
Watch	-.0008	–	-.00009
	(-0.03)	–	(-0.00)
Contact with Extension	.0374	–	.0193
	(1.51)	–	(0.76)
Reads Magazines	-.0689***	–	-.0421
	(-2.95)	–	(-1.53)
Age of Farmer	.0016**	–	.0019*
	(2.23)	–	(1.92)
Education of Farmer	.0013	–	.0017
	(0.40)	–	(0.46)

Variables	Probit Method (Marginal Effect)	Linear Probability Model with: Farmer Fixed Effects (Marginal Effect)	Village Fixed Effects (Marginal Effect)
Amritsar	-.1191***	–	–
	(-3.34)	–	–
Number of Plots	736	736	736
Number of Farmers	300	300	300
Log Likelihood	-151.01	–	–
R Squared	–	0.51	0.49
Psuedo R Squared	0.64		

Notes: Dependent variable is Combine. Combine=1 if the farmer used a combine-harvester on a plot and 0 otherwise. Figures in parenthesis are t-ratios. For probit regression the standard errors are clustered at the farmer level and robust standard errors are reported for the farmer and village fixed effects. *** indicates significance at the 1% level, ** indicates significance at the 5% level, * indicates significance at the 10% level.

Table 4: Marginal Effect of the Variables on the probability of burning crop residue

Variables	Probit Method (Marginal Effect)	Linear Probability Model with: Farmer Fixed Effects (Marginal Effect)	Linear Probability Model with: Village Fixed Effects (Marginal Effect)
Combine	.7960***	.7747***	.7102***
	(27.26)	(18.19)	(14.48)
Farm Size	-.0009	–	.0020
	(-0.34)	–	(0.65)
Number of Persons Equal to or Above 15 years of Age in the Household	-.0175*	– 0	-.0202**
	(-1.92)	–	(-2.20)
Watch	-.0098	–	-.0122
	(-0.37)	–	(-0.40)
Contact with Extension	.0084	–	-.0147
	(0.28)	–	(-0.62)
Reads Magazines	-.0417	–	-.0537*
	(-1.23)	–	(-1.75)
Age of Farmer	.0012	–	.0012
	(1.22)	–	(1.38)
Education of Farmer	-.0002	–	-.0022
	(-0.05)	–	(-0.58)
Amritsar	-.2332***	–	–
	(-4.79)	–	–
Number of Plots	736	736	736
Number of Farmers	300	300	300
Log Likelihood	-190.957	–	–
R Squared	–	0.70	0.50
Psuedo R Squared	0.60		

Notes: Dependent variable is Burnt. Burnt=1 if the farmer burnt residue on a plot and 0 otherwise. Figures in parenthesis are t-ratios. For probit regression the standard errors are clustered at the farmer level and robust standard errors are reported for the farmer and village fixed effects. *** indicates significance at the 1% level, ** indicates significance at the 5% level, * indicates significance at the 10% level.

Table 5 : Comparison of plot characteristics across users of Happy Seeder

Variables	Description	Unit	Means (Standard Deviation in Parenthesis)		
			Plots sown with Conventional Tillage	Plots sown using Happy Seeder	Entire Sample
Yield per hectare	Per hectare wheat produced on a plot	Quintals	43.81 (4.317)	43.31 (6.193)	43.57 (5.286)
Cost per hectare	Per hectare expenditure on preparing the field of wheat	INR	7288.54 (2657.56)	6225.3 (1235.1)	6780.32 (2161.80)
Profit per hectare	Per hectare profit from wheat production	INR	40024.4 (5318.05)	40548.27 (6644.97)	40274.81 (5975.51)
Happy Seeder	Whether or not farmer used Happy Seeder to sow wheat 1= Happy Seeder is used ,0=otherwise	No. of plots	—	—	(0.48) (0.50)
Plot Size	Size of a plot	Hectares	6.039 (5.760)	5.342 (5.630)	5.706 (5.691)
Fertilizer	Per hectare fertilizer applied to wheat	Kg	473.09 (87.88)	461.00 (97.09)	467.28 (92.30)
Price of Fertilizer	Mean price of fertilizers	Price per Kg	–	–	7.14 (0.28)
Age	Age of farmer	No. of farmers	48.92 (13.08)	49.83 (12.45)	49.35 (12.75)
Education	Years of Education of Farmer	No. of farmers	10.30 (2.67)	10.05 (3.27)	10.18 (2.96)
Watch	Does the farmer watch a television programme on farming? 1=Yes,0=No	No. of farmers	0.57 (0.50) (0.50)	0.59 (0.50) (0.50)	0.58 (0.50) (0.50)
Contact with Extension	Did an extension agent visit the farmer in the year before the survey? 1=Yes,0=No	No. of farmers	0.69 (0.47)	0.65 (0.48)	0.67 (0.47)
Reads Magazines	Does the farmer read agricultural magazines? 1=Yes,0=No	No. of farmers	0.48 (0.50)	0.49 (0.50)	0.48 (0.50)
Percentage of plots	Percent of plots in the sample	No.	52	48	100
Number of Farmers	Number of farmers in the sample	No.	66	66	66

Notes : The Happy Seeder technology was made available to 22 respondents free of cost whereas 1 farmer could not be contacted for obtaining the data on the yield of the wheat crop. 3 farmers burnt the rice stubble prior to using Happy Seeder. This reduced the sample size to 66 farmers for the profitability analysis.

Table 6 : Estimates of Yield, Cost and Profit per hectare from Wheat Production in Punjab in 2009-2010

	Yield per Hectare			Cost per Hectare			Profit per Hectare		
Variables	RE (1)	FE (2)	POLS (3)	RE (4)	FE (5)	POLS (6)	RE (7)	FE (8)	POLS (9)
Happy Seeder	-0.509 (-0.70)	-0.692 (-0.95)	-0.385 (-0.49)	-1063.0*** (-3.04)	-1054.5*** (-3.13)	-997.1**** (-2.61)	571.2 (0.57)	598.6 (0.61)	466.1 (0.44)
Yield per Hectare	–	–	–	18.65 (0.59)	4.704 (0.10)	24.31 (0.81)	–	–	–
Plot Size	0.0950* (1.94)	0.0661 (1.29)	0.110* (2.12)	38.68 (1.28)	-36.06* (-1.87)	113.7*** (3.19)	11.84 (0.20)	64.97 (1.29)	-52.70 (-0.67)
Fertilizer	0.0654*** (3.35)	-0.00405 (-0.05)	0.0673*** (3.60)	–	–	–	–	–	–
Fertilizer Squared	-0.00001*** (-3.33)	-0.00002 (-0.35)	-0.00008*** (-3.52	–	–	–	–	–	–
Price of Fertilizer	–	–	–	449.2** (2.09)	–	636.5** (2.60)	-3452.0*** (-2.93)	–	-3805.4*** (-2.91)
Age	0.005 (0.13)	–	0.0008 (0.02)	-7.065 (-0.42	–	-10.68 (-0.55)	-34.52 (0.64)	–	25.96 (0.47)
Education	-0.421** (-1.98)	–	-0.446** (-2.08)	32.82 (0.62)	–	25.61 (0.39)	-97.98 (-0.45)	–	-86.62 (-0.38)
Watch	0.553 (0.50)	–	0.184 (0.16)	730.6 (1.36)	–	508.5 (0.91)	-1598.1 (-1.16)	–	-1790.6 (-1.36)
Contact with Extension	-0.933 (-0.75)	–	-1.345 (-1.11)	170.1 (0.38)	–	319.3 (0.60)	-279.5 (-0.20)	–	-739.5 (-0.51)
Reads Magazines	-0.200 (-0.17)	–	-0.077 (-0.06)	-272.0 (-0.58)	–	-458.9 (-0.89)	-438.9 (-0.30)	–	249.4 (0.17)
Number of Plots	223	223	223	159	159	159	159	159	159

Notes: Figures in parenthesis are t-ratios. For OLS regressions the standard errors are clustered at the farmer level and robust standard errors are reported for the farmer fixed and random effects. *** indicates significance at the 1% level, ** indicates significance at the 5% level, * indicates significance at the 10% level.

Table 7 : Mean Differences between the plots of Users of Happy Seeder and Representative Farmers

	Means, Sample of Plots Cultivated using Conventional tillage by Representative Farmers	Means, sample of Plots Cultivated using Conventional Tillage by Users of Happy Seeder	Means, sample of Plots Cultivated using Happy Seeder by Users of Happy Seeder	T-test, Differences between Means in Column 1 and Column 2	T-test, Differences between Means in Column 1 and Column 3	T-test Differences between Means in Column 2 and Column 3
	(1)	(2)	(3)	(4)	(5)	(6)
Characteristics						
Yield Per Hectare	43.84	43.67	43.65	0.169	0.194	0.025
	(0.269)	(0.468)	(0.736)	(0.566)	(0.662)	(0.844)
Quanity of Fertilizer Applied per hectare	505.31	472.91	456.86	32.40***	48.45***	16.05
	(4.80)	(7.92)	(9.22)	(10.02)	(10.94)	(12.08)
Per Hectare Expenditure on weedicide	1115.09	980.73	899.39	134.37***	215.71***	81.33
	(19.97)	(33.54)	(47.13)	(41.66)	(47.23)	(56.24)
Number of Plots	438	122	101			
Number of Farmers	267	70	88			

Notes: Figures in parenthesis are standard errors. *** indicates significance at the 1% level, ** indicates significance at the 5% level, * indicates significance at the 10% level.

Table 8 : Descriptive Statistics and Mean Differences between the Users of Happy Seeder and Representative Farmers

	Means, Sample of Representative Farmers that used Conventional Tillage	Means, Sample of Farmers that used Happy Seeder	T-test, Differences between means in column 1 and column 2
	(1)	(2)	(3)
<u>Characteristics</u>			
Age of the farmer	51.81	49.36	2.45
	(0.87)	(1.34)	(1.70)
Number of Years of Education of the Farmer	8.16	9.95	-1.80***
	(0.25)	(0.36)	(0.48)
Number of Farmers that Watched a Television Programme on Farming	0.55	0.61	-0.06***
	(0.03)	(0.05)	(0.06)
Number of Farmers that were contacted by an Extension Agent in the year preceding the survey	0.24	0.64	-0.40***
	(0.03)	(0.05)	(0.05)
Number of Farmers that read Agricultural Magazines	0.19	0.47	-0.27***
	(0.02)	(0.05)	(0.05)
Number of Farmers	267	88	

Notes: Figures in parenthesis are standard errors.

*** Significant at the 1% level