INSIGHTS

POLICY FORUM

AGRICULTURE AND ENVIRONMENT

Fields on fire: Alternatives to crop residue burning in India

Farmer profit can be increased and air quality improved

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Although intentional use of fires to transform land has decreased globally (*1*, *2*), particularly among highly capitalized countries through regulatory and market-oriented approaches and moral suasion, regulatory strategies have been less effective in southern and eastern Asia (see table S21). Some densely populated agricultural regions in China and India buck the global trend, showing increases in agricultural fires (*2*). This is particularly true in northwestern India, where rice residue burning makes a substantial contribution to air pollution and short-lived climate pollutants (*3*, *4*). Regulations are in place to reduce agricultural fires, but burning continues because of uncertainty regarding policy implementation and regarding access and returns to alternative technologies. With the field burning season soon upon us, we synthesize emerging evidence on alternatives to burning, clarify the business case for alternative practices, identify remaining uncertainties, and discuss approaches to increase their widespread adoption. Often, there are difficult trade-offs between environmental improvement and profitable economic opportunities. The case of crop residue management in northwestern India does not appear to fit this pattern and provides lessons that may be useful elsewhere.

Some of the least healthy air in the world is in India (*5*), where polluted air is the second-highest health risk factor (*6*). Seasonal smog imposes enormous costs, such as major transportation disruptions and the closure of 4000 schools in Delhi in November 2017 (*7*). The risks peak during October and November with the burning of rice crop residues in agricultural areas (*8*, *9*). During this period, crop residue burning contributes to major particulate pollution in Delhi and northern India (*9*–*11*).

Eighty percent of agriculture in northwestern India's Indo-Gangetic plains is based on a rice-wheat cropping system (~4.1 million ha). Concerns over groundwater withdrawals have led to a planting cycle that allows the rice crop to benefit from monsoon rains. This cycle creates a short period (~10 to 20 days) to harvest rice, manage rice crop residue, and plant wheat. Many of the 2.5 million farmers in northwestern India prepare for wheat planting by burning an estimated 23 million metric tons of rice residue in their fields (*12*).

India's national government recognizes both the air pollution risks and the crucial role of crop residue burning. Despite federal and state regulations since 2014 and related advisories and bans, directives against burning have been only partially enforced. The reluctance to enforce existing policies arises, in part, from the belief that profitable alternatives to burning crop residue do not exist. Any alternative to crop residue burning must be feasible, affordable, and capable of scaling to adoption by thousands of farmers. Burning could be avoided by changing the overall cropping system (e.g., growing different crops) or by adopting different rice-wheat management practices. The focus to date has been on these latter options, which we include in the scope of this study.

After mechanical harvesting of rice, farmers in northwestern India have different options for sowing wheat. All options include some combination of rice residue treatments (mulching by cutting and on-field distribution, baling and removal from the field, incorporation by tilling into the field, and on-field burning), land preparation (no additional preparation, rotavate, disc and tine harrow, and plank), and seeding of wheat (using Happy Seeders, conventional seeders, other zero-till seeders, and rotaseeders). Not all

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Open crop field burning in the Indo-Gangetic plains is a source of seasonal air pollution in many parts of northern India.

combinations of these options are regularly used in northwestern India, and we focus on 10 combinations that are commonly practiced or are viewed as potentially scalable (fig. S1). The majority of farmers currently choose to burn rice straw, plow fields, and sow wheat using conventional seeders. Given variation in practices, we evaluate the public and private costs and benefits and potential scalability of 10 alternative farming options, three of which result in residue burning.

DO PROFITABLE ALTERNATIVES EXIST?

We assessed the annual average per hectare net profit to farmers from each farming system (see the figure). We used data from published, peer-reviewed experimental field trials, real farmer field trials, farm household surveys (n = 34, covering 2004 to 2019), government-published data (n = 7), and a primary dataset (n = 1). These data cover the Indian states of Punjab and Haryana, where most of the residue burning occurs. Mean values for farm inputs and outputs per hectare for any of the 10 options were extracted from each data source (n = 42) to construct a range of inputs and outputs for each farming system. In light of uncertainty over the relative reliability of different sources of data (e.g., controlled trials versus farmer surveys), data from all available quantitative studies were given equal weight.

Net profit was calculated as the difference between revenues (yields multiplied by market prices) and input costs, including annualized fixed costs (such as machine capital costs or rental rates) and variable costs (fertilizer, labor, etc.). Using mean values across studies, we calculated the mean and the highest and lowest profits per hectare for each farming system (see the figure and table S9). Prices reflect inflation-adjusted mean rental and input and output prices taken from the literature (table S2). Because the same prices are applied to all alternatives, differences in profits reflect real differences in yields and inputs (see supplementary materials for details).

The results show that Happy Seeder–based systems are on average more profitable than alternative farming practices, being ~10% more profitable than the most profitable burning option (with zero-till seeders) and ~20% more profitable than the most common burn system (with conventional seeders) (see the figure). Propelled by a tractor, the Happy Seeder cuts and lifts rice straw, sows wheat directly into the soil, and deposits the cut straw as mulch over the sown area. Higher profits from the Happy Seeder system stem from slightly higher yields and lower input costs for land preparation. Baling is, on average, not as profitable as Happy Seeder options but shows profits equivalent to burning. Incorporation of residues into soil offers the lowest average returns. Even though the Happy Seeder option is the most profitable on average, a range of outcomes is possible. Considering the full range of variation, the maximum profit the average farmer can gain by switching from the most common burning system to the most profitable Happy Seeder system is 22,254 INR/ha (+44%). On the other hand, the farmer could, in the worst-case scenario, lose 4012 INR/ha (–7%) by switching (see fig. S2). The relative profitability of the Happy Seeder option suggests that farmers could transition away from burning while improving their bottom line, but variation in returns may contribute to low adoption.

To examine responsiveness of net revenues to changes in prices and capital investment costs, we undertook sensitivity analyses by (i) varying all input prices, and (ii) lowering the implicit rental rates on conventionally used machinery, assuming that farmers own and have paid off the capital costs on such machines. We also undertook a qualitative assessment of sensitivity to land size (see supplementary materials). Rankings are not sensitive to price changes or implicit rental rates unless there are large shifts in rental prices (fig. S4). Farm size does affect costs and productivity, but the direction of these changes is not influenced by the type of farming system practiced.

MAKING A PUBLIC CASE

In addition to private returns, a major motivation for the current debate around farming operations is the associated public cost of air pollution from burning (health impacts, school closures, transportation disruptions, etc.). To account for this and other public interests associated with farm operation choices, we also examined a set of public costs: relevant government subsidies, particulate air pollution emissions as contributors to health and economic costs, greenhouse gas (GHG) emissions leading to climate change, and water withdrawals as a driver of groundwater depletion. Subsidies reflect government-financed price reductions for farm inputs, GHG emissions result from on-farm fertilizer and diesel use and burned residue, particulate matter is mainly associated with residue burning, and water withdrawals reflect water use for irrigation. These public costs were estimated for on-farm activities associated with the 10 prevalent farming systems on the basis of available peer-reviewed literature (e.g., on-farm agronomic experiments) or published coefficients from government datasets. Given limitations in monetary estimates of social costs, we present estimates in physical units (table S12) for all impacts except government subsidies.

For each hectare of farmland, all seven farming options that do not include burning have lower social costs in terms of particulate air pollution (figure S3). The largest potential GHG and air pollution reductions are associated with Happy Seeder options, which would eliminate air pollution from burning and reduce GHG emissions per hectare from on-farm activities by more than 78% relative to all burning options, thereby lowering agriculture's contribution to India's GHG emissions [~18% of total emissions in 2010 (*13*)] (fig. S3). Public costs associated with subsidies and water withdrawals were comparable across all 10 options considered (fig. S3).

Our research does not provide a full life-cycle comparison of the economic, social, and environmental impacts of alternative farming practices. The impacts do not include, for instance, total GHG emissions for manufacturing and transport of farm machinery. There are also additional impacts that could be measured, such as soil quality and climate risk reductions. The gold standard would be to assess the public and private benefits of each of the 10 options through a large-scale randomized control trial and undertake a full life-cycle analysis, which would help to reduce any remaining uncertainties regarding private and public returns associated with different farming practices.

ADOPTION AND SCALING

Any viable alternative to crop residue burning must be at least as profitable and scalable to allow widespread adoption by the 2.5 million farmers practicing rice-wheat farming in northwestern India. Agricultural technology adoption and scaling present challenges globally, with success tied to reductions in credit and cost constraints, farming risks, and learning and information frictions (*14*).

In lieu of in-depth analysis of technology adoption in northwestern India, we examine some critical barriers to scaling Happy Seeder and baling. We do not explore options that include straw incorporation, which are on average less profitable than burning.

Although Happy Seeder use is still relatively low, it is rapidly increasing with government of India subsidies in 2018 for in situ residue management (*15*). Scaling adoption in the initial stages to ~50% of the rice-wheat cropped area will require some ~16,000 Happy Seeder machines (see table S13 for alternative scenarios). This would entail an investment of ~INR 2.4 billion (~US $34.5 million), which is less than one-quarter of the subsidy currently allocated to finance residue management.

Use of the crop residue baling approach is minimal. The main market for baled residue is a small number of power plants in the state of Punjab that use residue to produce 0.5% of the state's electricity. Discussions with power plant managers suggest that using residue to produce electricity is largely constrained by upfront investments [INR 41 to 69 million (US $600,000 to $1 million) for a 1 MW plant; that is, a total investment of ~INR 33 to 55 billion (~US $500 to $800 million) if 50% of currently burned residue is converted to energy (table S13)], purchasing power agreements with the government, and transportation and storage constraints. This form of bio-energy also has to compete with solar and other forms of energy. Thus, expansion of baling as an alternate to burning will depend on private-sector willingness to make required capital investments and the ability of crop residue–based bio-energy to grow competitively in a dynamic energy market.

Accelerated adoption of Happy Seeder systems also faces obstacles. Key barriers are upfront machinery costs, lack of knowledge of no-burn alternatives and external impacts of burning, limited incentive to change practices given uncertainties about new technologies and no-burn policy implementation, and supply chain and rental market constraints (see table S20). These barriers will need to be addressed through a combination of government action and private-sector investment.

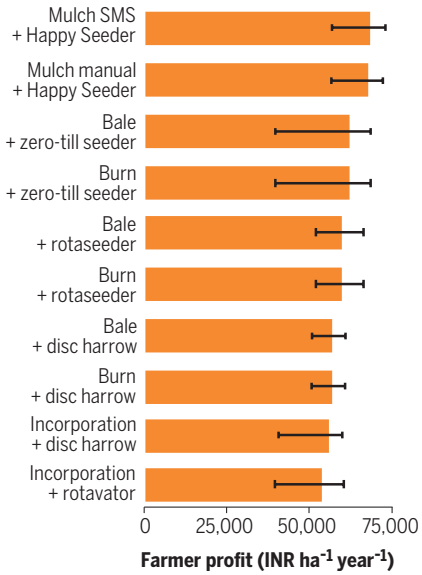
Capital cost barriers are being partially addressed by the 2018 subsidy from the government of India for no-burn agricultural equipment. To increase knowledge and confidence, extension centers are providing demonstration and training of Happy Seeder use. However, farmers often learn best from each other; this kind of trusted knowledge as well as access to the Happy Seeder is currently limited (tables S18 and S19). Thus, nongovernmental organizations (NGOs) and universities (represented by some of the authors), in partnership with government agencies, are attempting to reduce learning frictions by creating farmer communication campaigns and developing farmer-to-farmer learning opportunities and business plans to engage small operators in rental service provision, which will be particularly helpful to capital-constrained small farmers. Supply constraints appear to also be easing as manufacturing of the Happy Seeder has increased in the past 2 years. Full scaling of Happy Seeder adoption would require additional private-sector actions (increased manufacturing and service provision), government support (burning ban enforcement, education, and financial incentives) and NGO and university commitments (communication, social nudging through trusted networks, and demonstration and training for farmers). The adoption response is likely to depend on factors such as the quality of extension services, farmers' trust in the information received and decisions under uncertainty, whether supply-side financial constraints are adequately eased, etc. Globally, less is known about technology adoption in response to simultaneous easing of financial, risk, and information constraints (*14*). Given the spread of current and proposed residue management interventions, this calls for further evaluation of outcomes, possibly using quasi-experimental methods.

Our analysis suggests that it is possible to reduce air pollution and GHG emissions in a way that is profitable to farmers and scalable. Further investigation using a large-scale randomized control trial would enable causal attribution of the no-burn solutions identified here and would reduce remaining uncertainties by clarifying how profits may vary according to local factors such as soil type or access to markets and capital. Yet each year of additional burning imposes unnecessary and substantial health and environmental costs. We thus offer compelling evidence, based on synthesizing and analyzing the best available data, that governments and decision-makers should invest in these economically viable no-burn alternatives now in order to accelerate change, save lives, and increase incomes.

Agricultural fires continue to be a challenge in many parts of the world. Our analysis strongly suggests that India has an opportunity, through coordinated public and private actions, to reduce burning, increase incomes, and transition to more sustainable agriculture while addressing the urgent problem of seasonal air pollution. India's efforts can provide lessons for other countries facing similar risks and challenges. ■

Comparable profitability: Burning versus nonburning

The size of the bar reflects calculated profits using the mean of the means for each input and output parameter across studies. Error bars reflect calculated profits using the lowest and highest means across studies.



SMS, straw management system; INR, Indian rupees. See supplementary materials for details, fig. S2 for difference in profits between options, and tables S1 to S4 for raw data.

GRAPHIC: N. CARY/SCIENCE

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ACKNOWLEDGMENTS

We thank officials from various Indian government agencies for their time, data, and insightful discussions, particularly the Indian Council of Agriculture Research, farmers, plant managers, manufacturers, and the CGIAR research programs on Wheat Agri-Food Systems and on Climate Change, Agriculture, and Food Security. **Funding:** Supported by the Craig and Susan McCaw Foundation and the Institute on the Environment at the University of Minnesota. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** All data are available in the main text or the supplementary materials.

SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/365/6453/536/suppl/DC1

10.1126/science.aaw4085

Science

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Science **365** (6453), 536-538.
DOI: 10.1126/science.aaw4085