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Climate impacts of natural farming:

A cradle to gate comparison between conventional practice and Andhra Pradesh Community Natural Farming

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Intensification of Indian agriculture has resulted in burgeoning costs for producers and severe environmental degradation. Andhra Pradesh Community Natural Farming (APNCF) emerged as an alternative, and the government of Andhra Pradesh now aims to convert 8 million acres and 6.5 million farmers to this technique by 2024. Recent work has examined the level of adoption and the associated impacts on land health, economics, and nutrient cycling. Here we investigate the climate impacts. Using methods consistent with Life Cycle Analysis (LCA), we estimate the greenhouse gas (GHG) emissions (i.e., the carbon footprint) of APCNF and conventional management practices for six cropping systems—paddy rice, groundnut, maize, chilies, cotton, and Bengal gram—that account for more than 80% of total crop area in the state. Boundaries of the analysis extend from production and transportation of inputs to the point where products leave the farm (cradle to gate). Data detailing crop production practices were collected from a survey of 1,467 farmers of the aforementioned crops. Our estimates indicate that APCNF techniques would reduce emissions acre^{-1} by an average of 46% across the six crops by comparison to conventional techniques, with a range from 23% (paddy rice) to 60% (maize). When applying metrics that account for the importance of food production (i.e., kg GHG kg product^{-1}), the relative performance of APCNF to conventional is even more favorable for four of six crops. Transition to APCNF for these six crops could reduce emissions by 5.1 million tons CO_2eq year^{-1}, equivalent to approximately 30% emission reduction from these croplands. Even so, massive potential for emissions reductions remains untapped, particularly in terms of the paddy rice water management and livestock, two of the largest emission sources in Andhra Pradesh's agriculture. Potential emission reductions should be taken in context and future work needs to investigate trade-offs of emission reductions against other environmental concerns, ranging from impacts on water and land use to human and ecosystem toxicity. Limitations to our approach include relying on farmer recall and failing to explicitly match households based on demographics. Opportunities for improvement and future analysis include improved precision when characterizing farm management practices and using more sophisticated models for predicting impacts.

Introduction: Natural farming and climate

Agriculture drives the Indian economy. The agricultural sector is the largest single contributor to the country's Gross Domestic Product (GDP), generating nearly 20% of the total (WITS 2017), which is approximately US$2.36 trillion per year (average 2014–2018) (Export.gov 2019; World Bank 2018). The Indian agricultural sector employs at least 49% of the country's population (World Bank Group 2018); this amounts to roughly 645 million people (World Bank 2018), or 1 out of every 12 people on the planet (The World Bank 2019). Growth of the agricultural sector has been historically slow and highly volatile, expanding at an average of 3% annually (World Bank Group 2018). In contrast, the Manufacturing (8.1% annual growth) and Services (7.4%) sectors have expanded rapidly, setting the pace for overall GDP growth in one of the fastest-growing economies in the world (World Bank 2018).

Indian agriculture is a critical determinant of national food security. The sector has made enormous strides since the 1990s, moving from widespread food deficits to net food exports and surpluses in spite of population growth (World Bank Group 2018). India reached staple grain self-sufficiency over the past five years, and this trend is expected to continue in the future (Export.gov 2019). For example, the 2016–2017 harvest produced 275 million tons of grain—enough to meet national demand for the entire population (Jitendra 2018). Significant increases in productivity have been catalyzed by wide-scale adoption of Green Revolution-era intensification techniques, such as high-yield hybrid varieties, fertilizers, and other chemical inputs. This has led to measurable improvements in food security and health for large segments of the population.

While intensification has been a crucial part of agricultural growth and development in India, the agricultural sector remains extremely resource inefficient in terms of inorganic fertilizer use, water consumption, mechanization, cropping intensity, and livestock herd size. For example, Indian agriculture consumes about 90% of the nation's water resources (GFFA 2017). Total fertilization rates are comparable to those of Europe in 2016, at approximately 165 kg/ha/yr (World Bank 2018). However, fertilizers are typically applied imprecisely, resulting in low crop uptake. Consequently, yield increases are minimal, and much of the fertilizer is released into the air, soil, and water as pollutants.

Greenhouse gas emissions are an important negative externality of intensive Indian agriculture. India's agriculture sector contributes nearly 1/5th of the total annual emissions. Primary production—input generation and on-farm production—generates the vast majority of agricultural related emissions in India (87%) occur during (Pathak et al. 2010). The most significant emission sources include livestock digestion (methane, CH_4), manure storage (nitrous oxide, N_2O, and CH_4), flooded soils (CH_4), inorganic and organic fertilizer use (N_2O), production of agricultural inputs, energy use on the farm, and residue management (carbon dioxide, CO_2).

Many opportunities for mitigating climate change are available for Indian agriculture. Sapkota et al. (2019) modeled the cost-effectiveness of eight crop, eight livestock, and six communal land abatement options, including improved water management, zero-tillage, and fertilizer burning, among others. The results show that adoption of these measures is economically feasible and could reduce emissions by 85.5 Megatonne[1] CO_2equivalents (MtCO_2eq) relative to a 515 MtCO_2eq business-as-usual scenario (17%). This sets the bar for what is possible. Wholesale changes in production systems, such as the adoption of agroecological approaches, were not examined in this study, suggesting that additional reductions may be plausible.

Agriculture in Andhra Pradesh is a GHG emission hotspot among Indian states (Vetter et al. 2018) and the government's most recent estimate suggests emissions from this sector are 17.5 Mt CO_2eq year^{-1} (Vision 2029, 2018). Programs and policies to reduce emissions from Andhra Pradesh agriculture require identifying the magnitude and sources of emissions both from conventional management and potential alternative management practices. Natural Farming emerged as an alternative management system in 2002. Natural Farming has gained momentum, particularly in Andhra Pradesh, where the government aims to convert 8 million acres and 6.5 million farmers to Andhra Pradesh Community Natural Farming (APCNF) by 2024 (Rythu Sadhikara Samstha Programme 2019). The initiative—implemented by the government agency Rythu Sahikara Samstha (RySS)—started in 131 village clusters in 2016 and has quickly expanded into 268 other village clusters, with approximately 500,000 farm family participants to date. This already makes it one of the largest agricultural and food systems transformations on the planet (UN Environment 2018).

APNCF aims to improve soil health and plant productivity by mimicking and catalyzing natural processes. APCNF consists of four primary principles known as "wheels" following the principles of Zero Budget Natural Farming developed by Subhash Palekar: (1) *jiwamrita*, applying fermented cow dung, urine, jaggery, and pulse flour to soil; (2) *beejamrita*, treating seeds with a mixture of manure and lime; (3) *acchadana*, using living or residue-based mulching; and (4) *whapahasa*, the improved water management and soil structure resulting from the other three wheels (Bishnoi and Bhati 2017).

APCNF has been the focus of a number of recent scientific investigations, but potential GHG emissions have not yet been studied. The majority of previous studies have

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[1] 1 Megatonne = 1,000,000 metric tons

focused on the social movement behind Zero-Budget Natural Farming (the progenitor of APCNF), the scale at which it was adopted, and motivations for its use (Khadse et al. 2018; Cacho et al. 2018). More recently, several investigations have evaluated the performance of APCNF, specifically addressing the critical questions of whether APCNF involves fewer variable costs (e.g., inputs) and whether substitution of APCNF wheels for Green Revolution techniques results in a yield penalty. Although some of these results have not undergone peer review, they suggest that APCNF may reduce costs while maintaining, or in some cases increasing, yields as compared to conventional farming. Bharucha et al. (2020) analyzed crop-cutting data from 1,531 paired plots of either 25 m^2 or 100 m^2 across all 13 districts surveyed by RySS. They found that APCNF yielded significantly more than conventional techniques for paddy rice, rainfed rice, rainfed maize, irrigated groundnut, rainfed groundnut, millet, and cotton. Further, costs associated with APCNF were 24% lower than those of conventional management practices across all crops. The combination of increased yields and reduced costs amounted to a 50% net income increase per ha when using APCNF practices, or 54,000 Indian Rupees (Rs) versus 36,000 Rs per ha. Although more limited in scope in terms of both crop types and districts, Gupta et al. (2020) also found lower costs and higher incomes for farmers using Natural Farming practices versus those employing conventional practices. The Centre for Economics and Social Studies (CESS) reported mixed yield results from crop cutting experiments during the *Rabi* (dry) season, but the statistical significance of their results was not evaluated. For paddy rice, groundnut, sugarcane, jowar, and maize, small and likely nonsignificant mean differences were found between Natural Farming and conventional practices (<8%). Grams (Bengal, black and green; 12 - 28%) and banana (38%) appeared to present the most significant yield gains under Natural Farming. Regardless of changes in yield, however, net returns were positive for all crops under Natural Farming practices as a result of lower costs; net returns ranged from 10 to 133% difference as compared with the same crop grown under conventional management (Galab et al. 2019).

Here, World Agroforestry (ICRAF) and Rythu Sahikara Samstha (RySS), with support from Azim Premji Philanthropic Initiatives (APPI), conducted a comparative assessment of APCNF and conventional management systems across six cropping systems in Andhra Pradesh. The assessment focuses on GHG emissions, a key gap in the recent literature. Given the potential for APCNF to affect multiple ecological, economic, and social aspects of farming, we also briefly comment on preliminary results for yields, costs, gender-differentiated labor, ecosystem impact, and human toxicity by synthesizing the available literature and reporting preliminary results from our own data collection.

Methods: A Cradle-to-Gate Comparison

Methods for our cradle-to-gate carbon footprint are consistent with International Standards Organization 14040 and 14044 (International Standardization Organization 2006b; 2006a; Ridoutt et al. 2016). Selected crops, system boundaries[2], functional units[3], and impacts were determined in collaboration with stakeholders and based on the hypotheses for how APCNF alters environmental, economic, and social outcomes of farming (Table 1). Crops were selected based on their importance in Andhra Pradesh. The six crops investigated—paddy rice, groundnut, maize, chilies, cotton, and Bengal gram—account for more than 80% of crop area in the state (Supplementary Table S1).

Table 1 | Hypothetical impact of switching adopting APCNF.

Impact category	Hypothesis[1]	Potential mechanisms	Section in this report
Climate	<	Fewer emissions from fertilizer production, nitrous oxide emissions from nitrogen use.	Main text
Yield	> or =	Moisture is conserved through mulch and *whapahasa* and stimulation of soil microbial activity improves soil fertility.	Supplementary information
Costs	<	Less reliance on external inputs reduces the overall cost of production.	
Labor	?	Few data are available to enable prediction on the direction of change for labor	
Eco-toxicity and human toxicity	<	Agroecological approaches reduce chemical use and related exposure.	

[1] Hypotheses respond to the statement that performance of APNCF is greater than (>), less than (<), or equal (=) to conventional respective impact category.

The boundaries of the systems extend from cradle to gate; that is, the analysis begins with the production and transportation of inputs and ends when the products leave the farm. We explicitly include the farm inputs phase because APCNF eliminates of chemical inputs in favor of livestock-based inputs. Post-farmgate unit processes,[4] such as storage, distribution, and processing, are not included because products from the two management systems are sold into the same value chains and therefore, emissions are assumed to be the same between them. Importantly, this assessment accounts for both

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[2] System boundaries define which activities that are included or not in the LCA calculation. This varies according to the objectives of the study, data availability, and data quality

[3] The reference measure of unit for which inputs and outputs are related.

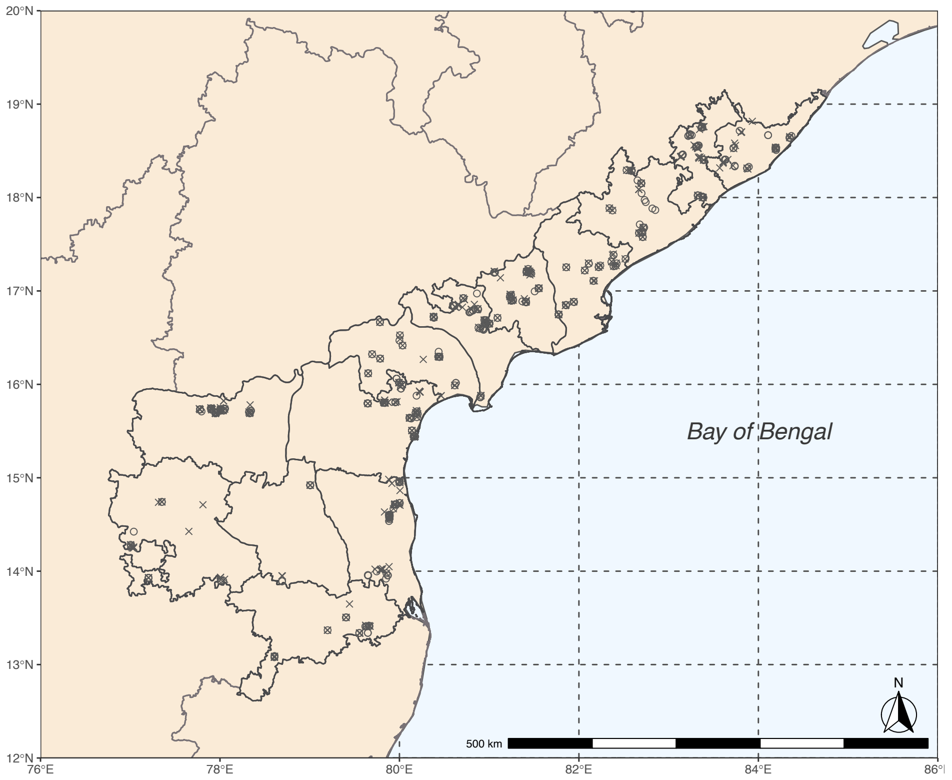
[4] Unit processes refer to activities that influence impacts and are accounted for in the assessment. For example, the amount of fertilizer applied or the amount of fuel used.

organic and inorganic inputs (e.g., manure and chemical fertilizer) and the impacts of producing those inputs (e.g., enteric emissions from cattle, factory emissions) to ensure consistency when comparing the two systems. Functional units were defined per crop (e.g., quintals, bags) and standardized to kilograms (kg) to be comparable across products. This pilot project focuses on climate impacts by using indicators of GHG emissions (t CO_2eq) and GHG intensity (kg CO_2eq kg product^{-1}).

Data detailing crop production practices were collected from two primary sources. One, we surveyed 1,467 farmers to characterize the range of field management practices (Figure 1, Table S1). Participating farmers were selected through a multi-stage sampling procedure. Sampling effort was proportionate to crop significance, as determined by area coverage in the state. Villages were randomly selected by RySS operations. Within each village, surveyed APCNF farmers were randomly selected from among all the APCNF farmers in the village. The nearest neighbor to each selected APCNF farmer using conventional farming was then surveyed as well. Farmers were interviewed on a range of specific farm management activities, e.g. land preparation, fertilization, seed and transplant sources, machine and labor use, costs, harvesting, and on-farm postharvest processing, among others. This information was used to detail the farm production environment. Data were recorded via mobile phone using the application SurveyCTO (2020). The farmer survey provided the input data for the farm-level carbon footprint (that is, the sum of GHG exchange between the atmosphere and the biosphere). The farmer surveys were supplemented with secondary sources where survey data did not provide sufficient precision (e.g., the amount of manure used to create *jiwamrita)*. Two, detailed crop calendars estimating typical farming activities were constructed during two training workshops of 75 RySS Natural Farming Fellows (NFF). The NFF all hold agricultural degrees and are stationed in villages across the state of Andhra Pradesh. They work closely with and observe how farmers manage both APCNF and conventional fields. As such, the Fellows have firsthand knowledge of current practices in both systems. The exception in this process was conventional cotton; the NFF felt insufficiently experienced with this crop and management option to develop a full calendar. Data from the crop calendars are presented in Supplementary Information for comparative purposes and to triangulate results found in the survey.

Data were cleaned and statistics were computed in R (R Core Team 2019) using well-established models and GHG emission factors. In brief, we removed extreme outliers (that is, those that are more than three times the interquartile range) from the dataset assuming they were the results of enumerator error. The number of outliers removed (per crop and management technique) are reported as footnotes to their respective figure or table in the Supplementary Information. Locally applicable conversion and emission factors were applied (Table S2). For example, livestock enteric CH_4 emissions were based on estimates for Andhra Pradesh developed by Sapkota et al. (2019). N_2O emissions from fertilizer and organic materials were based on application rates and a recent synthesis of emissions in tropical countries (Albanito et al. 2017). Emissions from biomass burning were based on harvest indices and recently updated emission factors (Andreae 2019). Methane emissions from flooded rice were calculated based on the coefficients described in IPCC (2006) and Yan et al. (2005), which account for length of season, organic amendment, and irrigation regime. Emissions were converted to 100-year global warming potential (GWP), without feedbacks, according to IPCC guidance, specifically 28 kg CO_{2eq}/1 kg CH_4 and 265 CO_{2eq}/1 kg N_2O (Intergovernmental Panel on Climate Change 2014).

Figure 1 | Location of farms surveyed in Andhra Pradesh. Within Andhra Pradesh, borders represent districts. Outside of Andhra Pradesh, borders separate states. Solid circles are locations of conventional farms and Xs are locations for APCNF farms. About 20% of surveys did not collect field coordinates and thus are not included here.



Given that some farmer survey records were incomplete and/or included outliers, we used Monte Carlo techniques to simulate emissions from 10,000 farms of each crop based on the mean values of management reported by farmers for both conventional and APCNF systems and assuming a standard deviation of 32.5% of the mean. That standard deviation means that 95% of the values will fall within 75% (2 SDs) of the mean; this aligns with the most common level of uncertainty reported on emission factors (IPCC 2000). The percentage of theoretical farmers applying each management technique in each system was equal to the percentage of actual farmers that reported using that management practice in the survey. The Monte Carlo simulations generated both the most likely (average) rate of emission and the plausible extremes that may found in a landscape. GHG emission intensity was calculated relative to yields reported by farmers, except for maize GHG emission intensity, which was based on secondary sources because the reported yields were nearly 50% greater than all other estimates (see Table S12). We then compare the potential emissions of the conventional and APCNF systems to determine the difference in emissions between the two.

The cumulative mitigation potential of APCNF was estimated by extrapolating our results to the areal extent of cropland growing these six crops across the State. We estimate the carbon footprint for the number of acres of each crop based on the distributions of likely emission profiles generated in the 10,000 farms. These calculations assume activity implementation rates are identical to those reported in the survey.

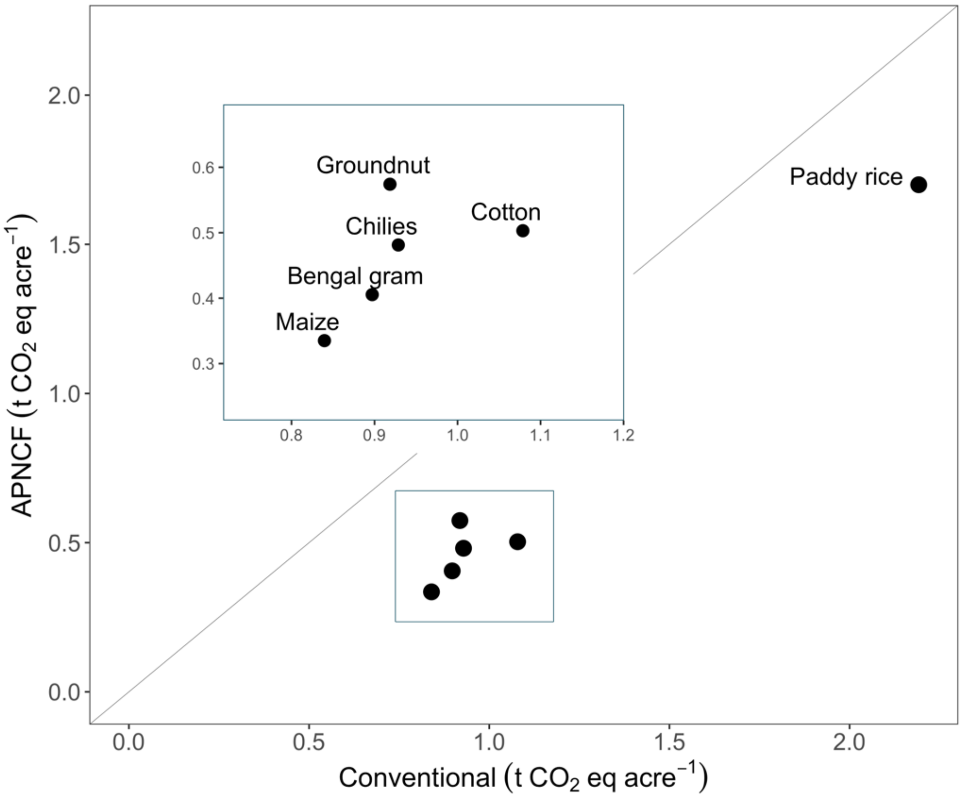
Results & Discussion

Climate impacts

Our estimates indicate that APCNF techniques reduce the impact of agriculture on the climate system as compared to the same crops grown under conventional techniques. Based on management activities carried out on typical farms, the footprint of APCNF farms was lower than that of the conventionally grown crops for all six production systems. The difference ranged between 23% for Paddy rice to 60% for maize (Figure 2). For three of the six crops (Bengal gram, cotton, and maize), emissions on average APCNF farms could be expected to be less than half that of conventional farm emissions. These results indicate that a farm using APCNF is likely to have a much more benign impact on the climate system and is more environmentally sustainable in terms of GHG emissions than a conventional farm producing the same crops.

The carbon footprints estimated for conventional crops were generally greater than the range of those estimated in other studies for the same crops (Table 3). Differences between our results and previous efforts can likely be attributed to differences in system boundaries and/or assumptions about farm management. We included more emission sources in our estimates as compared with previous studies (e.g., Vetter et al. 2017) to better enable a *like-to-like* comparison between conventional and APCNF. Specifically, our estimates for crop production include the fraction of enteric methane and manure management emissions produced during production practices across crops. Where significant amounts of manure were applied, either as solid farmyard manure or through *ghana jiwamrita*, the leverage on the carbon footprint was often nontrivial. Higher estimates may also have been the result of different assumptions on farm management, such as the burning of crop residues or water management (particularly in paddy rice). The consequence of these assumption can be significant, highlighting the importance of quality data on farm activities and emission factors to provide robust estimates. For example, Vetter et al. (2017; 2019) revised their 2017 calculations and reduced the emission estimate for rice by more than 50% to 1547 t CO_2eq acre^{-1} because of revised assumptions about water management.

Figure 2. Relative greenhouse gas (GHG) budgets for the six crops investigated. Diagonal line is a 1:1 line indicating where emissions from conventional and APCNF would be equal. Values on either side of that line indicate differences in GHG emissions between the two methods for the same crop. Area in the box is magnified for interpretation. Data used in these calculations derived from the farmer survey.



Despite uncertainties, the prescribed APCNF techniques are likely to reduce GHGs when compared to alternatives, even other agroecological approaches. The range of APCNF emissions in this study rarely exceeded 1 t CO_2eq acre^{-1}. This range of emission rates is comparable with those of Sub-Saharan African farming systems, including diversified low input farms in Central Madagascar (Rakotovao et al. 2016). It is particularly notable that the GHG emissions from APCNF paddy rice were lower than the well-known System of Rice Intensification (SRI) approach (Gathorne-Hardy et al. 2016) and just a fraction of the mixed cattle and crop systems in Central Kenya (Ortiz-Gonzalo et al. 2017).

Table 3 | Emission estimate for India crops grown by conventional techniques (kg CO_2eq acre^{-1}). Emission estimates from this study are means +/- standard deviation for 10,000 simulated farms based on the results from the farmer survey.

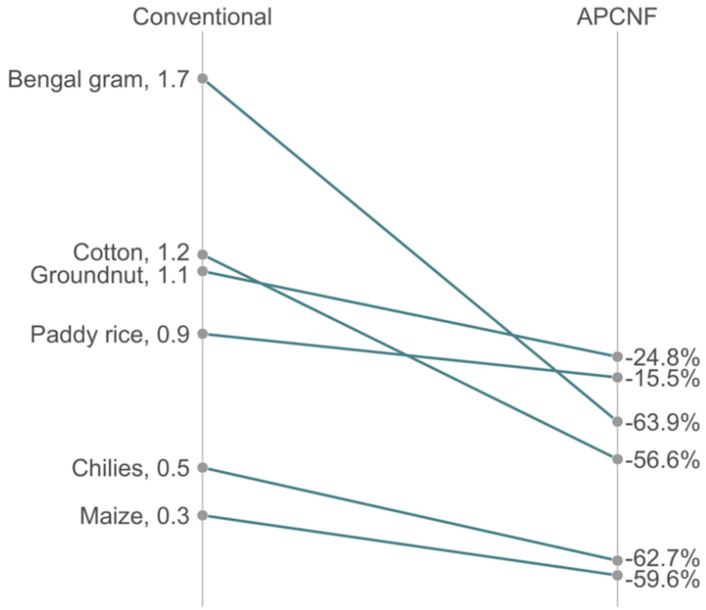
Crop	This study	Vetter 2017	Sapkota 2018	Other
Bengal gram	897 ± 384	248	125	
Chilies	929 ± 398		76	
Cotton	1,079 ± 431	472	159	499
Groundnut	919 ± 257	250	198	
Maize	840 ± 380	404	125	
Paddy rice	2,192 ± 617	1,547	584	1654 - 5,660

[1] Cotton (Mancini 2006), Paddy rice (Gathorne-Hardy, Venkatanarayana, and Harriss-White 2013)

Scaling up these data based on the area planted (Table S1) suggests that conventional production on about 80% of the cropland in Andhra Pradesh emits 15.2 million tonnes CO_2 eq season^{-1}. Conversion of the same lands to APCNF would only produce 10.1 million tons CO_2 eq year^{-1}. This suggests that a transition to APCNF for these six crops has the potential the reduce emissions by around 30%. Our estimate may even be conservative, since it assumes that scaling would reflect the APCNF practices reported by these 1,467 farmers. In reality, APCNF implementation could be refined and improved (see discussion below), implying even greater emission reductions.

Reducing the absolute emissions from agriculture, given its leverage on climate change, is a crucial goal and directly relevant to the Indian government's commitments. However, it is also important to account for the food security and economic prominence of agriculture while addressing GHG emissions. When food security is a challenge, GHG intensity (kg CO_2eq kg^{-1} of product) is often a more useful metric. Such metrics capture the tradeoffs between food and climate (Groenigen et al. 2010). When viewed through this lens, the relative performance of APCNF by comparison to conventional techniques improves even further (Figure 4). Similar to absolute emissions, the GHG intensity of APCNF is an average of 47% lower than that of conventional practices across all the crops but production of four of the six crops represents nearly a 60% reduction in GHG intensity. This is function of emissions being lower under APCNF even as yields remain largely the same (Figure S2).

Figure 4 | Greenhouse gas intensity (kg CO_2eq kg product^{-1}) and percentage change with use of APCNF.



Whereas this analysis has focused on climate impacts, APCNF is likely to have broad social, economic, and ecological outcomes well beyond GHGs, many of which could be more directly relevant to the farmers' day-to-day operations and interests. Our survey included questions about costs, labor, pesticide use, and gender, among other topics. Preliminary results hint at a few key issues that warrant consideration in future analyses (see Supplementary Information). For example, conventional farmers report applying 60 unique pesticides to the six crops. Some of these may induce non-cancerous and cancerous impacts for humans and determinantal environmental outcomes (Table S14). It also appears that the division of labor between men and women may differ between farm families using APCNF and conventional practices (Figure S3). Given the diversity of plausible impacts, we recommend a full LCA quantifying, at minimum: water use, energy use, labor, yields, quality, nutrient budgets, household economics, and erosion, and including, if possible, full cost accounting balancing of private and social costs for both conventional and APCNF farming practices. This comprehensive analysis would enable full consideration of benefit and tradeoffs alongside GHG emissions.

Opportunities for additional emission reductions

The improved environmental performance of APCNF as compared to most other systems (both conventional and low-emissions) largely rests on the four *wheels* at the core of APCNF. APCNF farms eliminate the use of chemical fertilizers, which eliminates GHG emissions from both energy-intensive synthesis of ammonia and N_2O emitted from the field. These are among the most significant contributors to farm CO_2 budgets; they alone can be responsible for more than 30% of the climate impacts of crops that require relatively high N fertilize application rates, such as maize. While manure is the base product for APCNF inoculants, it is used in relatively small quantiles and therefore neither emissions from storage and application nor from enteric fermentation are typically significant. Retaining crop residues has potential to increase soil carbon and therefore offset some emission. Importantly, although mulch is a central tenant of APCNF, it is still not widely practiced by APCNF farmers, likely because it is a significant change from common residue management practices, such as burning, feeding to livestock, or thatching roofs. Depending on the cropping system, between 13 and 66% of APCNF farmers in our survey reported leaving crop residues on the field. This suggests that more consistent implementation of APCNF mulching practices could lower emissions even further.

Paddy rice produces far greater emissions than any other crop grown in Andhra Pradesh (Figure 3). CH_4 is produced by methanogenic bacteria under the anaerobic waterlogged soil conditions of rice paddies. Our estimates suggest emissions from paddy rice are about twice that of the other five crops under the same management practice (conventional or APCNF) despite the fact that our paddy rice emissions estimates are be on the low end of the expected range.[5] Given that paddy rice is grown on more than 1/3 of total Andhra Pradesh cropland, at least 60% more area than any other crop in the state, significant emissions reductions could be achieved by integrating complementary practices into APCNF. The most promising GHG mitigation option for rice (without reducing area) relate to water management. It is well established that mid-season drainage or alternate wetting and drying[6] practices reduce CH_4 emissions by 50% or more (Yan et al. 2009). Studies in neighboring Tamil Nadu suggest that 40% reduction are possible under very similar conditions to that found in Andhra Pradesh (Oo et al. 2018). Increased fluctuations in soil moisture can, however, stimulate additional N_2O

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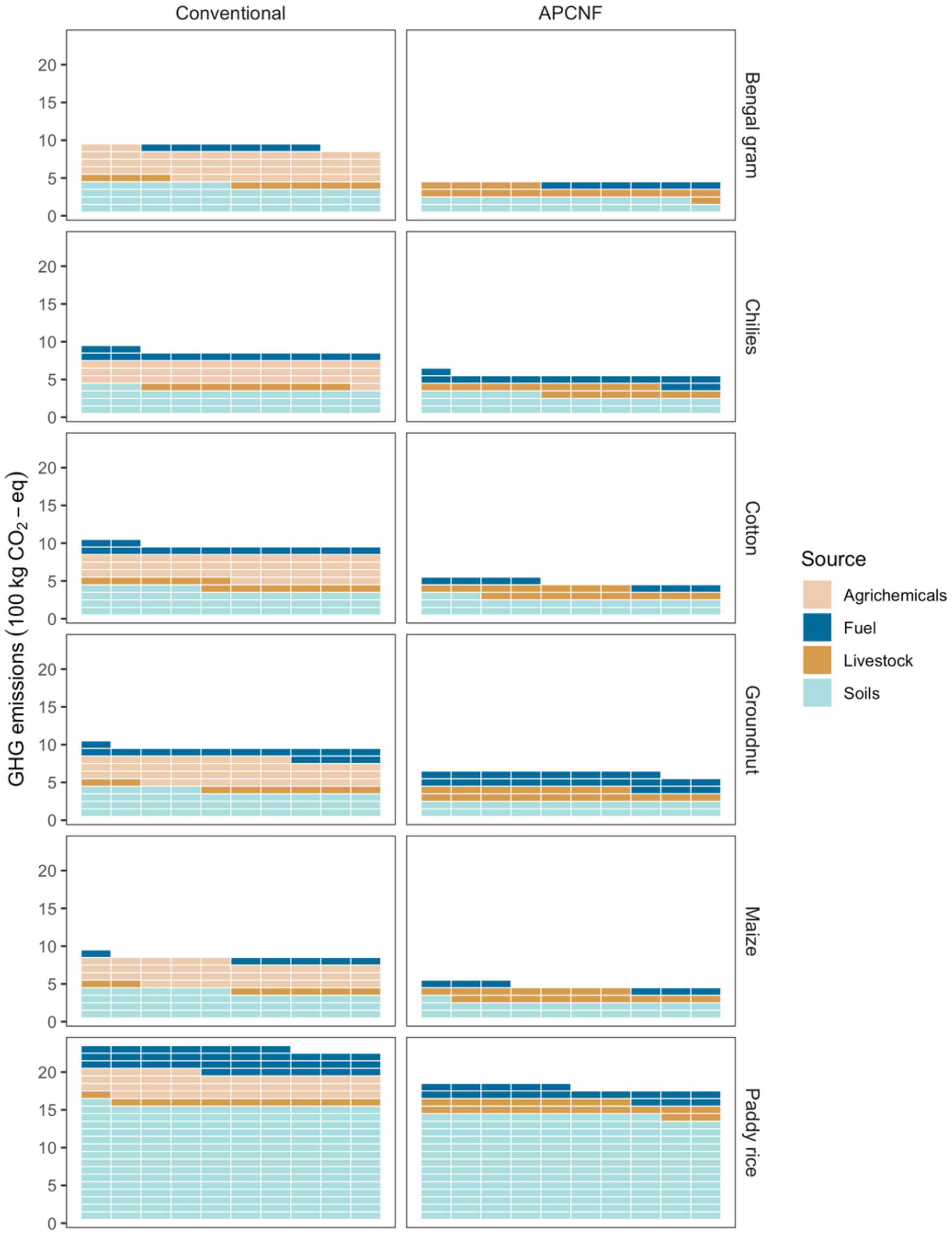
[5] We applied an emission factor that relates CH_4 to growing season length and length of drying period between crops (Yan et al. 2009). This emission factor is justified given the continuous flooding conditions of paddy rice cultivation in Andhra Pradesh (GoI 2018), as well as the less than six-month period between *Kharif* (monsoon) and *Rabi* (dry) crops, but lower than other estimates employed for Indian rice systems (e.g., 0.24 g CH_4 m^{-2} day^{-1}, IPCC (2006); 0.14 g CH_4 m^{-2} day^{-1}, NATCOM in Gupta et la. (2009)).

[6] Alternative wetting and drying consists of drying rice fields, and subsequently rewetting them throughout the season based on changes in soil moisture.

emissions, primarily during denitrification (Kritee et al. 2018). Regardless, on balance, water management lowers emissions from flooded rice (Wassmann et al. 2019). These techniques have the added benefit of reducing water use by up to 80% and thus improve the resource efficiency and adaptive capacity of rice farming without comprising yield (Oo et al. 2018). The ability to implement these practices is subject to sufficient water control, alignment with governance and institutions however (Sander et al. 2019).

Figure 3. Relative sources of GHGs in conventional and APCNF farms. Each block = 10 kg CO_2eq. The more blocks in the panel, the greater the emissions. Residue-related management (burning and mulch) not pictured.



Addressing emissions from livestock would also mitigate APCNF's impact. Livestock-related emissions may be from enteric fermentation during digestion or via manure management or soil N_2O off-gassing and are the second-largest source of GHG emissions in Andhra Pradesh's agriculture. It is possible to attenuate livestock emissions by ensuring good health through diet and preventative medical care. However, the most predictable way to reduce animal emissions is to reduce the size of the herd. This objective stands in direct contrast to some policies being promoted around Natural Farming—specifically widespread distribution of livestock. It has been suggested that APCNF requires 1 cow for every 30 acres, later calculated to 1 cow for every 16 to 24 acres (Smith et al. 2020). This would appear to be the case given that *beejiwamrita* and *dharva jiwamrita* both require only about 10 kg manure. However, *ghana jiwamrita* requires much more manure (and hence animals) and has not historically been included in manure requirement estimates. According to our study, *ghana jiwamrita* is employed by 72-98% (depending on crop) of APCNF farmers and is applied at up to 400 kg manure acre^{-1} season^{-1}, ranging on an average from about 226 kg manure acre^{-1} for Bengal gram and 344 kg manure acre^{-1} for chilies (Table S5). A cow produces about 10 kg manure day^{-1} or 3,650 kg manure year^{-1}. This implies that for *ghana jiwamrita* alone, one cow is needed for every 9 acres. Given that there are two production seasons in Andhra Pradesh and *ghana jiwamrita* may be applied in each, this becomes one cow per year for 4.5 acres. This is nearly 400% the previous highest estimate of cows acre^{-1} under APCNF management. Even so, only about 2 million cows would be needed to practice APCNF on all farmland in Andhra Pradesh. This is well below the state's current population of approximately 9.4 million cows. Innovative methods of animal husbandry, manure distribution, and APCNF process scaling could enable significant reductions in total state herd size even while expanding APCNF. This represents an opportunity to radically reduce GHG emissions.

Increasing tree cover on Andhra Pradesh farmlands presents a further prospect for climate change mitigation. Indeed, agroforestry is one of the most promising options for meeting mitigation, adaptation, land degradation, and food security goals (IPCC 2019). Depending on the species, planting configuration, and management, trees on farms can accumulate more than 7 Mg of C year^{-1} in above- and below-ground biomass (Cardinael et al. 2018). Our study did not account for trees on farms because trees were largely absent from much of the farming landscape. With the interest and promotion in the APCNF '5-layer system', which create polycultures on the farm, we expect biomass carbon to become and increasing significant carbon pool in the future. Until then, it remains an untapped opportunity. Initial landscape-level surveys indicate low species diversity when trees are present (L. Winowiecki, pers. communication). Thus, programs to increase tree cover will require the development of extensive tree germplasm development and distribution systems.

Limitations

The simple accounting approach used here has some limitations, and there are uncertainties in the underlying data. Our data are based on mental recall and interviewing, both of which have known limitations (Fraval et al. 2019). Farm recall data in particular is often poorly correlated with actual activity, even when corresponding to major events such as yield and demographics. While efforts were made to produce random samples, this cannot be guaranteed, particularly in light of this study having employed 75 survey enumerators. There is a chance that the households that employed conventional versus APCNF practices are fundamentally different; this would potentially confound the farm activity data. Using farmer recall and failing to explicitly match households based on demographics inherently creates conditions for selection bias. Despite the limitations, the trends between APCNF and conventional farm CO_2 budgets appeared robust. The data derived from the crop calendars and farmer surveys align well (see Table S3). This would seemingly suggest that the survey, despite using a large number of enumerators, generated a reasonable characterization of the average farm in Andhra Pradesh. Opportunities for improvement and future analysis include better quantifying farm management techniques via, for example real-time activity data collection.

Carbon footprints, even when using detailed activity data and the best available emission factors, provide an initial scoping of the potential emission profile of the agricultural systems. Depending on the emissions source and location, emissions factors may be derived from 10s or 100s of measurements (e.g., nitrous oxide from soils), while others are often generated from process-based models or expert opinion (e.g., enteric methane emissions). Emissions factors by design represent average relationships between an activity and emission. Yet, production conditions for any specific farm are never average. In this analysis, we applied emission factors relevant for the local conditions, and often times ones developed specifically for India. Where specific data were not available, we used standard emissions factors and quantification approaches. This, however, may overestimate emissions for some sources. For example, the IPCC recommends estimating that 2% of the nitrogen in manure is emitted as N_2O. However, studies from low-input systems, including cattle that feed on low protein diets, show that emissions from manure may be at least an order of magnitude lower (Tully et al. 2017; Pelster et al. 2016). At this time, there are no empirical data to calibrate models of the impact of the APCNF inoculants on emissions. Thus, we applied the most reasonable emission factors for manures, the primary ingredient of the inoculants. Our estimate, upwards of 15% or more of the respective carbon footprint, could underestimate emissions, particularly in light of the fact that the inoculants are meant to stimulate soil microbe, which may drive emissions. Similarly, we estimated emissions from pesticide use based on the number of applications. This is a blunt tool given pesticide use accounted for about 20% of emissions for some crops and the diversity of active ingedients and sources.

Conclusions

This study represents the first effort to estimate APCNF emissions, and the results suggest that that APCNF emissions are likely to be significantly lower than those of conventional systems. We found that APCNF would reduce emissions by at minimum 23% in comparison to conventional practices at the field level. We estimate that a transition to APCNF could save on average of 5.1 million tons CO_2eq year^{-1}, which is approximately equal to mitigating 30% of emissions from this cropland. Massive potential for emissions reductions remain untapped in terms of residue management, paddy rice water management, livestock, and agroforestry. Trends in preliminary data on other social and environmental outcomes support previous studies, and would seem to indicate that APCNF may generate substantial benefits for the people and landscapes of Andhra Pradesh.

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SUPPLEMENTARY INFORMATION

Climate impacts of natural farming: A cradle to gate comparison between conventional practices and Andhra Pradesh Community Natural Farming

Contents

Significance of the included crops

Andhra Pradesh is among India's most agriculturally productive states. It produces substantial portions of national paddy rice and groundnut crops and is known throughout the country for high-quality chilies. Agriculture covers more than 10 million acres of land (Department of Agriculture, Cooperation, and Farmers' Welfare 2017). While the State produces a wide variety of products, ranging from coffee to cotton, the majority of the agricultural area is covered with just five crops. Paddy rice covers about 4 million acres, or roughly 40% of the land area used for agriculture (Table S1). Bengal gram, typically grown during the Rabi season, is another widely planted crop, using ~2.5 million acres. The importance of these crops, in terms of economics and land area, provided a clear focus for our analysis. The analysis considered six crops and two management techniques.

Table S1 | Crop-wise target and sown areas during 2018 (provisional data provided by RySS, February 2019). 1 Lakh = 100,000. 1 ha = 2.46 acres.

Crop	Target area		Sown area	
	Lakh acres	% of total	Lakh acres	% of total
Paddy rice	40.0	38	38.1	39
Groundnut	22.6	22	20.4	21
Cotton	14.3	14	16.0	16
Chilies	3.2	3	3.2	3
Maize	3.2	3	2.5	2
Total	83.4	80	80.0	81

Key conversion and emission factors

Carbon footprints convert information on unit processes into estimates of environmental impact, one of which is GHG emissions (Pajula et al. 2017). The results reported in the main text focus on GHG emissions and GHG intensity, and additional impact categories are discussed in the following sections. Conversion of unit processes is done through a series of factors that are dependent on the process and regional conditions. The main conversion factors, emission factors, and sources used in our analysis are detailed below (Table S2).

Table S2 | Conversion coefficients and GHG emission factors used to calculate source-based emissions and CO_2 budgets. Where possible, conversions and emissions were used on factors developed in similar conditions to Andhra Pradesh, if not Andhra Pradesh itself.

Source or sink	Activity data	Product	Factor	Source
Fertilizer production	Amount and type applied (kg)	CO_2	0.13-17.2* kg kg^{-1}	Kool et al. 2015, Ecoinvent 2006, Hilier et al. 2011
Manure use – APCNF	Ghana jiwamrita (kg, times)	Manure N	332 g N 100 dm^3	Smith et al. 2020
	Dharva jiwamrita (kg, times)	Manure N	157 g N 225 dm^3	Smith et al. 2020
	Beej-jiwarmrita (kg, times)	Manure N	66 g N 37 dm^3	Smith et al. 2020
Manure storage	Manure applied (kg)	CH_4	1.27 VS kg/day, 0.13 Bo, 0.05 MCF	IPCC 2019
		N_2O	0.14175 N excretion/day, 0.5% EF	IPCC 2019
Livestock required	Manure applied (kg)	Livestock	10 kg manure day^{-1}	Smith et al. 2020
Enteric fermentation	Livestock number	CH_4	30 kg $head^{-1}$	Sapkota et al. 2018
Harvest index	Yield by crop	Residue applied	0.27-0.5	Ramakrishna et al. 2005
Biomass burning	Residue applied (kg)	N_2O	0.071 g kg^{-1}	Andreae 2019
		CH_4	5.7 g kg^{-1}	Andreae 2019
Soil emissions - upland	N fertilizer	N_2O	1.33%, 0.3% (rice)	Albanito et al. 2019, IPCC 2006
	Residue, manure N	N_2O	2%	IPCC 2014
	Residue, tillage	CO_2	140-180 kg	Hillier et al. 2011
Soil emissions – flooded	Days in season, residue, manure	CH_4	0.09-0.24 g m^2 day^{-1}	IPCC 2014, Yan et al. 2005
Crop protection	Applications (#)	CO_2	20.5 kg/application	Hillier et al. 2011
Petrol	liters	CO_2	31.5 MJ/L, 0.07/MJ	
Diesel	Liters	CO_2	38 MJ/L, 0.07/MJ	

[1] Emissions factor depends on the product being applied.

Potential for bias in the household survey

There is potential for selection bias with household surveys. Selection bias is introduced when randomization is not achieved and so the sample is not representative of the population. Selection bias limits the inference that can be made from results. We cannot fully rule out selection bias with our household survey. There are chances that individual decisions of farmer selection were not completely random as farmers were selected in consultation with local RySS authorities and sometimes had to be adjusted in the field based on logistical constraints. Typically, one would compare standard household demographic and wealth parameters to understand if the samples were similar. However, because our survey was principally intended to capture farm management and not farm household demographics, only a few factors are available to compare the respondents using conventional and APNCF techniques. Based on land area and tenure, which can be broadly translated as proxies for assets and socioeconomic status, we found little difference between the sample groups (Table S3). These results suggest that, while we cannot rule out selection bias, it is unlikely to have had a significant impact on our results.

Table S3 | Average farm characteristics of conventional and APCNF farms surveyed. Land area and tenure are proxies for socioeconomic status. Conventional and APCNF farms of the same crop were similar (Mann-Whitney Test) for total area, cropped area, and ownership.

	Bengal gram		Chilies		Cotton		Groundnut		Maize		Paddy rice	
Factor	Conv.	APCNF	Conv.	APCNF	Conv.	APCNF	Conv.	APCNF	Conv.	APCNF	Conv.	APCNF
Gender (*N*)												
Male	57	51	40	35	126	123	125	135	59	60	259	272
Female	6	13	2	2	5	6	5	37	3	7	19	33
Area (acres)[1]												
Total[2]	4.0	3.9	2.8	2.7	3.1	2.7	2.9	3.1	2.8	2.6	2.7	2.5
Cropped[3]	3.2	2.5	1.5	1.3	2.0	1.7	1.7	1.6	1.2	1.0	1.6	1.3
Tenure (%)[4]												
Own	93.7	89.1	92.9	86.5	88.5	96.2	96.2	94.2	85.5	88.1	90.3	87.9
Rent	4.8	9.4	4.8	10.8	10.7	2.3	2.3	4.7	11.3	11.9	9.3	10.2
Both	1.6	1.6	2.4	2.7	0.8	3.1	1.5	1.2	3.2	-	0.4	2.0

[1] Nine outliers removed across 1467 farms. [2] Average total land (acres), [3] Average area cropped to the identified management practice (acres). [4] Percentage of farmers for the respective crop/management.

Farm management in Andhra Pradesh

Farm management drives GHG emissions (and carbon stock changes). Many farm activities, including using fertilizers, processing manures, and burning biomass, affect carbon and nitrogen cycles and stimulate emissions. Production of inputs also emits GHGs. The mode of implementation of APCNF (or any management practice) can have significant effects on its sustainability. For example, theoretical questions have been raised about the sustainability of APCNF's reliance on soil nutrient reserves and the implications of the same on sustainability (Smith et al. 2020). Understanding how farms are being managed is the first step in estimating GHG emissions.

Yet there are few data available regarding how APCNF is implemented. Multiple surveys have recently tried to document APCNF use; however, they are typically limited to a few districts or number of indicators (e.g., Bharucha, Mitjans, and Pretty 2020). Meanwhile, the largest survey to date (*N* > 5,000 households) seems to suggest that most farmers adapt and/or only partially adopt the APCNF wheels. As such, the documented characterization the farm practices resulting from this study is arguably equally as important as the climate impact results. Our survey fits within the constellation of previous work by adding key information on farm management as reported by a considerable number of APCNF farmers (*N* = 765) across all 13 districts of Andhra Pradesh. We collected data on farm management from 1,467 farmers in total (Table S4). Sampling methods and locations are described in the main text of the report. The farmer survey was undertaken to characterize the range of potential management strategies ongoing across Andhra Pradesh.

Table S4 | Number of Conventional and APCNF farms surveyed in April/May 2019 by crop. Sampling effort was proportional to the areal extent of the respective crop in the State as much as possible.

Crop	Conventional	APCNF	Total
Bengal gram	62	63	125
Chilies	40	36	76
Cotton	131	128	159
Groundnut	130	168	198
Maize	60	65	125
Paddy rice	279	305	584
Total	702	765	1,467

We also detailed farm management during the training workshop of Natural Farming Fellows (NFF). Crop calendars were derived from two training workshops that took place in Guntur, Andhra Pradesh in February and March of 2019. The purpose of these workshops was to strengthen the NFF's knowledge base in terms of climate change, agriculture's role in the same, and LCA methodologies. A total of 75 NFFs participated in one of the two workshops. During the workshops, NFFs worked in groups of 3-5 to diagram the management practices that take place on APCNF and conventional farms for each of the target crops. Crop calendars were then reconciled cross groups working on a given crop by management combination. The resulting crop calendars represent the typical farms that NFFs interact with on in their daily work. The crop calendar data offer an additional point of comparison for the farm survey results.

Fertilizer use

Chemical fertilizer use is a cornerstone of Green Revolution techniques common across Andhra Pradesh. Chemical fertilizers, and especially the materials containing nitrogen, are a principle source of emissions on farms. In some cases, emissions from production and use of fertilizers can be 30% or more of a farms CO_2 budget (Ortiz-Gonzalo et al. 2017). Production of nitrogen fertilizer requires significant amounts of energy (typically natural gas) and thus generates significant GHG emissions (Erisman et al. 2008). Furthermore, application of nitrogenous materials supercharges the N cycle of soil microorganisms; this can lead to N_2O emissions during nitrification and denitrification (Davidson et al. 2000) and initiate a cascade of environmental and health impacts (Galloway et al. 2004). Average fertilizer use in India is reported as 24 kg nitrogen acre^{-1} season^{-1} (Land and Water Development Division 2005). Average nitrogen fertilizer use in the Government of India's Cost of Cultivation Studies for Andhra Pradesh, as compiled by Vetter et al. (2017), were (kg acre^{-1}): cotton (56.8), groundnut (15.3), maize (57.4) and paddy rice (60.1). Data from our surveys exceeded these values (Table S5).

Table S5 | Typical fertilizer use (kg product acre^{-1}) and nitrogen applied in those products (kg N acre^{-1}) per season reported by Natural Farming Fellows (NFF) and average fertilizer use reported during the farmer survey (FS). Typical fertilizer use by farmers represents the average amount of fertilizer for each of the materials named by at least 10% of the farmers for each material.

	Bengal gram		Chilies		Cotton		Groundnut		Maize		Paddy rice	
Fertilizer	NFF	FS	NFF	FS	NFF	FS	NFF	FS	NFF	FS	NFF	FS
Urea		68	35	49.5	48	54		74	160	63	120	54
Diammonium phosphate	50	61	20				50	61		73		68
Compound N-P-K	100	34	20								50	
Compound N-K				32				59			50	
Super phosphate			10				100					
Triple super phosphate									150			
Muricate of potash			40			78			40	87	24	70
Potassium sulfate							100					
Nitrogen applied	24	47.4	22.7	22.7	80.2	24.8	9.0	45.0	73.6	42.1	69.7	37.1

Manure use

Animal manures are a key fertilizer in crop production systems that do not use chemical fertilizers. In these systems, manures are applied to provide plant nutrients at levels sufficient to support growth and development and, as a co-benefit, improve soil health. Animal manures in APCNF play a different role. APCNF uses manure-based inoculants to stimulate soil fauna and mobilize existing soil nutrients. Therefore, the manure-sourced nutrients are supplied in small quantities (e.g., 5-8 kg N acre^{-1}). This has led to concerns about soil nutrient mining, a common issue in low-input systems (Sanchez 2019). Smith et al. (2020) provide a comprehensive analysis of the issue and the sources of nitrogen (e.g., manure, residues, jiwamrita, symbiotic bacteria) and suggest that APCNF is likely only to provide 52-80% of the nitrogen requirement of the crop, therefore concluding there is some potential for nutrient mining. Our study does not comment on the potential for nutrient mining directly. However, this work does provide important new insights into how APCNF is being implemented, thus helping to reduce the uncertainty in sources of nutrient supply. For example, we now have better information on manure use (Table S6), residue use and retention (Table S7), and intercropping (Figure S1). A logical next step would be to calculate nutrient balances and simple input-output accounting to understand the relative amounts of nutrients exported off the farm vs input into the system (Vitousek et al. 2009).

Table S5 | Manure use and storage on conventional and APCNF farms. Values are averages based on the farmer survey. Values in parentheses represent the amount of manure applied as described in the crop calendars.

	Conventional			APCNF								
	Farmyard manure			Farmyard manure		Beejamrita		Ghana jiwamrita		Dhrava jiwamrita		
Crop	% of farmers	Quantity (kg acre^{-1})	Storage (days)	% of farmers	Quantity (kg acre^{-1})	% of farmers	Apps (#)	% of farmers	Quantity (kg acre^{-1})	% of farmers	Apps (#)	Storage (days)
Bengal gram	23	1359	176	32	809	94	1 (1)	94	314 (400)	94	3 (3)	98
Chilies	25	1,178 (1500)	219	56	426	74	1	72	344 (200)	77	5	110
Cotton	32	1,332	151	32	965	98	1	95	289 (400)	98	5 (3)	148
Groundnut	49	590 (2000)	158	44	629	97	1	94	303 (400)	95	4 (3)	114
Maize	40	671	130	63	518	95	1	98	228 (400)	96	4 (4)	87
Paddy rice	60	588	172	54	879	98	1 (1)	95	263 (200)	92	4 (5)	117

[1] Compost was added by less than 1% of respondents. Almost 1/5 of paddy rice APCNF farmers (17%) report using *Azolla* during cropping. Number of outliers removed for conventional FYM: Bengal gram (3), Chilies (5), Cotton (9), Groundnut (4), Maize (4), Paddy rice (24) and APCNF FYM: Bengal gram (9), Chilies (6), Cotton (17), Groundnut (16), Maize (9), Paddy rice (93).

Residue management

A core principle of APCNF is mulching, typically with crop residues. Historically, crop residues in India are either burned, fed to livestock, or used for household needs including thatch or fuel (Jain, Bhatia, and Pathak 2014). APCNF is thus advocating for a change in the ways crop residues are managed. When used as mulch on top of the soil, decomposing residues provide essential nutrients such as nitrogen and carbon, help shelter the soil from wind and water erosion, and conserve soil moisture. The amount of nitrogen in residues depends on the crop, variety, and production conditions affecting growth patterns (e.g., harvest ratio[7]) (Unkovich, Baldock, and Forbes 2010). The amount of carbon added to and retained in the system through mulch depends on weather conditions, quality of crop residues, and soil type. Available data on yields, harvest index, and nitrogen concentrations can provide a reasonable estimate for general carbon footprints such as was conducted in this study (Table S7, Table S8).

Table S6 | Crop residue use and nitrogen in crop residues. Harvest index and N in residues based on yield and respondents in the farmer survey. Conventional use of residues represents the most frequent response among farmers of that crop. For APCNF, the results only report the number of farmers that use mulch as is recommended by APCNF.

		N in	Conventional				APCNF		
	Harvest index[1]	residue (g kg^{-1})[3]	Use	% of farmers	Residue (kg acre^{-1})	Residue N (kg acre^{-1})	% of farmers that mulch	Residue (kg acre^{-1})	Residue N (kg acre^{-1})
Bengal gram	0.49	6.5	removed	60	538	3.5	26	681	4.4
Chilies	0.5	7.6	burned	44	1951	14.8	26	2714	20.6
Cotton	0.3	10	burned	69	2161	21.6	39	2324	22.4
Groundnut	0.27	9.7	removed	78	1871	18.1	12	2249	21.8
Maize	0.5	6	livestock	38	5079	30.5	53	3481	20.9
Paddy rice	0.4	6	livestock	63	2813	16.9	21	3375	20.3

[1] Ramakrishna et al. (2005) for all crops except chilies (Simon and Tesfaye 2014); [2]Smith et al. (2020) except chilies which reflects a generic value for herbaceous crops; [3]Jain et al. (2005) except chilies which reflects a median based on USDA Crop Nutrient Tool.

Table S8 | Carbon inputs in residue. Averages derived from farmer surveys and harvest indices.

Crop	Carbon concentration in residue (kg t^{-1})[1]	Carbon in residue (kg acre^{-1})	
		Conventional	APCNF
Bengal gram	409	220	278.5
Chilies	430	838.9	1,167.0
Cotton	510	1,102.1	1,185.2
Groundnut	411	772.3	924.3
Maize	411	2,088.0	1,430.7
Paddy rice	368	1,035.2	1,242.0

[1] Carbon concentration based on compilation in Sharma et al. 2018.

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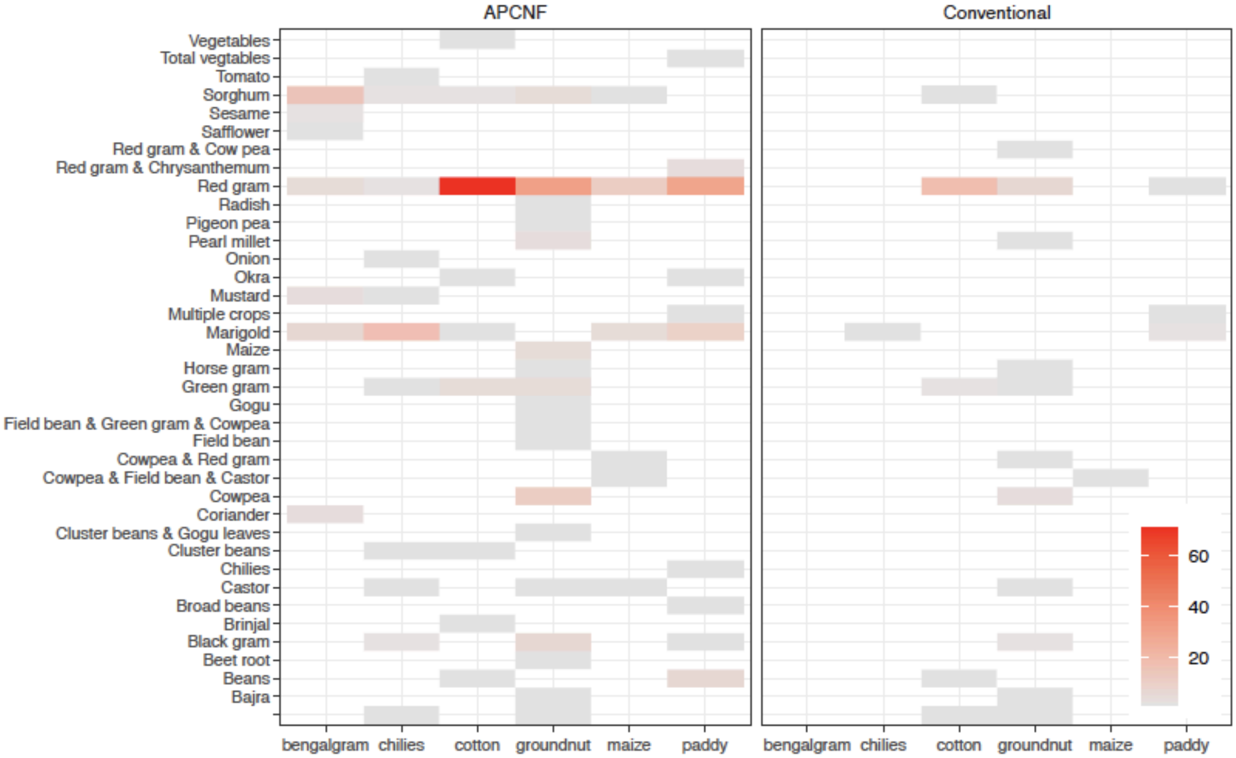
[7] The ratio of product to total above ground biomass.

Intercropping

APCNF endorses intercropping to provide a living mulch and build soil health. Intercrops can influence carbon cycles by providing additional biomass into the system. They also influence nitrogen cycles during decomposition of biomass and, when leguminous intercrops are used, through biological nitrogen fixation. Intercrops can thus build soil carbon even while stimulating nitrous oxide emissions, making their impact on carbon footprints difficult to predict. Intercropping was not accounted for in the analysis because of the diversity of practices used by farmers (Figure S1), the relatively small proportion of any crop-management combination under intercrop (except APCNF cotton and red gram), and the relatively small influence of intercrops as compared to enteric emissions, fertilizer productions, and other sources.

Figure S1 | Intercropping practices used by APCNF and Conventional farmers.



Livestock

Cattle are integral parts of both APCNF and conventional production systems to which manure is applied. Methanogenic bacteria in the rumen convert carbon in feed to methane during digestion. The amount of carbon produced is subject to the quality and characteristics of the feed and the condition of the animal (Hristov et al. 2015). Though livestock are important to APCNF, not all farmers own livestock and a single cow can produce more manure than is needed for one acre of land. We include the emissions related to livestock in the analysis to be consistent with including the emissions related to fertilizer production. We did not include emission related to feed production, thus emissions from livestock in this analysis should be considered conservative. The number of livestock allocated to a specific production system was based on the amount of manure applied and the expected amount of manure produced for the common breeds in Andhra Pradesh (Table S9).

Table S9 | Livestock required to provide the average amount of manure used on farms that use manure based on farmer survey (FS) and crop calendars (NFF).

Crop	Conventional		APCNF	
	FS	NFF	FS	NFF
Bengal gram	0.37		0.22	0.12
Chilies	0.32	0.41	0.12	0.05
Cotton	0.36		0.26	0.12
Groundnut	0.16	0.55	0.17	0.12
Maize	0.18		0.14	0.12
Paddy rice	0.16		0.24	0.12

Crop protection

Conventional farmers report that they are using more than 60 different pesticides, including insecticides, fungicides, and herbicides. Production and distribution of these crop protection chemicals generates emissions. Sophisticated production and transportation modeling can be used to transport-related emissions. More common for this type of emission scoping, though, is simply to calculate emissions from crop protection based on the number of applications (Table S10).

Table S10 | Number of chemical pesticide applications for conventional production. With the farmer survey, values are average and range.

Crop	Farmer survey	Crop calendars
Bengal gram	7.9 [5-12]	4
Chilies	9.2 [5-16]	12
Cotton	9.7 [6-21]	7
Groundnut	6.3 [5-8]	3
Maize	6.1 [5-16]	4
Paddy rice	7.4 [5-16]	8

Fuel use

Use of petrol and diesel fuel generates emissions. Farmers use fuel whenever machinery is used for e.g., land preparation, irrigation, pest control, and harvesting. The amount of fuel used on a farm is highly variable in Andhra Pradesh because many of the unit processes can be performed with either machinery or animals. Indeed, only about 80% of farmers report using any fuel (Table S10).

Table S10 | Percentage of farmers reporting fuel use (%) and average fuel use (L).

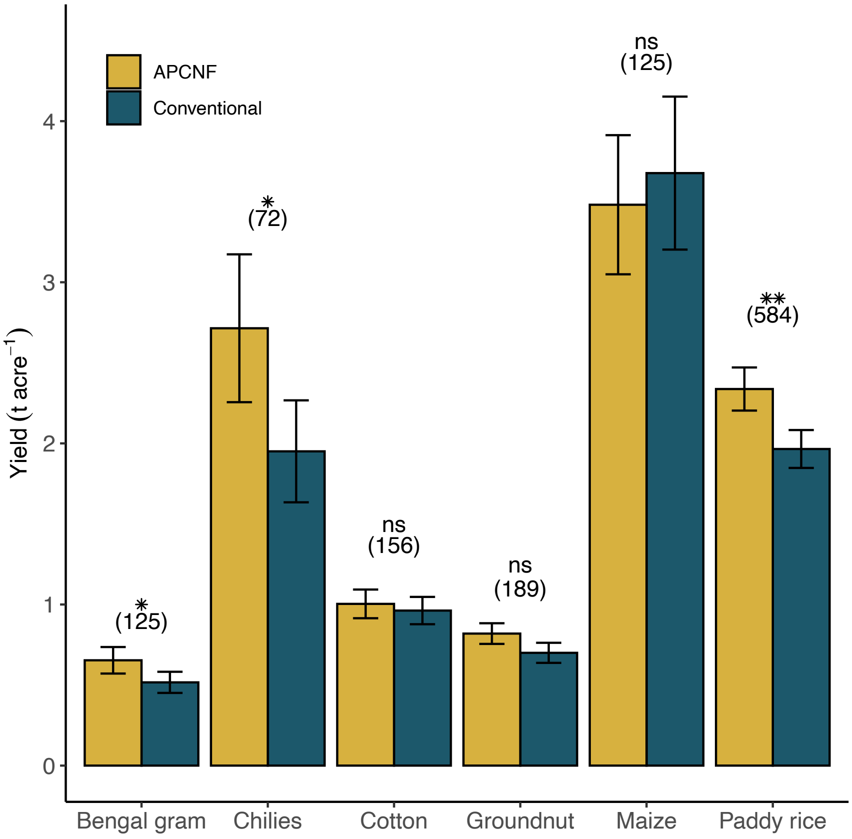
	Conventional			APCNF		
Crop	Farmers	Diesel	Petrol	Farmers	Diesel	Petrol
Bengal gram	81	13.2	2.7	79	13.7	0.5
Chilies	78	25.5		83	28.2	0.5
Cotton	76	25.2	18.7	77	15.8	1.25
Groundnut	82	29.7	1.8	80	80.6	0.5
Maize	75	13.4		75	13.4	3
Paddy rice	81	69.5	6.9	81	38.2	10.5

Number of outliers removed by crop and management (Conventional/APCNF): Chilies (1), Cotton (3/1), Groundnut (8/11), Maize (1), Paddy rice (11/5).

Crop Yield

The impact of APCNF adoption on crop yield is a central question to understanding its suitability for widespread scaling. Recent reports, both peer reviewed (Smith et al. 2020; Bharucha, Mitjans, and Pretty 2020) and grey literature (CEWW, CEES), have examined this issue (see main text for discussion). Our survey also asked farmers to recall their recent yields in order to calculate GHG intensity. Farmers reported that APCNF management produces similar or greater yields than conventional management (Figure S2). In absolute terms, average yields of 5 of the 6 crops (except maize) were greater under APCNF than conventional management. Yields of Bengal gram, chilies, and rice were significantly higher under APCNF. The remainder of the crops—cotton and groundnut—are only slightly higher under APCNF. This indicates no yield penalty, and in some cases significant gains, when substituting agroecological techniques for chemical inputs across more than 1,400 farms.

Figure S2 | Yields of fields management under conventional and zero-budget natural farming (APCNF) practices. Values based on farmer recall from 1,467 farms. Units of measure that could not reliably be converted to kilograms were omitted. Extreme outliers were removed.[8] Significance difference is indicated as 0.1 *, 0.05* and 0.01***, or non-significant. Values in parentheses are the number of farms.



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[8] Extreme outliers are those that are more or less than three times the interquartile range. We assume that extreme outliers were enumerator data entry errors.

Yields under both APCNF and conventional production were variable, with average coefficient of variation (CV)[9] of 39.3%. However, CVs for APCNF grown crops were generally greater than that of crops grown using conventional techniques (5 of 6 crops). Only with chilies were yields more variable in conventional than APCNF systems. The lower CV in chilies may be an artifact of the relatively small sample size of chilies farmers. Nevertheless, there appears to be a trend in these data: reported yields are more variable among farmers using APCNF than among farmers growing the same crop under conventional practices. Higher magnitudes of variability likely reflect the wide range of ways that APCNF treatments are being applied including the types of intercrops, how crop residues are handled, and the amount of manure and compost applied (see description above).

The survey results were generally consistent with yields reported by others (Table S12). The only exception was for maize, where the yield level reported by surveyed farmers here were somewhat outside of the range expected. For example, these results partially support those of Bharucha et al. (2020), who reported yields from paired APNCF and conventional farms across seven crops, including rice, maize, groundnut, and cotton. They found that APNCF yielded significantly more than conventional management across all crops. The partial difference in results may due to distinct data collection procedures. Bharucha et al. (2020) used data from crop cutting experiments, while the data presented here are based on farmer recall. Average yields reported by farmer recall were between -12.9% (paddy conventional) and 70.9% (maize conventional) different than reported by Bharucha et al. (2020). Variation in results may also be attributed to interannual variation in yields; Bharucha et al. (2020) collected data in 2016, and our survey collected farmer recall data from 2018-2019. The relative similarity in results suggests that farmer recall provided a reasonable approximation of productivity. Despite these differences, findings across studies point toward the same conclusion that APCNF implies no yield penalty. Randomized studies based on field measurements over multiple seasons are needed to evaluate performance.

The yield data we report are not based on field observations, but rather cross-sectional surveys and farmer recall, and thus cannot be reliably used to identify the modes of action by which APCNF maintains yield, nor the long-term potential of these mechanisms. Recent research on ‘biostimulants’ that, similar to APCNF inoculants, improve plant productivity despite containing relatively small amounts of essential plant nutrients, may provide some insights about emergent properties of complex

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[9] Coefficient of variation (CV) = standard deviation/mean

physiological, biological, physical and chemical interactions (Yakhin et al. 2017, Abbott et al. 2018).

Table S12 | Comparison recently reported yield data (t acre^{-1}) for Andhra Pradesh Community Natural Farming (APCNF) and conventional farming.

	Conventional					APCNF		
Crop	This study	Vetter et al. 2017	Bharucha et al. 2020	GoI	CESS	This study	Bharucha et al. 2020	CESS
Bengal gram	0.52	0.33	0.34	0.49	0.38	0.65	0.38	0.48
Chilies	1.95					2.71		
Cotton	0.93		0.63	0.70		1.00	0.74	
Groundnut	0.69	0.55	0.75	0.59	0.62	0.83	0.93	0.66
Maize	3.68		2.20	2.05	2.60	3.48	2.37	2.57
Paddy	2.42	1.46	2.21	2.34	1.97	2.23	2.42	2.02

[*] Value relative to general 'gram' reported in the study. Black gram in Bharucha et al. (2020)

Costs and Labor

Implementation of APCNF changes many management operations on the farm as compared to conventional techniques, and thus has the potential to dramatically alter the costs of production. Indeed, lowering costs and reducing farmer debt has historically been one of the primary goals of APCNF. A number of studies have nearly universally reported lower farm costs using APCNF versus conventional management (Table S13). Reductions in costs range from about 3% to nearly 40%. Among the many comparisons across multiple studies, only one crop in one study showed a cost increase under APCNF.

Table S13 | Comparison of costs from existing literature (Rs).

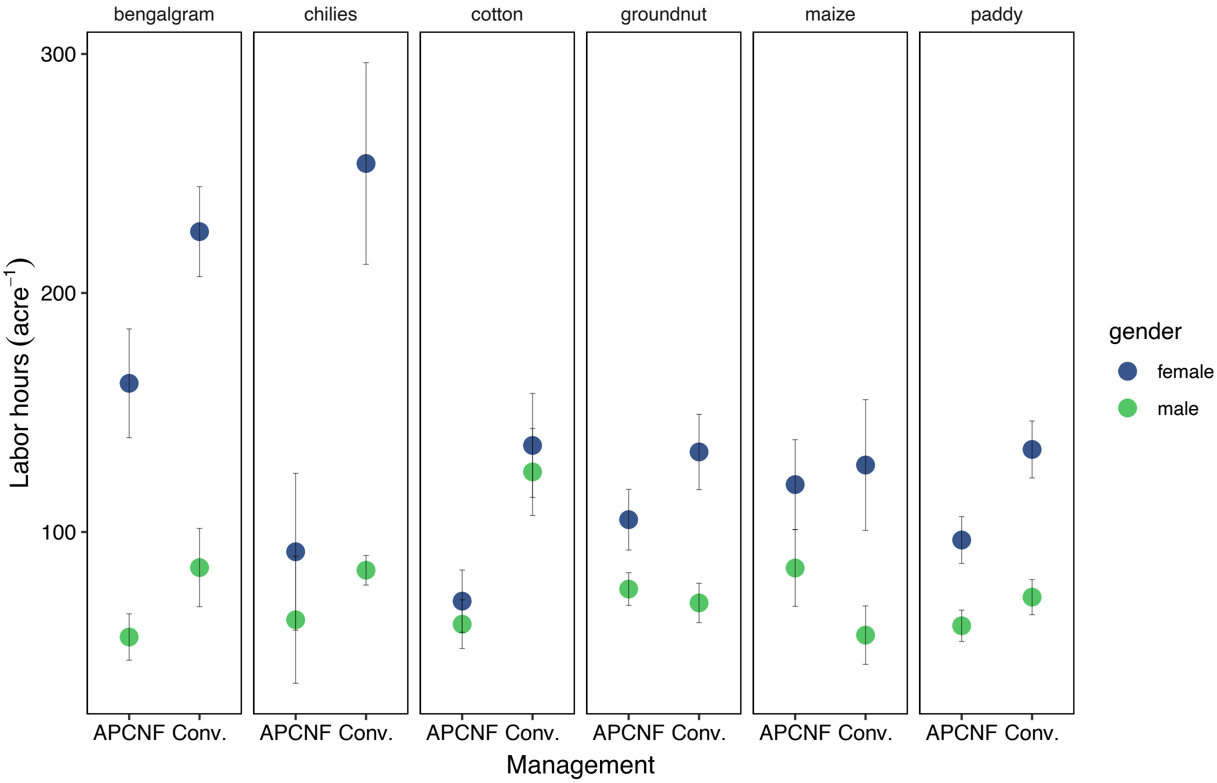
	Bharucha et al. 2020			CEEW et al. 2020			Gupta et al. 2020		
Crop	Conv	APCNF	% **Δ**	Conv	APCNF	% **Δ**	Conv	APCNF	% **Δ**
Bengal gram				10,851	6,693	-38.3			
Chilies									
Cotton	23,532	15,849	-32.7						
Groundnut	15,386	11,406	-25.8	15,564	15,023	-3.5	12,759	16,637	30.4
Maize	10,565	9,124	-13.6	20,581	14,835	-27.9	23,534	16,672	-24.9
Paddy rice	17,529	12,486	-28.8	19,597	13,962	-28.8	18060	1,4267	-21

* Rainfed.

Interpretation of cost results are nevertheless difficult. Studies to date have provided scant details about data collection and costs included in their calculations. Some of the studies focus on a very narrow portion of farm budgets, such as inputs, that may be less than ~15% of variable costs and less than 10% of total costs (Economics and Statistics 2019). Limited methodological descriptions make it difficult to determine whether the value of household labor and opportunity costs are included. Improved resolution in this regard could be established relatively easily by reconciling methodologies across studies to date. Depending on the conclusions of that synthesis, future work may focus on detailed studies of a large number of farms to capture both the diversity of implementation (as documented in our farm survey), and the concomitant impacts on production costs. Estimating farm enterprise budgets is error prone, however. Information recall is often based on uncertain quantities distributed over uncertain areas. As part of this study, enumerators asked farmers about costs of production and labor for activities. The data ranged from reasonable to unbelievable (e.g., orders of magnitude greater than the expected costs based on other literature). Relative costs of APCNF versus conventional thus remains a lingering question, and real-time cost documentation as part of a targeted study is likely required.

In addition to financial costs, distribution of labor is a critical concern with changing management techniques. No data has been rigorously collected that can respond adequately to the question of whether APCNF will change total labor demand or intrahousehold workload. We attempted to collect data on this issue in our survey. About 50% of the resulting dataset was outside the bounds of likely possibility, and significant pruning of these extreme outliers was needed. Nevertheless, a few interesting trends emerged (Figure S3). First, the data suggests that women do more work than men across all crops and all management systems, sometimes considerably so (e.g., in conventional chilies). Second, it seems that the difference in workload between men and women may be smaller under APCNF than under conventional management. Our data on gender-differentiated labor are only suggestive and should be interpreted as very preliminary. They do, however, suggest a potential role for APCNF in reducing the demand for women's time and increasing work equity.

Figure S3 | Gender differentiated labor with APCNF and conventional production. Outliers above 500 hours acre^{-1}, which is the upper bound reported in the Cost of Cultivation Studies, were removed.



Human and Ecosystem Toxicity from Pesticide Use

Heavy use of crop protection chemicals jeopardizes the health of soil biota, water quality (Sharma and Singhvi 2017), and the people producing and consuming food (Nicolopoulou-Stamati et al. 2016). India is one of the global epicenters of ecosystem and health impacts associated with the use of organic and inorganic (e.g., copper-based) pesticides and non-persistent chemicals; residue levels are high in Indian water, soil, and air (Yadav et al. 2015). The accumulation of pesticides has both direct and indirect effects on flora and fauna, including pollinating insects (Crenna et al. 2020), birds, and humans (Fantke, Friedrich, and Jolliet 2012). Livestock and human food sources are also impacted (Jayaraj, Megha, and Sreedev 2016). Of 312 bovine milk samples from the Punjab, 12 samples exceeded the maximum residue limit for γ-HCH (lindane), 18 exceeded the limits for DDT and chlorpyrifos, and 1 sample exceeded the limits for endosulfan, cypermethrin, and profenophos (Bedi et al. 2015). Virtually all randomly selected blood samples from four Punjab villages contained six to thirteen pesticides, including HCH, Aldrin, DDT, Monocrotophos, Endosulfan, Phosphamidon, Chlorpyrifos and Malathion (Mathur et al. 2005).

Conventional farmers in our survey reported applying 60 different pesticides. Each one may have properties that can induce non-cancerous and cancerous effects for humans, as well as determinantal outcomes for environmental health. Impact characterization factors for freshwater ecotoxicity and human toxicity were produced based on the USEtox modeling framework (http://usetox.org). USEtox was developed to be a scientific consensus tool for modeling freshwater ecotoxicity and human toxicity in LCAs (Rosenbaum et al. 2008; Hauschild, Dreyer, and Jørgensen 2008). It is based on global average factors. Hence, it works best when considered as a general screening tool for identifying toxicity-related hotspots.

Characterization factors (CF) for human toxicity span over 5 to 7 orders of magnitude per emission compartment, with mean non-cancerous CF of 1.3×10^{-6} cases kg emitted^{-1} for emissions to continental rural air, 4.7×10^{-6} cases kg emitted^{-1} for emissions to continental freshwater, and 6.1×10^{-7} cases kg emitted^{-1} for emissions to continental agricultural soil. Highest human toxicity non-cancerous impact potentials are found for substances abamectin (CAS: 71751-41-2), hexaconazole (CAS: 79983-71-4), and methyl benzoate (CAS: 93-58-3) for emissions to rural air and freshwater, and for methyl benzoate (CAS: 93-58-3) for emissions to agricultural soil. CF for freshwater ecotoxicity span over 8 to 9 orders of magnitude per emission compartment, with mean CF of 2. 3 × 103 PAF m^{3} d kg emitted^{-1} for emissions to continental rural air, 5.8 × 104 PAF m^{3} d kg emitted^{-1} for emissions to continental freshwater, and 7.9 × 102 PAF m^{3} d kg emitted^{-1}

for emissions to continental agricultural soil. Highest freshwater ecotoxicity impact potentials are found for the three copper-related substances (CAS: 20427-59-2, 1332-40-7 and 1344-73-6) for emissions to rural air and agricultural soil, and for cypermethrin (CAS: 52315-07-8) for emissions to freshwater. Differences in ranking of substances across emission compartments are mainly due to differences in substance volatility (higher impact potential for emissions to air and via inhalation exposure), lipophilicity (higher impacts for emissions to soil and via food ingestion exposure), and solubility (higher impacts for emissions to freshwater and via drinking water ingestion exposure). These effects are non-existent under APCNF, when practiced according to the standards. However, a few farmers who identify as APCNF reported applying some chemicals.

Table S14 | Midpoint characterization factors for human and ecological toxicity due to pesticide, insecticide and herbicides reported used by farmers in Andhra Pradesh. More than 60 chemicals are commonly applied in the production of the six crops. Values generated using USEtox, the life cycle assessment modeling framework for chemical use.

Substances		Human toxicity characterization factor $[cases/kg_{emitted}]$						Ecotox. Charact. factor $[PAF.m^3.d/kg_{emitted}]$		
#	CAS RN	*Emission to cont. rural air*		*Emission to cont. freshwater*		*Emission to cont. agric. soil*		*Em.airC*	*Em.fr.waterC*	*Em.agr.soilC*
		cancer	non-canc.	cancer	non-canc.	cancer	non-canc.	freshwater	freshwater	freshwater
1	10605-21-7	n/a	1.0E-07	n/a	1.5E-06	n/a	1.2E-07	2.6E+04	7.4E+05	1.8E+04
2	106-42-3	n/a	1.7E-07	n/a	2.8E-07	n/a	2.4E-07	2.4E-02	2.7E+02	2.2E+00
3	107534-96-3	n/a	5.0E-07	n/a	7.5E-06	n/a	4.8E-07	2.4E+03	6.9E+04	7.5E+02
4	108-94-1	0	8.5E-10	0	7.4E-09	0	7.1E-09	1.3E+00	6.6E+01	1.3E+01
5	115-29-7	0	2.2E-06	0	3.0E-05	0	1.3E-06	3.1E+03	5.9E+05	1.3E+03
6	116714-46-6	n/a	6.4E-06	n/a	9.3E-06	n/a	6.6E-06	2.3E+00	8.8E+02	2.4E+00
7	120068-37-3	n/a	1.8E-05	n/a	3.3E-04	n/a	2.3E-05	5.9E+04	2.2E+06	1.7E+04
8	12071-83-9	n/a	8.6E-07	n/a	1.4E-05	n/a	6.8E-07	1.6E+02	4.9E+03	5.8E+01
9	123312-89-0	n/a	2.3E-05	n/a	6.0E-05	n/a	3.5E-05	1.8E+02	8.1E+02	2.2E+02
10	131860-33-8	n/a	1.2E-06	n/a	2.3E-06	n/a	1.8E-06	1.3E+04	7.7E+04	1.6E+04
11	1332-40-7	n/a	2.1E-05	n/a	8.1E-08	n/a	6.8E-05	2.2E+06	5.9E+06	3.1E+06
12	1344-73-6	n/a	8.7E-06	n/a	3.4E-08	n/a	2.8E-05	9.2E+05	2.4E+06	1.3E+06
13	135410-20-7	n/a	1.0E-07	n/a	2.8E-07	n/a	6.6E-08	1.0E+02	2.9E+03	4.3E+01
14	13593-03-8	n/a	6.3E-06	n/a	2.6E-04	n/a	9.0E-06	4.6E+02	6.3E+04	7.2E+01
15	138261-41-3	n/a	1.3E-06	n/a	2.5E-06	n/a	2.0E-06	8.8E+02	3.2E+03	1.2E+03
16	141517-21-7	n/a	5.0E-07	n/a	2.8E-07	n/a	2.4E-08	6.1E+00	2.5E+02	5.0E-02
17	155569-91-8	n/a	7.8E-07	n/a	7.2E-06	n/a	4.0E-07	3.9E+03	1.5E+05	1.5E+01
18	1563-66-2	0	6.4E-06	0	3.7E-05	0	9.1E-06	7.3E+03	1.1E+05	5.9E+03
19	158062-67-0	n/a	1.5E-07	n/a	4.1E-07	n/a	3.8E-11	3.9E+00	1.5E+02	2.6E-03
20	168316-95-8	n/a	4.1E-06	n/a	1.3E-04	n/a	2.7E-08	1.3E+02	6.8E+03	9.0E-01
21	173584-44-6	n/a	4.8E-07	n/a	6.4E-06	n/a	1.8E-07	3.5E+03	1.6E+05	4.3E+01

22	1912-24-9	7.0E-07	8.1E-07	3.7E-06	4.3E-06	8.1E-07	9.3E-07	4.9E+03	8.7E+04	3.4E+03
23	20427-59-2	n/a	2.3E-05	n/a	8.9E-08	n/a	7.4E-05	2.4E+06	6.5E+06	3.4E+06
24	2157-98-4	n/a	5.5E-05	n/a	2.0E-04	n/a	8.6E-05	7.9E+02	6.5E+03	7.9E+02
25	25417-20-3	n/a	3.4E-07	n/a	5.8E-06	n/a	1.7E-07	7.4E+04	1.9E+06	3.3E+04
26	2634-33-5	n/a	5.2E-06	n/a	9.0E-06	n/a	8.0E-06	1.2E+03	7.9E+03	1.2E+03
27	272451-65-7	n/a	2.3E-06	n/a	3.9E-06	n/a	3.6E-06	3.4E+01	1.6E+02	3.6E+01
28	283594-90-1	n/a	2.1E-06	n/a	5.2E-08	n/a	2.9E-08	1.3E+01	3.6E+03	7.5E-02
29	2921-88-2	0	3.0E-06	0	4.6E-04	0	7.8E-06	8.4E+03	6.2E+06	7.1E+03
30	298-02-2	n/a	1.8E-06	n/a	7.3E-05	n/a	5.0E-05	2.5E+02	4.2E+05	1.2E+04
31	30560-19-1	3.4E-08	9.5E-05	2.5E-07	6.9E-04	3.7E-08	1.0E-04	5.4E+01	6.3E+02	4.4E+01
32	39807-15-3	n/a	3.0E-07	n/a	3.2E-08	n/a	1.6E-07	1.6E+02	6.7E+03	1.8E+01
33	40487-42-1	n/a	1.2E-07	n/a	5.9E-07	n/a	3.7E-07	2.3E+03	4.6E+05	2.2E+03
34	41198-08-7	n/a	2.3E-06	n/a	6.1E-05	n/a	3.0E-06	2.7E+05	1.6E+07	2.8E+04
35	41814-78-2	n/a	2.4E-07	n/a	2.1E-06	n/a	2.3E-07	1.5E+02	3.1E+03	8.1E+01
36	447399-55-5	n/a	2.9E-07	n/a	1.3E-06	n/a	8.1E-08	2.1E+04	4.7E+05	1.1E+04
37	500008-45-7	n/a	2.4E-07	n/a	1.3E-07	n/a	3.5E-07	2.9E+03	2.6E+04	3.4E+03
38	52315-07-8	n/a	9.4E-07	n/a	4.1E-06	n/a	1.2E-07	3.8E+05	5.0E+07	1.3E+04
39	55965-84-9	n/a	7.1E-07	n/a	5.5E-07	n/a	5.4E-07	2.5E+04	8.7E+04	3.2E+04
40	56-81-5	0	1.3E-06	0	1.2E-06	0	1.5E-06	4.3E-02	2.1E-01	5.8E-02
41	57837-19-1	n/a	2.3E-07	n/a	6.0E-07	n/a	3.8E-07	1.5E+02	9.6E+02	1.7E+02
42	60207-90-1	n/a	1.5E-06	n/a	1.5E-05	n/a	2.1E-06	9.6E+02	2.2E+04	5.0E+02
43	60-51-5	0	8.0E-07	0	4.2E-06	0	1.3E-06	1.3E+03	1.8E+04	1.3E+03
44	62-73-7	1.6E-06	8.6E-06	2.2E-05	6.1E-05	5.7E-07	1.7E-06	1.1E+04	7.2E+05	7.0E+03
45	67375-30-8	n/a	1.1E-06	n/a	5.2E-06	n/a	6.6E-08	2.5E+05	3.5E+07	4.8E+03
46	68085-85-8	n/a	2.2E-06	n/a	4.3E-05	n/a	1.7E-07	2.0E+04	5.1E+06	7.9E+02
47	6923-22-4	n/a	5.5E-05	n/a	2.0E-04	n/a	8.6E-05	7.9E+02	6.5E+03	7.9E+02
48	69327-76-0	n/a	2.1E-06	n/a	1.1E-05	n/a	5.2E-06	3.6E+00	8.9E+02	5.0E+00
49	6980-18-3	n/a	1.4E-06	n/a	2.2E-07	n/a	1.4E-07	1.2E+01	1.1E+02	1.5E+01
50	71697-59-1	n/a	9.4E-07	n/a	4.1E-06	n/a	1.2E-07	3.8E+05	5.0E+07	1.3E+04
51	71751-41-2	n/a	2.5E-04	n/a	4.9E-03	n/a	1.2E-06	3.5E+04	1.7E+06	1.4E+02
52	732-11-6	n/a	3.5E-07	n/a	8.0E-06	n/a	4.9E-07	2.2E+04	1.4E+06	1.1E+04
53	76703-62-3	n/a	2.2E-06	n/a	4.3E-05	n/a	1.7E-07	2.0E+04	5.1E+06	7.9E+02
54	7704-34-9	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
55	7789-75-5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
56	79983-71-4	n/a	1.8E-04	n/a	2.8E-04	n/a	3.2E-04	3.0E+03	1.2E+04	3.2E+03
57	80060-09-9	n/a	6.6E-07	n/a	2.7E-06	n/a	4.3E-10	3.5E+04	2.3E+06	8.4E+00
58	8018-01-7	n/a	1.6E-07	n/a	2.2E-06	n/a	2.1E-07	2.2E+03	5.3E+04	2.0E+03
59	9003-41-2	0	8.5E-10	0	7.4E-09	0	7.1E-09	1.3E+00	6.6E+01	1.3E+01
60	93-58-3	n/a	1.9E-04	n/a	9.1E-04	n/a	2.2E-03	8.8E+00	2.5E+02	8.4E+01

Midpoint CF can be translated into damages on human health (expressed in disability-adjusted life years, DALY) and damages on ecosystem quality (expressed as potentially disappeared fraction, PDF, of species), using generic severity factors for translating impacts into damages. For human health, 11.5 DALY cancer case^{-1} and 2.7 DALY non-cancer case^{-1} were used (Huijbregts et al. 2005), and for ecosystem quality, 0.5 PDF PAF^{-1} (potentially affected fraction of species) was used (Jolliet et al. 2003). At the level of DALY kg^{-1} emitted, human health CF can be aggregated across cancer and non-cancer effects. Unfortunately, the data collected on the quantities used were incomplete, and thus we could only partially conduct this analysis. The presented USEtox results can be readily combined with substance emission information to yield impact scores relevant for LCA as outlined elsewhere (e.g., Hauschild, Dreyer, and Jørgensen 2008; Fantke et al. 2018).

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