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# Potential yield challenges to scale-up of zero budget natural farming

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## Abstract

Under current trends, 60% of India's population (>10% of people on Earth) will experience severe food deficiencies by 2050. Increased production is urgently needed, but high costs and volatile prices are driving farmers into debt. Zero budget natural farming (ZBNF) is a grassroots movement that aims to improve farm viability by reducing costs. In Andhra Pradesh alone, 523,000 farmers have converted 13% of productive agricultural area to ZBNF. However, sustainability of ZBNF is questioned because external nutrient inputs are limited, which could cause a crash in food production. Here, we show that ZBNF is likely to reduce soil degradation and could provide yield benefits for low-input farmers. Nitrogen fixation, either by free-living nitrogen fixers in soil or symbiotic nitrogen fixers in legumes, is likely to provide the major portion of nitrogen available to crops. However, even with maximum potential nitrogen fixation and release, only 52–80% of the national average nitrogen applied as fertilizer is expected to be supplied. Therefore, in higher-input systems, yield penalties are likely. Since biological fixation from the atmosphere is possible only with nitrogen, ZBNF could limit the supply of other nutrients. Further research is needed in higher-input systems to ensure that mass conversion to ZBNF does not limit India's capacity to feed itself.

**R**ising global population and economic growth are resulting in a rapidly increasing demand for food, especially in low- to middle-income countries such as India[1]. The population of India, which is currently 17.71% of the total world population[2], is predicted to increase by 33% from 1.2 billion in 2010 to 1.6 billion in 2050[3]. Under business-as-usual, by 2050, 60% of India's population, equivalent to over 10% of the people on Earth, will experience severe deficiencies in calories, digestible protein and fat[4] (Supplementary note 1.1). If India is to maintain its capacity to produce its own food, crop production must increase in line with these increasing demands.

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**Author Contributions**
J.S. was primarily responsible for the conception and design of the work, the acquisition, analysis and interpretation of data and the drafting of the manuscript. J.Y., P.S. and D.R.N. contributed towards the conception and design of the work and revision of the manuscript. D.R.N. also contributed to the creation of software used in the work.

**Competing Interests**
The authors declare no competing interests.

Between 1961 and 1999, increased crop production was achieved by a combination of intensification (increased yields per unit area of land) and extensification (cultivation of more land)[5]. However, increased irrigation and use of synthetic fertilizers, especially since the Green Revolution in India, have resulted in inefficient use of resources[6], with North India highlighted as a global hotspot for low nutrient efficiency[1]. A maximum of only 16% of the land area in India remains for potential conversion to agriculture, and much of this is unsuitable for cultivation (for example, mountainous or urban) (Supplementary note 1.2). Therefore, to meet increased demands for food on a shrinking area of available land, efficiency of crop production must increase[7]. However, climate change, soil degradation and depopulation present challenges to increasing the efficiency of Indian agriculture. Climate change has already reduced food production in India by ~0.8% between 1974 and 2013[8] (Supplementary note 1.3). By 2005, 48% of India's land area was already degraded[9], with annual costs for 2009 compared with 2001 estimated to be $US5.35 billion[10] (Supplementary note 1.4). Depopulation of rural areas results in a reduction of the agrarian population needed to produce food, with a projected reduction of ~12% between 2018 and 2050 (Supplementary notes 1.5 and 1.6).

## Family farming and zero budget natural farming

In the context of increased pressures on farming and the agrarian crisis due to depopulation, the UN (United Nations) has recognized the importance of small-scale family farmers to global food security[11] (Supplementary note 2.1) and launched a global action plan to benefit family-run farms (Supplementary note 2.2). Zero budget natural farming (ZBNF) is a grassroots movement that is attempting to improve India's capacity to produce its own food by farming with nature and ending farmers' reliance on purchased inputs and credit[5]. It is highly compatible with the principles of family farming, which is one reason why it is receiving increasing support from communities and governments alike[12]. It is considered by many in the Indian government to be the future for sustainable farming in India[13,14].

'Zero budget' refers to financial inputs; it is seen as a way of over-coming the inability of many poor farmers to access improved seed and manufactured agrochemicals, and to avoid vicious cycles of debt due to high production costs, high interest rates and volatile market prices (Supplementary note 3.2). These stresses have been reflected in high suicide rates in farmers; over 2,530 farmers in India have taken their own lives since 1995[15]. In 2010, ~3% of adult deaths were due to suicide, suicide rates in rural areas were double those of urban areas[16] and there was a significant positive relationship across states between the percentage of marginal farmers, cash crop production and levels of farmer debt[17]. Furthermore, substantial detrimental health impacts have been associated with the use of agrochemicals in India[18,19]. The ZBNF system avoids the use of external inputs such as synthetic fertilizers, pesticides and herbicides, in particular avoiding purchases from large corporations[20], so maintaining the cycle of production within villages instead of farmers obtaining inputs from cities. Therefore, it has the potential to retain more farmers and economic resources in rural areas.

'Natural farming' refers to a farming approach that emphasizes the importance of co-production of crops and animals so that synergistic effects of different parts of the system can be used, relying on easily available ‘ingredients’ to produce crop treatments on-farm, and microorganisms or mycorrhizae to build fertility of the soil[12,21]. The approach is built on the ‘four wheels’ of ZBNF[20]: (1) stimulation of microbial activity to make nutrients available to plants and protect against pathogens using a microbial inoculum, ‘*jiwamrita*’; (2) protection of young roots from fungal and soil-borne diseases using another microbial culture, ‘*beejamrita*’; (3) production of stabilized soil organic matter and conservation of top-soil by mulching (‘*acchadana*’) and (4) soil aeration (‘*whapahasa*’) by improving soil structure and reducing tillage. By focusing on soil microorganisms and fauna, and by mulching to increase soil organic matter, it is proposed that ZBNF has the potential to greatly improve soil health and so increase efficiency of nutrient and water use, contributing to improved efficiency of crop production.

ZBNF is now one of the largest ‘experiments’ in agroecology in the world. In Karnataka, where it originated in 2002[21], unpublished data cited by the FAO (Food and Agriculture Organization of the UN)[5] suggest that over 100,000 farming households are already following ZBNF methods. In neighbouring Andhra Pradesh, according to the official website of the ZBNF programme, by August 2019, 523,000 farmers had converted to ZBNF in 3,015 villages across 504,000 acres (204,000 ha)[20]. This is equivalent to 13% of the area of the state under productive agriculture (as defined by area sown to more than one crop)[22]. The long-term aim of the government of Andhra Pradesh is to roll out ZBNF to all six million farmers in the state by 2024[23]. Nationally, ZBNF leaders suggest that the number converting to ZBNF is in the order of millions, and Prime Minister Narendra Modi recently told the UN conference on desertification that, in future, India will focus on ZBNF[13,24], while Minister of Finance Nirmala Sitharaman called for a ‘back to basics’ approach with an emphasis on ZBNF[14].

## The controversy surrounding ZBNF

Strict ZBNF differs from traditional organic farming in that it does not attempt to provide the nutrients needed for crop growth using animal manures, but instead aims to change the functioning of the soil–crop system so that nutrients are made available to crops without the need for external inputs. It uses zero inputs of synthetic fertilizers to avoid reliance on purchased inputs and credit, and low inputs of animal manures to avoid limitations in available manure. This is important to the movement because if all farmers in India were to convert to traditional organic farming, only ~50% of the nitrogen applied to crops as synthetic fertilizers would be available from manures (Supplementary note 4.1). By contrast, the manure used in a strict ZBNF system would require only 18–21% of cows reported in the 2012 Livestock Census[25] (Supplementary note 4.1).

Although the nutrients applied in ZBNF systems are very low, the leaders of ZBNF claim that 88% of farmers have observed higher yields in the first season after conversion[26]. This anecdotal evidence needs to be supported by controlled, replicated and randomized field trials, but if there is indeed no yield penalty, the sources of nutrients, especially nitrogen, need to be better understood. It is claimed that the soil already contains all the nutrients needed for plant growth and that the action of microbial cultures added to the soil releases these nutrients from the soil itself[27]. If the supply of nitrogen in a ZBNF system was provided only by stimulating release from the top-soil, there would be an associated loss of soil organic matter; for a typical top-soil in India, all organic matter would be gone within 20 years (Supplementary note 4.2). Such a degradation would result in reduced crop yields, reduced resilience to droughts and increased rates of erosion, causing a substantial decline in crop production in India. Therefore, there is concern that ZBNF might have a detrimental impact on farmers' incomes and food security in India[13].

With farmers converting to ZBNF on a massive scale in Andhra Pradesh, and governments of other states potentially following the Andhra Pradesh example, if nitrogen is supplied by 'mining' soil organic matter, potential loss of soil nutrient supply within 20 years (Supplementary note 4.2) could result in a catastrophic crash in food production across India. Therefore, there is an urgent need to examine the potential mechanisms of nitrogen supply to crops in ZBNF systems to understand where it is coming from and what levels of crop production could be sustained over the longer term.

Given the high stakes associated with potential mass conversion of farms across India to ZBNF, we examine sources of nitrogen potentially available within a strict ZBNF system and assess the possible long-term impacts on soils of widespread conversion. We do so on the basis of estimates of nitrogen and carbon turn-over, using a combination of dynamic simulation modelling and data drawn from the peer-reviewed literature. The collated data are derived from Indian studies where possible, but we draw on wider sources as necessary. We then discuss additional experimental evidence needed to understand processes occurring in ZBNF, so that the likely impacts of conversion can be better understood and quantified.

## Results

### Provision of nitrogen for crop growth

Each of the four wheels of ZBNF has the potential to provide or retain nitrogen that can be used by the crop and to have a longer-term impact on the organic matter content and productivity of the soil. Potential sources or savings of nitrogen in ZBNF are direct input and fixation by the soil inoculum (*jiwamrita*) and seed treatment (*beejamrita*), and release following mulching (*acchadana*) and reduced tillage (as part of soil aeration, *whapahasa*). Here, we collate best-available scientific evidence on the impacts of these practices and estimate overall impacts on nitrogen supply, expressed as a proportion of the national average nitrogen fertilizer application.

### *Jiwamrita* (soil inoculum)

The fermented microbial culture, *jiwamrita*, provides some nutrients, but more importantly, aims to promote growth of microorganisms and increase earthworm activity. Two types of *jiwamrita* are prepared: the wet form prepared as a slurry, '*dhrava jiwamrita*', and the dried form prepared for storage, '*ghana jiwamrita*'. Accounting for all ingredients used to produce *jiwamrita*, up to 8.3 ± 0.4 kg ha$^{-1}$ yr$^{-1}$ could be provided in *dhrava jiwamrita*, and 3.3 ± 0.2 kg ha$^{-1}$ in *ghana jiwamrita*; this is equivalent to ~7% and ~3% of national average nitrogen fertilizer application, respectively (Supplementary note 5.1). *Jiwamrita* could also add nitrogen to the soil by increasing non-symbiotic nitrogen fixation. Levels of nitrogen-fixing rhizobia have been observed to increase during preparation of *dhrava jiwamrita* to 4,400% of the starting mixture[28]. The impacts of this are dependent on rhizobia survival and activation once applied to the soil, but given the range of nitrogen fixation by heterotrophic bacteria observed in the literature[29], extra input of nitrogen is unlikely to be more than ~10 kg ha$^{-1}$ per crop (Supplementary note 5.3), 18% of the national average nitrogen fertilizer application.

## ***Beejamrita*** **(seed treatment)**

The seed/seedling treatment, *beejamrita*, also provides a small amount of nutrients to the soil, but its main impact is considered to be the protection of young roots from fungus and soil or seed-borne diseases. Accounting for all ingredients used to produce *beejamrita*, up to 0.16 ± 0.02 kg ha$^{-1}$ nitrogen per crop could be provided in *beejamrita*, equivalent to just 0.3% of the nitrogen fertilizer application (Supplementary note 6.1). Inoculation of soybean seed with bacterial isolates from *beejamrita* has been observed to improve germination and to increase seedling length and vigour[30]. Therefore, there is good evidence for the beneficial action of *beejamrita*, but further work is needed to fully understand the pathways of disease resistance and quantify its impacts in terms of yield and nutrient capture by the plant.

## ***Acchadana*** **(mulching) and** ***whapahasa*** **(soil aeration)**

Three types of mulching are recommended in ZBNF[27]: (1) soil mulching, (2) mulching with dried biomass and (3) live mulching.

Soil mulching involves tillage of the soil as normal, but to a reduced depth of only 10–15 cm. Compared with no-till, tillage to 15 cm is likely to reduce competition with weeds[31], but in some conditions, may reduce yields due to delayed planting and restrictions to rooting depth[32]. Compared with conventional tillage, it is likely to increase carbon content at depth, especially in clay loam soils[33] (Supplementary note 7.1).

Mulching with dried biomass usually uses mulch from previous crops, with the intention of rapidly decomposing and increasing soil organic matter while releasing nutrients under the action of increased microorganisms from the application of *jiwamrita*. Measurements of changes in the microbial population during culturing *jiwamrita* have shown huge increases in the organisms responsible for heterotrophic decomposition: an increase of 18,000% in bacteria, 12,000% in fungi and 15% in actinomycetes[28,34] (Supplementary note 5.2). If these microorganisms survive and then proliferate once added to the soil, this suggests that the rate of decomposition could indeed be greatly increased by the addition of *jiwamrita*, potentially releasing a large proportion of nitrogen held in crop residues. Given the proportions of crops grown in India and the proportions used for fodder, fuel or other domestic purposes, if, under the action of *jiwamrita*, all nitrogen was released to the next crop, this could provide additional nitrogen to the crop of up to ~12 kg ha$^{-1}$ yr$^{-1}$ on average, 10% of the national average nitrogen fertilizer application (Supplementary note 7.2).

In addition to dried crop residues, some farmers following ZBNF systems have been reported to apply ~2 t per acre (4.9 t ha$^{-1}$) of farm-yard manure in the last ploughing before sowing (Supplementary note 7.4). This is not part of a strict ZBNF system, but if organic manures are applied at this rate, an additional 12–14 kg ha$^{-1}$ of nitrogen would be applied, 21–24% of the national average nitrogen fertilizer application rate (Supplementary note 7.4).

Live mulching is mainly done as intercropping, which aims to supply potassium, phosphorus and sulfur using monocotyledons (such as rice and wheat) and nitrogen using dicotyledons (such as legumes)[12]. From a review of the contribution of different types of legumes to associated non-legume crops and the proportions of crops grown in India, the average nitrogen provision for major crops grown in India is ~28 kg ha$^{-1}$, which is equivalent to 24% of the national average nitrogen fertilizer application (Supplementary note 7.5). *Azolla pinnata* is a special case of an aquatic plant that is widely used to fix nitrogen in rice paddies and has been observed to fix 30–100 kg ha$^{-1}$ per crop[29]. Given the proportion of paddy rice grown in India (21% of the total area cropped annually[35]), this could contribute, on average, 6–21 kg ha$^{-1}$ yr$^{-1}$ of additional nitrogen, 5–18% of the national average nitrogen fertilizer application (Supplementary note 7.5).

**Total nitrogen provided by ZBNF—**The above estimates of nitrogen provided by different practices used in ZBNF suggest that even if nitrogen fixation is stimulated and immobilization of nitrogen due to straw incorporation is avoided by the application of *jiwamrita*, a strict ZBNF system might have the potential to provide only 52–80% of the average nitrogen fertilizer application used across India (Fig. 1). Only if additional nitrogen is applied in the 4.9 t ha$^{-1}$ farmyard manure (as reported by the not-for-profit company Rythu Sadhikara Samstha (RySS)[20]) is the system likely to have the potential to provide all of the nitrogen required to maintain current national levels of crop production. Therefore, without the application of additional manure, ZBNF systems are, on average, likely to be more deficient in nitrogen than conventional systems. If nitrogen fixation is lower than estimated here, or nitrogen immobilization with straw incorporation is not avoided, deficiencies in crop nitrogen could be even more pronounced.

In the above analysis, nitrogen potentially available in a ZBNF system has been compared with the national average fertilizer application rate of India[36]. This includes a wide range of different systems, from high-yielding, high-input systems to low-input systems with lower yields. In low-input systems, nitrogen supply is expected to increase with conversion to ZBNF, whereas in high-input systems, it is more likely to decline. Yield increases associated with increased nitrogen supply may, in part, explain the observation from 88% of farmers that converting to ZBNF has achieved increased yields in the first season after conversion[26]. Assuming that farmers with low income also use low inputs, if ZBNF mainly focuses on low-income farmers, then it is more likely to achieve improved yields than in the cropping systems of high-income, high-input farmers.

On a national scale, if cropping is nitrogen limited, and assuming a linear response to nitrogen limitation, without the additional application of manures, crop production could be reduced by at least 20–48% due to conversion to ZBNF. With food demand expected to rise to 136% between 2009 and 2050[37] and only 16% of India's land area remaining uncultivated or unforested (Supplementary note 1.2), this would represent a substantial decline in India's capacity to produce its own food and could have serious consequences for food security. It could also greatly increase pressures on land, leading to agricultural expansion into natural ecosystems. If, however, conversion to ZBNF is limited to farmers with currently low-yielding crops, national food production could be improved. Ensured improvement in national food production may require high-production systems to be maintained as conventional until practices needed to achieve high yields with ZBNF can be established. It is, therefore, important that farmers are targeted for conversion to ZBNF according to the likelihood that they will be able to maintain current yields after conversion.

### Restoration of soils

None of the practices included in ZBNF are likely to result in a reduction in soil organic matter, so concerns over the potential mining of organic matter and associated nutrients are not substantiated. The application of *jiwamrita* and *beejamrita* is expected to have minimal direct impact on soil carbon: the amount of carbon contained in the applied cultures is very small, and although the potential increased rate of heterotrophic decomposition is likely to speed up decomposition of fresh plant material, this will result in more rapid stabilization of organic matter in the soil, rather than a long-term decline (Supplementary note 5.2). The mulching practices recommended by ZBNF are predicted to substantially increase soil carbon. Mulching with dried biomass could increase soil carbon by 10–21%, depending on the specific conditions at the site (Supplementary note 7.3). Tillage to only 15 cm is likely to increase soil carbon deeper in the soil profile (Supplementary note 7.1). Improved soil aeration (*whapahasa*) could increase the decomposition of soil organic matter, but in already aerated agricultural soils, this is likely to be minimal. Therefore, implementation of ZBNF is expected to contribute substantially to increasing soil organic matter, so helping to restore India’s degraded soils. Conventional farming in India is associated with a long-term decline in soil organic matter[9]. Taken together, climate change and soil degradation are expected to reduce crop yields globally by 10% by 2050[38]. The potential increase in soil organic matter under ZBNF would increase the water-holding capacity of the soil[39], thus also increasing the resilience of crops to adverse climatic conditions and helping to maintain food production under water-stressed conditions. Therefore, over the longer term, recovery of soil condition may provide yield benefits even in higher-input systems.

## Discussion

The above analysis brings together best-available evidence on the impact of ZBNF practices on the nitrogen available to crops and the organic matter content of the soil. Given the reduced nitrogen inputs, it is highly likely that national-scale production in high-input systems would be reduced by ZBNF systems in the short term, but there may be yield benefits in specific conditions and over the longer term. To make ZBNF work for India, further research is needed to strengthen our understanding of the processes controlling crop production in ZBNF systems and the specific conditions in which farm incomes are likely to be improved. The extra work needed is summarized in Table 1. This includes improved understanding of the practices used by ZBNF farmers, the impacts on farm income, yields, nutrients and soil carbon, the impacts on the activities of soil fauna and the influence of soil inocula, seed treatments and mulching techniques.

To avoid yield penalties, ZBNF should initially be encouraged on only low-income farms, where lower inputs of nitrogen to crops can more easily be maintained than on high-income farms. Before ZBNF is promoted among higher-income farmers, further work is needed to quantify sources of nitrogen, understand the impacts of ZBNF on soil organic matter and ensure that higher levels of nutrients continue to be available to crops, so that crop yields can be maintained over both the short and long term.

This analysis suggests that although ZBNF has a substantial role to play in improving the productivity and viability of low-income farms, if it is strongly promoted to high-income farmers, an immediate decline in national food production is likely. However, because soil organic matter is predicted to increase under ZBNF, this is not the catastrophic and long-lasting crash in food production feared: food production is likely to immediately recover when high-income farmers restore nutrient supplies to their crops. Nitrogen fixation, either by free-living nitrogen fixers in the soil or by symbiotic nitrogen fixers in legumes, is likely to provide a major portion of the nitrogen available to crops within a ZBNF system. Since biological fixation from the atmosphere is possible only with nitrogen, ZBNF could present further limitations with respect to other nutrients. Further analysis is therefore needed to quantify the impacts of ZBNF on other macro- and micronutrients required by crops.

## Methods

This study examines sources of nitrogen potentially available within a strict ZBNF system and assesses the possible long-term impacts on soils of widespread conversion. The national impact on crop yields is estimated by comparison against national average fertilizer application rates. Changes in nitrogen and carbon turnover are determined using a combination of dynamic simulation modelling and data drawn from the peer-reviewed literature. The model used has previously been rigorously evaluated under Indian conditions[40]. The collated data are derived from Indian studies where possible, but we draw on wider sources where necessary.

### Potential impact of nitrogen being supplied only by the soil

Many practitioners of ZBNF believe that the nutrients used by the crop are not added in the applied treatments or fixed by microorganisms, but are instead provided by the soil itself[27]. If the supply of nitrogen in a ZBNF system was provided only by stimulating the release of nitrogen from the soil, there would be an associated loss of soil organic matter. The national average amount of nitrogen that would need to be supplied by the soil, $N_{\text{soil}}$, was estimated from the national average rate of nitrogen fertilizer application in conventional systems ($N_{\text{con,in}}$ = 118 kg ha$^{-1}$ yr$^{-1}$ for a two-crop system[36]), minus the direct inputs of nitrogen in a ZBNF system, $N_{\text{ZBNF,in}}$:

$$N_{\text{soil}} = N_{\text{con,in}} - N_{\text{ZBNF,in}} \tag{1}$$

The typical direct inputs of nitrogen in a ZBNF system were obtained from the nitrogen excreted by a cow each year ($N_{\text{cow}}$ = 6.5–100 kg yr$^{-1}$, depending on the intensity of management[41]) and the rate of application claimed by ZBNF of manure from “one cow for every 30 acres of land”[27] ($r_{\text{cow}}$ = 1/(30×0.405) cows per hectare, where ‘0.405’ converts acres to hectares):

$$N_{\text{ZBNF,in}} = r_{\text{cow}} \times N_{\text{cow}} \tag{2}$$

The annual loss of carbon, $C_{\text{soil}}$ (t ha$^{-1}$ yr$^{-1}$), associated with the soil organic matter releasing this amount of nitrogen ($N_{\text{soil}}$) was then estimated using a conservative assumption of a stable carbon-to-nitrogen ratio for the organic matter of ~8.5[42]:

$$C_{\text{soil}} = 8.5 \times N_{\text{soil}}/1,000 \tag{3}$$

The total amount of carbon held in the soil, $C_{\text{tot}}$ (t ha$^{-1}$) was estimated from the percentage of carbon in the soil, $P_{\text{C}}$ (most soils in India contain less than 0.5% carbon[43]), and the soil bulk density, $D_{\text{soil}}$ (typically ~1.4 g cm$^{-3}$)[43], to a depth, $d$, of 30 cm:

$$C_{\text{tot}} = P_{\text{C}} \times D_{\text{soil}} \times d \tag{4}$$

This then allowed calculation of the time required for all carbon and nitrogen held in the top 30 cm of soil to be lost if the supply of nitrogen continued at the rate required to maintain current levels of production, $t_{\text{soil}}$ (yr):

$$t_{\text{soil}} = C_{\text{tot}}/C_{\text{soil}} \tag{5}$$

## Nitrogen available in organic farming systems

The percentage of nitrogen applied in conventional systems that could be applied as manure if all farmers in India were to convert to organic farming, $P_{\text{manure}}$, was calculated from the number of cattle in India ($n_{\text{cow}}$ = 1.91×10$^{8}$, according to the 2012 Livestock Census[25]), $N_{\text{cow}}$ (6.5–100 kg yr$^{-1}$)[41], the area of arable land in India ($A_{\text{arable}}$ = 1.797×10$^{8}$ ha for the year 2016[44]) and $N_{\text{con,in}}$:

$$P_{\text{manure}} = (100 \times n_{\text{cow}} \times N_{\text{cow}})/(A_{\text{arable}} \times N_{\text{con,in}}) \tag{6}$$

Note that this is the maximum potential nitrogen available because not all nitrogen in the manure will be available to plants and because organic manures have many other important uses in rural India, for example, as a household fuel[45].

## Manure used in ZBNF

The percentage of manure available in India if all farmers were to convert to a strict ZBNF system, $P_{\text{cow,ZBNF}}$, was calculated from the number of cows required to provide the dung and urine used in the recipes for the inocula applied in ZBNF ($n_{\text{cow,ZBNF}}$) and $n_{\text{cow}}$:

$$P_{\text{cow,ZBNF}} = 100 \times (n_{\text{cow,ZBNF}}/n_{\text{cow}}) \tag{7}$$

The value of $n_{\text{cow,ZBNF}}$ was calculated from the mass of dung produced by a cow each year ($M_{\text{dung,cow}} = 365\times(10 \pm 2)\ \text{kg yr}^{-1}$)[46], the mass of dung used in the recipes for the inocula, $M_{\text{dung,ZBNF}}$, and $A_{\text{arable}}$:

$$n_{\text{cow,ZBNF}} = (A_{\text{arable}} \times M_{\text{dung,ZBNF}})/(M_{\text{dung,cow}} \times 0.405) \tag{8}$$

where ‘0.405’ converts acres to hectares. For urine, $n_{\text{cow,ZBNF}}$ was calculated on a volume basis:

$$n_{\text{cow,ZBNF}} = (A_{\text{arable}} \times V_{\text{urine,ZBNF}})/(V_{\text{urine,cow}} \times 0.405) \tag{9}$$

where $V_{\text{urine,cow}}$ is the volume of urine produced by a cow each year ($365\times(5\pm1)\text{dm}^3\text{yr}^{-1}$)[46] and $V_{\text{urine,ZBNF}}$ is the volume of urine used in the recipes for the inocula. As shown in Supplementary note 4.1, $M_{\text{dung,ZBNF}} = 180\ \text{kg yr}^{-1}$ and $V_{\text{urine,ZBNF}} = 170\ \text{dm}^3\ \text{yr}^{-1}$ per acre. The value of $n_{\text{cow,ZBNF}}$ was then taken to be the maximum of the values calculated for dung and for urine.

## Nitrogen supplied by ingredients of inoculum

The percentage of nitrogen applied in conventional systems that is provided by the ingredients of the inocula used in ZBNF, $P_{\text{ZBNF,in}}$, was calculated from $N_{\text{ZBNF,in}}$ and $N_{\text{con,in}}$:

$$P_{\text{ZBNF,in}} = 100 \times (N_{\text{ZBNF,in}}/N_{\text{con,in}}) \tag{10}$$

The value of $N_{\text{ZBNF,in}}$ is $8.3 \pm 0.4\ \text{kg ha}^{-1}\ \text{yr}^{-1}$ for *dhrava jiwamrita* and $3.3 \pm 0.2\ \text{kg ha}^{-1}\ \text{yr}^{-1}$ for *ghana jiwamrita* (Supplementary note 5.1) and $0.32 \pm 0.04\ \text{kg ha}^{-1}\ \text{yr}^{-1}$ for *beejamrita* (Supplementary note 6.1).

## Nitrogen supplied by mulching with crop residues

The percentage of nitrogen applied in conventional systems that could potentially be provided by mulching with crop residues in ZBNF, $P_{\text{ZBNF,res}}$, was calculated from the percentage of crop residues that are not used for other purposes, $P_{\text{unused}}$, the percentage of crop $i$ grown nationally, $P_{\text{crop},i}$, the nitrogen content of the residues, $N_{\text{res},i}$ (kg ha$^{-1}$), and $N_{\text{con,in}}$:

$$P_{\text{ZBNF,res}} = (P_{\text{unused}}/100) \times \sum_i (P_{\text{crop},i} \times (N_{\text{res},i}/N_{\text{con,in}})) \tag{11}$$

The value of $N_{\text{res},i}$ was obtained from the concentration of nitrogen in the residues, $C_{\text{Nres},i}$ (kg t$^{-1}$), and the amount of residues available for incorporation, which was estimated from the typical crop yield, $M_{\text{yld},i}$ (t ha$^{-1}$), and harvest index, $\text{HI}_i$ (t t$^{-1}$), obtained from the literature (Supplementary note 7.2):

$$N_{\text{res},i} = C_{\text{Nres},i} \times ((M_{\text{yld},i}/\text{HI}_i) - M_{\text{yld},i}) \tag{12}$$

Note that this provides a maximum estimate of nitrogen available from mulching with crop residues. This amount of nitrogen would be released to the following crop only if the action of heterotrophic bacteria in *jiwamrita* was to stimulate the immediate release of nitrogen contained in the crop residue.

## Nitrogen supplied by live crop mulching

The percentage of nitrogen applied in conventional systems that could potentially be provided by live mulching with legumes in ZBNF, $P_{\text{ZBNF,leg}}$, was estimated from the average nitrogen provided by legumes to the associated non-legume crop $i$, $\overline{N}_{\text{leg},i}\left(\text{kg ha}^{-1}\right)$, $P_{\text{crop},i}$ and $N_{\text{con,in}}$:

$$P_{\text{ZBNF,leg}} = 100 \times \left(\sum_i (\overline{N}_{\text{leg},i} \times P_{\text{crop},i})/N_{\text{con,in}}\right) \tag{13}$$

The value of $\overline{N}_{\text{leg},i}$ for each crop was obtained from a review of the literature (Supplementary note 7.5).

## Change in soil carbon due to mulching with crop residues

The input carbon associated with mulching with crop residues, $M_{\text{C,in}}$ (kg ha$^{-1}$), was calculated from $P_{\text{unused}}$, $P_{\text{crop},i}$ and the mass of carbon contained in the residues, $M_{\text{Cres},i}$:

$$M_{\text{C,in}} = P_{\text{unused}} \times \sum_i (M_{\text{Cres},i} \times P_{\text{crop},i}) \tag{13}$$

The amount of these carbon inputs retained in the soils depends on the weather conditions, cropping system, quality of the crop residues (decomposability and carbon-to-nitrogen ratio[42]) and soil type (carbon content, clay content and pH of the soil). Smith et al. used the ORATOR (Operational Research Assessment Tool for Organic Resources) model to simulate long-term changes in soil carbon with the incorporation of different amounts of biomass[40]. The simulations were evaluated using data from a sorghum–wheat cropping system on an alkaline silty clay loam soil (Haplic Vertisol) with low carbon content (only 0.61%) in a hot, semi-arid region (Maharashtra, mean annual rainfall 847 mm, and mean annual minimum and maximum temperatures 10.5 °C and 41.6 °C, respectively) (J.S., manuscript in preparation). The results of these evaluations showed that the simulations of soil organic carbon at this site had an error of 9% of the measured values, which was within the experimental error (15%) (J.S., manuscript in preparation). A 50% change in rainfall, air temperature, soil carbon and clay content was used to estimate the range of results possible across India (Supplementary note 7.3).

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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## Data availability

No datasets were generated or analysed during the current study. This is an analysis of existing data. All data were collated from literature sources as cited.

## Code availability

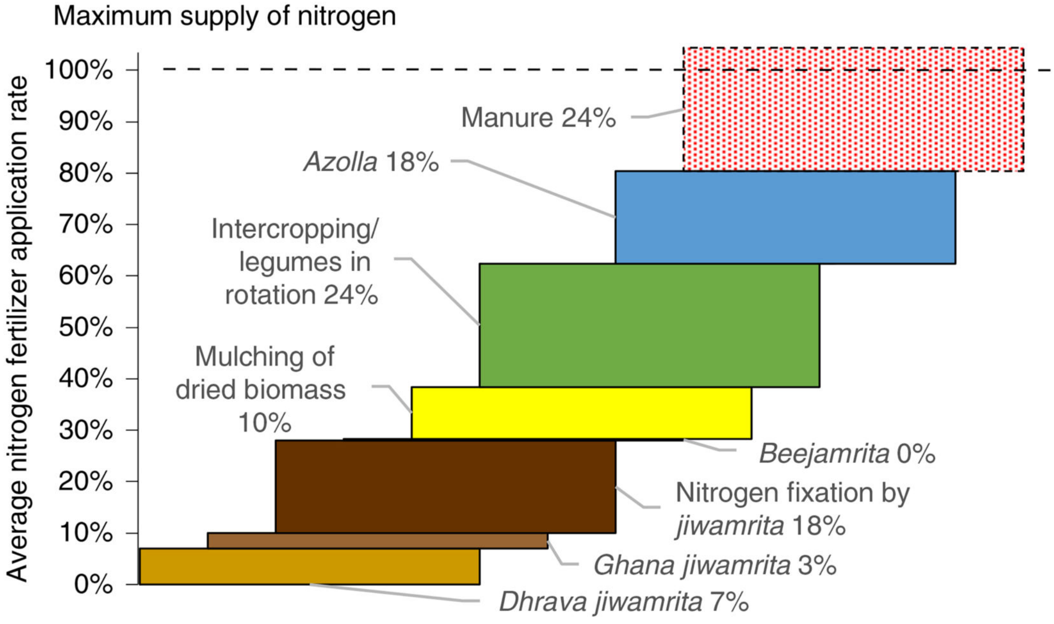
The ORATOR model has been described and published previously (see Supplementary Information) and will be made available from the corresponding author on request.

## References

1. Foley JA, et al. Solutions for a cultivated planet. Nature. 2011; 478: 337–342. [PubMed: 21993620]
2. India Population Live. Worldometers; 2019. https://www.worldometers.info/world-population/india-population/
3. World Population Prospects, the 2012 Revision. UN Department of Economic and Social Affairs; 2013. https://go.nature.com/37N2olc
4. Ritchie H, Reay D, Higgins P. Sustainable food security in India—domestic production and macronutrient availability. PLoS ONE. 2018; 13 e0193766 [PubMed: 29570702]
5. Bruinsma, J, editor. World Agriculture: Towards 2015/2030 An FAO Perspective. Earthscan; 2003.
6. Agoramoorthy G. Can India meet the increasing food demand by 2020? Futures. 2008; 40: 503–506.

7. Smith P. Delivering food security without increasing pressure on land. Glob Food Secur. 2013; 2: 18–23.
8. Ray DK, et al. Climate change has likely already affected global food production. PLoS ONE. 2019; 14 e0217148 [PubMed: 31150427]
9. Bhattacharyya R, et al. Soil degradation in India: challenges and potential solutions. Sustainability. 2015; 7: 3528–3570.
10. Mythili, G, Goedecke, J. Economics of Land Degradation and Improvement—A Global Assessment for Sustainable Development. Nkonya, E, , et al., editors. Springer; 2016. 431–469. https://go.nature.com/2FERCkZ
11. United Nations Decade of Family Farming 2019–2028 Global Action Plan. FAO and IFAD; 2019. https://reliefweb.int/sites/reliefweb.int/files/resources/ca4672en.pdf
12. 52 Profiles on Agroecology: Zero Budget Natural Farming in India. FAO; 2019. http://www.fao.org/3/a-bl990e.pdf
13. Govt. should stop promoting zero budget natural farming pending proof: scientists. The Hindu. 2019. September 11. https://go.nature.com/2FrKSH1
14. Sitharaman, N. Budget 2019–2020 speech. India Ministry of Finance; 2019. July 5, https://www.indiabudget.gov.in/budgetspeech.php
15. Sanhati Collective. Farmer Suicides in India: A Policy-induced Disaster of Epic Proportions. 2012. http://sanhati.com/excerpted/4504/
16. Patel V, et al. Suicide mortality in India: a nationally representative survey. Lancet. 2012; 379: 2343–2351. [PubMed: 22726517]
17. Kennedy J, King L. The political economy of farmers' suicides in India: indebted cash-crop farmers with marginal landholdings explain state-level variation in suicide rates. Glob Health. 2014; 10: 16.
18. Abhilash PC, Singh N. Pesticide use and application: an Indian scenario. J Hazard Mater. 2009; 165: 1–12. [PubMed: 19081675]
19. Kumari S, Sharma H. The impact of pesticides on farmer's health: a case study of fruit bowl of Himachal Pradesh. Int J Sci Res. 2012; 3: 144–148.
20. Zero Budget Natural Farming. RySS, Government of Andhra Pradesh; 2018. http://apzbnf.in
21. Khadse A, Rosset PM. Zero budget natural farming in India—from inception to institutionalization. Agroecol Sust Food. 2019; 43: 848–871.
22. Statistical Abstract Andhra Pradesh 2015. Directorate of Economics and Statistics, Government of Andhra Pradesh; 2016. https://desap.cgg.gov.in/jsp/website/gallery/Statistical%20Abstract%202015.pdf
23. RySS. Zero Budget Natural Farming as A Nature-based Solution for Climate Action. UNEP; 2019. https://wedocs.unep.org/handle/20.500.11822/28895?show=full
24. Report of the Global Environment Facility to the Fourteenth Session of the Conference of the Parties to the United Nations Convention to Combat Desertification. GEF; 2019. https://go.nature.com/2tzvntM
25. Patra AM. Accounting methane and nitrous oxide emissions, and carbon footprints of livestock food products in different states of India. J Clean Prod. 2017; 162: 678–686.
26. Kumar, V. India—innovations in agroecology. Engineering transformation through zero budget natural farming (ZBNF); Scaling Up Agroecology to Achieve the Sustainable Development Goals Proc 2nd FAO International Symposium; 2019. 250–251. http://www.fao.org/3/BU710EN/bu710en.pdf
27. Palekar S. Zero Budget Spiritual Farming. 2019. http://palekarzerobudgetspiritualfarming.org
28. Ram RA, Singha A, Vaish S. Microbial characterization of on-farm produced bio-enhancers used in organic farming. Indian J Agr Sci. 2018; 88: 35–40.
29. App AA, et al. Nonsymbiotic nitrogen fixation associated with the rice plant in flooded soils. Soil Sci. 1980; 130: 283–289.
30. Sreenivasa MN, Naik N, Bhat SN. Beejamrutha: a source for beneficial bacteria. Karnataka J Agric Sci. 2009; 22: 1038–1040.

31. Rao SC, Dao TH. Fertilizer placement and tillage effects of nitrogen assimilation by wheat. Agron J. 1992; 84: 1028–1032.
32. Erenstein O, Laxmi V. Zero tillage impacts in India’s rice–wheat systems: a review. Soil Till Res. 2008; 100: 1–14.
33. Singh A, Phogat VK, Dahiya R, Batra SD. Impact of long-term zero till wheat on soil physical properties and wheat productivity under rice–wheat cropping system. Soil Till Res. 2014; 140: 98–105.
34. Ram AR. Innovations in organic production of fruits and vegetables. Shodh Chintan. 2019; 11: 85–98.
35. National Crop Statistics. FAOSTAT; 2019. http://www.fao.org/faostat/en/#data/QC
36. Fertilizer Use by Crop in India. FAO; 2005. http://www.fao.org/tempref/agl/agll/docs/fertuseindia.pdf
37. Hamshere, P, Sheng, Y, Moir, B, Gunning-Trant, C, Mobsby, D. What India Wants: Analysis of India’s Food Demand to 2050 Report No 1416. ABARES; 2014. http://agriculture.gov.au/abares/publications
38. Montanarella, L, Scholes, R, Brainich, A, editors. The IPBES Assessment Report on Land Degradation and Restoration. IPBES; 2018. www.ipbes.net
39. Hati KM, Swarup A, Dwivedi AK, Misra AK, Bandyopadhyay KK. Changes in soil physical properties and organic carbon status at the topsoil horizon of a vertisol of central India after 28 years of continuous cropping, fertilization and manuring. Agr Ecosyst Environ. 2006; 119: 127–134.
40. Smith J, et al. Treatment of organic resources before soil incorporation in semi-arid regions improves resilience to El Niño, and increases crop production and economic returns. Environ Res Lett. 2019; 14 085004
41. Guidelines for Sustainable Manure Management in Asian Livestock Production Systems IAEA-TECDOC-1582. IAEA; 2008. https://www-pub.iaea.org/MTCD/Publications/PDF/TE_1582_web.pdf
42. Bradbury NJ, Whitmore AP, Hart PBS, Jenkinson DS. Modelling the fate of nitrogen in crop and soil in the years following application of 15N-labelled fertilizer to winter wheat. J Agric Sci. 1993; 121: 363–379.
43. Lal R. Soil carbon sequestration in India. Climatic Change. 2004; 65: 277–296.
44. FAO. World Development Indicators Agricultural Land (% of Land Area)—India. World Bank; 2019. https://data.worldbank.org/indicator/AG.LND.AGRI.ZS?locations=IN
45. Aggarwal GC, Singh NT. Energy and economic returns from cattle dung manure as fuel. Energy. 1984; 9: 87–90.
46. Saxena KL, Sewak R. Livestock waste and its impact on human health. Int J Agric Sci. 2016; 6: 1084–1099.



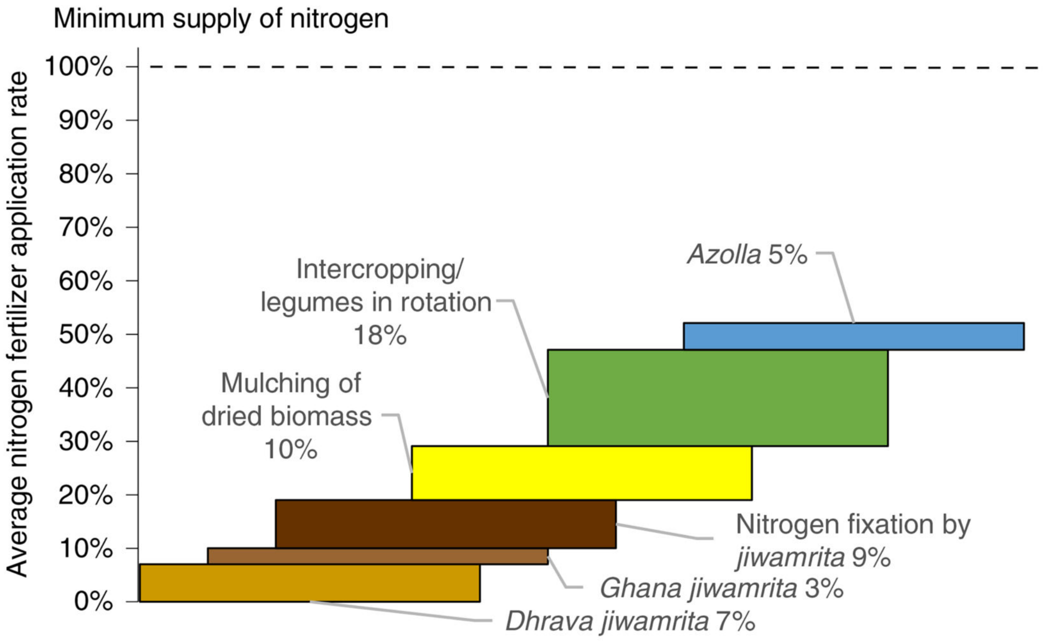


**Fig. 1. Estimated maximum and minimum supply of nitrogen from ZBNF systems compared with the national average fertilizer application rate.**

The national average fertilizer application rate is from ref. [36]. For *beejamrita, dhrava jiwamrita* and *ghana jiwamrita*, all nitrogen contained in the inoculum is assumed to be available to crops. Maximum release from mulching of dried biomass is assumed. In the case of minimum supply of nitrogen, only 50% of the potential maximum fixation by *jiwamrita* is assumed (as inoculation with nitrogen-fixing heterotrophs may not be completely successful), no extra manure is added, and minimum nitrogen fixation observed for *Azolla pinnata* is assumed.

## Table 1

### Additional evidence needed to improve understanding of the impacts of ZBNF on nitrogen available to plants and changes in soil carbon

| **Additional evidence needed** | |
|---|---|
| Whole system | • Survey of impacts on farm income<br>• Survey of practices used<br>• Controlled, replicated and randomized trials on short- and long-term changes in yield, nutrients and soil carbon (for example, long-term sites exist at Gurukul Kurukshetra, India)<br>• Impact of earthworms and other soil fauna on cycling of nutrients from deep in the soil profile |
| *Jiwamrita* (soil inoculum) | • Impact on microorganisms, earthworm activity, fungal and bacterial diseases<br>• Impact on heterotrophic decomposition of organic matter<br>• Heterotrophic microorganisms, and survival and action in the soil after inoculation<br>• Nitrogen-fixing microorganisms and their survival and action in the soil after inoculation |
| *Beejamrita* (seed treatment) | • Impact on microorganisms, earthworm activity, fungal and bacterial diseases<br>• Impacts on germination, seedling length and vigour, yield and nutrients captured by the plant |
| *Acchadana*(mulching) and *whapahasa* (soil aeration) | • Long-term impacts of tillage to only 15 cm depth on soil nitrogen, carbon and water<br>• Impact of *jiwamrita* on release of nutrients from dried biomass mulches<br>• Long-term experiments on soil organic matter retention with incorporation of crop residues in *jiwamrita*-treated soils |