ANALYSIS

Potential yield challenges to scale-up of Zero Budget Natural Farming

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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 fertiliser is expected to be supplied. Therefore, in higher-input systems, yield penalties are likely. Since biological fixation from the atmosphere is only possible with nitrogen, ZBNF could limit supply of other nutrients. Further research is needed in higher-input systems to ensure mass conversion to ZBNF does not limit India's capacity to feed itself.

Rising 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 1.2×10^9 in 2010 to 1.6×10^9 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 (S)1.1). If India is to maintain its capacity to produce its own food, crop production must increase in line with these increasing demands.

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 fertilisers, especially since the Green Revolution in India, has resulted in inefficient use of resources[6], with Northern 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 (e.g. mountainous or urban) (S1.2). 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 efficiency of Indian agriculture. Climate change has already reduced food production in India by ~0.8% between 1974 and 2013[8] (S1.3). By 2005, 48% of India's land area was already degraded[9] with annual costs for 2009 compared to 2001 estimated to be 5.35×10^9 US$[Error! Reference source not found.10] (S1.4). Depopulation of rural areas results in a reduction of the agrarian population needed to produce food, and this is projected to be ~12% between 2018 and 2050 (S1.5 and S1.6).

Family farming and Zero Budget Natural Farming. In the context of increased pressures on farming and the agrarian crisis due to depopulation, the United Nations has recognized the importance of small-scale family farmers to global food security[11] (S2.1) and launched a global action plan to benefit family-run farms (S2.2). 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 the reliance of farmers on purchased inputs and credit[125]. It is highly compatible with the principles of family farming, and this is one reason why it is receiving increasing support from communities and governments alike[12]. It is considered by many in 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 overcoming 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 (S3.2). These stresses have been reflected in high suicide rates in farmers; over 2.53×10^3 farmers in India have committed suicide since 1995[15]. In 2010, ~3% of adult deaths were due to suicide, suicide rates in rural areas were twice that 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, significant detrimental health impacts have been associated with use of agrochemicals in India[18,19]. The ZBNF system avoids use of external inputs, such as synthetic fertilisers, pesticides and herbicides, especially avoiding purchases from large corporations[20], so maintaining the cycle of production within villages instead of farmers obtaining inputs from cities. Therefore, it has potential to retain more farmers and economic resources in rural areas.

The term "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 microbes 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 stabilised soil organic matter and conservation of topsoil by mulching ("acchadana"); and (4) soil aeration ("whapahasa") by improving soil structure and reducing tillage. By focusing on soil micro-organisms and fauna, and by mulching to increase soil organic matter, it is proposed that ZBNF has potential to greatly improve soil health, and so increase efficiency of nutrient and water use, contributing to improved efficiency of crop production.

Zero Budget Natural Farming is now one of the largest "experiments" in agroecology in the world. In Karnataka, where it originated in 2002[21], unpublished data cited by FAO[125] suggests over 100,000 farming households are already following ZBNF methods. In neighbouring Andhra Pradesh, the official website of the ZBNF Programme stated that, by August 2019, 523,000 farmers had converted to ZBNF in 3015 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 6 million farmers in the state by 2024[23]. Nationally, ZBNF leaders suggest the number converting to ZBNF is in the order of millions, and Prime Minister Narendra Modi recently told the United Nations conference on desertification that, in future, India will focus on ZBNF[13,24], while Finance Minister Nirmala Sitharaman called for a "back to basics" approach with an emphasis on ZBNF[14].

The controversy surrounding Zero Budget Natural Farming. Strict ZBNF differs from traditional organic farming in that it does not attempt to provide 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 fertilisers 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 fertilisers would be available from manures (S4.1). By contrast, the manure used in a strict ZBNF-system would require only 18 – 21% of cows reported in the 2012 Livestock Census[25] (S4.1).

Although, the nutrients applied to 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 randomised 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 nutrients needed for plant growth, and 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 only provided by stimulating release from the topsoil, there would be an associated loss of soil organic matter; for a typical topsoil in India, all organic matter would be gone within 20 years (S4.2). Such a degradation would result in reduced crop yields, reduced resilience to droughts and increased rates of erosion, so causing a significant decline in crop production in India. Therefore, there is concern that ZBNF might have a detrimental impact on farmers' income 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 (S4.2) could result in a catastrophic crash in food production across India. Therefore, there is urgent need to examine potential mechanisms of nitrogen supply to crops in ZBNF-systems in order to understand where it is coming from and what level 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 possible long-term impacts on soils of widespread conversion. We do so based on estimates of nitrogen and carbon turnover using a combination of dynamic simulation modelling and data drawn from the peer-reviewed literature. The collated data are derived from Indian studies where ever possible, but we draw on wider sources where necessary. We then discuss additional experimental evidence needed to understand processes occurring in ZBNF, so that likely impacts of conversion can be better understood and quantified.

Results

Provision of nitrogen for crop growth. Each of the four wheels of ZBNF have 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 or 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 fertiliser application.

Jiwamrita (soil inoculum). The fermented microbial culture, jiwamrita, provides some nutrients, but more importantly, aims to promote growth of micro-organisms 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} y^{-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 fertiliser application, respectively (S5.1). 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 (S5.3), 18% of the national average nitrogen fertiliser 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 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 fertiliser application (S6.1). 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 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 to 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 to conventional tillage, it is likely to increase carbon content at depth, especially in clay loam soils[33] (S7.1).

Mulching with dried biomass usually uses mulch from previous crops which is intended to rapidly decompose and increase soil organic matter while releasing nutrients under the action of increased micro-organisms from application of jiwamrita. Measurements of changes in the microbial population during culturing jiwamrita showed 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] (S5.2). If these microorganisms survive and then proliferate once added to the soil, this suggests the rate of decomposition could indeed be greatly increased by 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, on average this could provide additional nitrogen to the crop of up to ~12 kg ha^{-1} y^{-1}, 10% of the national average nitrogen fertiliser application (S7.2).

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 farmyard manure in the last ploughing before sowing (S7.4). This is not part of a strict ZBNF-system, but if organic manures are applied at this rate, an additional 12 to 14 kg ha^{-1} nitrogen would be applied, 21 to 24% of the national average nitrogen fertiliser application rate (S7.4).

Live mulching is mainly done as intercropping, which aims to supply potassium, phosphorus and sulphur using monocots (such as rice and wheat) and nitrogen using dicots (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 fertiliser application (S7.5). *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[36]), this could contribute on average 6 – 21 kg ha^{-1} y^{-1} additional nitrogen, 5 – 18% of the national average nitrogen fertiliser application (S7.5).

Total nitrogen provided by Zero Budget Natural Farming. The above estimates of nitrogen provided by different practices used in ZBNF suggest that, even if nitrogen fixation is stimulated and immobilisation of nitrogen due to straw incorporation is avoided by application of jiwamrita, a strict ZBNF-system might have potential to provide only 52 – 80% of the average nitrogen fertiliser application used across India (Figure 1). Only if additional nitrogen is applied in the 4.9 t ha^{-1} farmyard manure (as reported by RySS[20]) is the system likely to have potential to provide all nitrogen required to maintain current national levels of crop production. Therefore, without 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 immobilisation 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 to the national average fertiliser application rate of India[37]. 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 associate 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[38]. Assuming farmers with low-income also use low inputs, if ZBNF mainly focusses 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 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[39], and only 16% of India's land area remaining uncultivated or unforested (S1.2), this would represent a significant 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 reduction in soil organic matter, so concerns over potential mining of organic matter and associated nutrients are not substantiated. Application of jiwamrita and beejamrita are 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 stabilisation of organic matter in the soil rather than a long term decline (S5.2). The mulching practices recommended by ZBNF are predicted to significantly increase soil carbon. Mulching with dried biomass could increase soil carbon by 10 – 21% depending on the specific conditions at the site (S7.3). Tillage to only 15 cm is likely to increase soil carbon deeper in the soil profile (S7.1). 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 provide a significant contribution 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[40]. The potential increase in soil organic matter under ZBNF would increase water holding capacity of the soil[41], so also increasing 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 nitrogen available to crops and 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 processes controlling crop production in ZBNF-systems and specific conditions where farm incomes are likely to be improved. Extra work needed is summarised in Table 1. This includes improved understanding of the practices ZBNF farmers use, the impact on farm income, yields, nutrients and soil carbon, the impact on activity of soil fauna, and the influence of soil inocula, seed treatments and mulching techniques.

To avoid yield-penalties, ZBNF should initially be encouraged only on 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 impacts of ZBNF on soil organic matter, and ensure 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, while ZBNF has a significant 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 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 only possible with nitrogen, ZBNF could present further limitations with respect to other nutrients. Further analysis is therefore needed to quantify impacts of ZBNF on other macro and micro-nutrients required by crops.

Methods

This study examines sources of nitrogen potentially available within a strict ZBNF-system and assesses possible long-term impacts on soils of widespread conversion. The national impact on crop yields is estimated by comparison against national average fertiliser 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[49]. The collated data are derived from Indian studies where ever possible, but we draw on wider sources where necessary.

Potential impact of nitrogen being supplied only by the soil. Many practictioners of ZBNF believe that the nutrients used by the crop are not added in the applied treatments or fixed by micro-organisms, but are instead provided by the soil itself[27]. If the supply of nitrogen in a ZBNF system was only provided by stimulating 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_{soil} (kg ha^{-1} y^{-1}), was estimated from the national average rate of nitrogen fertiliser application ($N_{\mathrm{con,in}}$ = 118 kg ha^{-1} y^{-1} for a two-crop system[42]), minus the direct inputs of nitrogen in a ZBNF system, $N_{\mathrm{ZBNF,in}}$ (kg ha^{-1} y^{-1}),

$$N_{\mathrm{soil}} = N_{\mathrm{con,in}} - N_{\mathrm{ZBNF,in}} \qquad (1)$$

The typical direct inputs of nitrogen in a ZBNF system were obtained from the nitrogen excreted by a cow each year (N_{cow} = 6.5 – 100 kg y^{-1} depending on the intensity of management[43]), and the rate of application claimed by ZBNF of manure from "one cow for every 30 acres of land"[27] ($r_{\mathrm{cow}} = {}^{1}/_{(30 \times 0.405)}$ cows per ha, where 0.405 converts acres to hectares),

$$N_{\mathrm{ZBNF,in}} = r_{\mathrm{cow}} \times N_{\mathrm{cow}} \qquad (2)$$

The annual loss of carbon, C_{soil} (t ha^{-1} y^{-1}), associated with the soil organic matter releasing this amount of nitrogen (N_{soil}) was then estimated using a conservative assumption of a stable carbon to nitrogen ratio for the organic matter of ~8.5[44],

$$C_{\mathrm{soil}} = 8.5 \times {}^{N_{\mathrm{soil}}}/_{1000} \qquad (3)$$

The amount of carbon held in the soil, C_{tot} (t ha^{-1}) was estimated from the carbon content of the soil, P_{C} (%) (most soils in India contain less than 0.5% carbon[45]), and the soil bulk density, D_{soil} (g cm^{-3}) (typically ~1.4 g cm^{-3} [45]), to a depth, d (cm), of 30 cm,

$$C_{\mathrm{tot}} = P_{\mathrm{C}} \times D_{\mathrm{soil}} \times d \qquad (4)$$

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_{soil} (y),

$$t_{\mathrm{soil}} = {}^{C_{\mathrm{tot}}}/_{C_{\mathrm{soil}}} \qquad (5)$$

Nitrogen available in organic farming systems. The percentage of nitrogen applied in conventional systems ($N_{\mathrm{con,in}}$) that could be applied as manure if all farmers in India were to convert to organic farming, P_{manure} (%), was calculated from the number of cattle in India (n_{cow} = 1.91 × 10^{8}, according to the 2012 Livestock Census[25]), the nitrogen excreted by a cow each year (N_{cow} = 6.5 – 100 kg y^{-1} [43]), the area of arable land in India (A_{arable} = 1.797 × 10^{8} ha – for year 2016[46]) and the national average rate of nitrogen fertiliser application ($N_{\mathrm{con,in}}$),

$$P_{\mathrm{manure}} = {}^{(100 \times n_{\mathrm{cow}} \times N_{\mathrm{cow}})}/_{(A_{\mathrm{arable}} \times N_{\mathrm{con,in}})} \qquad (6)$$

Note that this is the maximum potential nitrogen availability because not all nitrogen in the manure will be available to plants and because organic manures have many other important uses in rural India, e.g. for use as a household fuel[47].

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

$$P_{\mathrm{cow,ZBNF}} = 100 \times \left({}^{n_{\mathrm{cow,ZBNF}}}/_{n_{\mathrm{cow}}}\right) \qquad (7)$$

The number of cows required to produce the dung needed in ZBNF ($n_{\mathrm{cow,ZBNF}}$) was calculated from the mass of dung produced by a cow each year ($M_{\mathrm{dung,cow}}$ = (365 × (10 ± 2) kg y^{-1} [48]), the mass of dung used in the recipes for the inocula, $M_{\mathrm{dung,ZBNF}}$ (kg y^{-1}) and the area of arable land in India (A_{arable}),

$$n_{\mathrm{cow,ZBNF}} = {}^{(A_{\mathrm{arable}} \times M_{\mathrm{dung,ZBNF}})}/_{(M_{\mathrm{dung,cow}} \times 0.405)} \qquad (8)$$

where 0.405 converts from acres to hectares. For urine, $n_{\mathrm{cow,ZBNF}}$ was calculated on a volume basis,

$$n_{\mathrm{cow,ZBNF}} = \left(A_{\mathrm{arable}} \times V_{\mathrm{urine,ZBNF}}\right) \Big/ \left(V_{\mathrm{urine,cow}} \times 0.405\right) \qquad (9)$$

where $V_{\mathrm{urine,cow}}$ is the volume of urine produced by a cow each year (365 × (5 ± 1) dm^3 y^{-1} urine[48]) and $V_{\mathrm{urine,ZBNF}}$ is the volume of urine used in the recipes for the inocula (dm^3). As shown in S4.1, $M_{\mathrm{dung,ZBNF}}$ is 180 kg y^{-1}, and $V_{\mathrm{urine,ZBNF}}$ is 170 dm^3 y^{-1} per acre. The value of $n_{\mathrm{cow,ZBNF}}$ 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, $P_{ZBNF,in}$ (%), was calculated from the total nitrogen contained in the ingredients applied, $N_{ZBNF,in}$ (kg ha^{-1} y^{-1}), and the national average rate of nitrogen fertiliser application ($N_{con,in}$),

$$\mathrm{P}_{\mathrm{ZBNF,in}} = 100 \times \left(\mathrm{N}_{\mathrm{ZBNF,in}} \big/ N_{\mathrm{con,in}}\right) \qquad (10)$$

The value of $\mathrm{N}_{\mathrm{ZBNF,in}}$ is 8.3 (± 0.4) kg ha^{-1} y^{-1} for dhrava jiwamrita and 3.3 (±0.2) kg ha^{-1} y^{-1} for ghana jiwamrita (S5.1), and 0.32 (± 0.04) kg ha^{-1} y^{-1} for beejamrita (S6.1).

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, $\mathrm{P}_{\mathrm{ZBNF,res}}$ (%), was calculated from the percentage of crop residues that are not used for other purposes, P_{unused} (%), the percentage of the crop i grown nationally, $P_{\mathrm{crop,i}}$ (%), the nitrogen content of the residues, $N_{\mathrm{res,i}}$ (kg ha^{-1}), and the national average rate of nitrogen fertiliser application ($N_{\mathrm{con,in}}$),

$$\mathrm{P}_{\mathrm{ZBNF,res}} = \left(P_{\mathrm{unused}} \big/ 100\right) \times \sum_{\mathrm{i}} \left(P_{\mathrm{crop,i}} \times \left(N_{\mathrm{res,i}} \big/ N_{\mathrm{con,in}}\right)\right) \qquad (11)$$

The nitrogen content of the residues ($N_{\mathrm{res,i}}$) was obtained from the concentration of nitrogen in the residues, $C_{\mathrm{Nres,i}}$ (kg t^{-1}), and the amount of residues available for incorporation, which was estimated from the typical crop yield, $M_{\mathrm{yld,i}}$ (t ha^{-1}) and harvest index, HI_{i} (t t^{-1}), obtained from the literature (S7.2),

$$N_{\mathrm{res,i}} = C_{\mathrm{Nres,i}} \times \left(\left(M_{\mathrm{yld,i}} \big/ HI_{\mathrm{i}}\right) - M_{\mathrm{yld,i}}\right) \qquad (12)$$

Note that this provides a maximum estimate of nitrogen available from mulching with crop residues. This amount of nitrogen would only be released to the following crop if the action of heterotrophic bacteria in jiwamrita was to stimulate 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, $\mathrm{P}_{\mathrm{ZBNF,leg}}$ (%), was estimated from the average nitrogen provided by legumes to the associated non-legume crop i, $\overline{\mathrm{N}}_{\mathrm{leg,i}}$ (kg ha^{-1}), the percentage of the crop i grown nationally ($P_{\mathrm{crop,i}}$), and the national average rate of nitrogen fertiliser application ($N_{\mathrm{con,in}}$),

$$\mathrm{P}_{\mathrm{ZBNF,leg}} = 100 \times \left(\sum_{\mathrm{i}}\left(\overline{\mathrm{N}}_{\mathrm{leg},i} \times P_{\mathrm{crop,i}}\right) \big/ N_{\mathrm{con,in}}\right) \qquad (13)$$

The value of $\overline{\mathrm{N}}_{\mathrm{leg,i}}$ for each crop was obtained from a review of the literature (S7.5).

Change in soil carbon due to mulching with crop residues. The input carbon associated with mulching with crop residues, $\mathrm{M_{C,in}}$ (kg ha^{-1}) was calculated from the percentage of crop residues that are not used for other purposes (P_{unused}), the percentage of the crop i grown nationally ($P_{\mathrm{crop,i}}$), and the mass of carbon contained in the residues, $M_{\mathrm{Cres,i}}$ (kg ha^{-1}),

$$\mathrm{M_{C,in}} = P_{\mathrm{unused}} \times \sum_{\mathrm{i}} \left(\mathrm{M}_{\mathrm{Cres},i} \times P_{\mathrm{crop,i}} \right) \qquad (13)$$

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[44]) and soil type (carbon content, clay content and pH of the soil). Smith et al. used the ORATOR model to simulate long-term changes in soil carbon with incorporation of different amounts of biomass[49]. 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 are 10.5 and 41.6 ℃ respectively)[50]. 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%)[50]. A 50% change in rainfall, air temperature, soil carbon and clay content was used to estimate the range of results possible across India (S7.3).

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Author contributions

JS was primarily responsible for the conception and design of the work, the acquisition, analysis and interpretation of data and the drafting of the manuscript. JY, PS and DN contributed towards the conception and design of the work, and revision of the manuscript. DN also contributed to the creation of software used in the work.

Conflicts of Interest

The authors declare no conflicts of interest.

Supplementary information

Supplemententaty information is available for this paper.

Data availability statement

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

Computer 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.

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Figure legends

Figure 1 – Estimated maximum and minimum supply of nitrogen from Zero Budget Natural Farming systems compared to the national average fertilizer application rate[37]. Notes: (1) all nitrogen assumed to be available; (2) inoculation with nitrogen fixing heterotrophs is not completely successful, so assumed only 50% of the potential maximum fixation; (3) maximum release from mulching of dried biomass assumed; (4) no extra manure added; (5) minimum nitrogen fixation observed for *Azolla* assumed.

Tables

Table 1 – Additional evidence needed to improve understanding of the impacts of Zero Budget Natural Farming on nitrogen available to plants and changes in soil carbon

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