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Integrated land systems for sustainable food production and biodiversity conservation in the semi-arid to moist tropics: stakeholder perspectives from Andhra Pradesh, India

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Land systems must urgently be transformed for social and environmental sustainability, which necessitates a better integration of food system and biodiversity governance. This is particularly pronounced in the south-Indian state Andhra Pradesh, where one of the largest agroecological transitions globally, namely Zero Budget Natural Farming (ZBNF), is currently underway, but involvement of conservation scientists and practitioners has been minimal and policy spheres are disjunct. Here, we report the results of a multi-stakeholder exercise to ascertain the multi-scalar and multi-institutional transformations needed for Andhra Pradesh 's landscapes to deliver both food and biodiversity targets. To achieve a vision of an equitable and sustainable food system and of multifunctional and nature-positive land systems, we advocate for an end to harmful subsidies, improvements in infrastructures and social organisations, dietary shifts, and creation of both supporting financial structures and sustainable and transparent value chains. We stress that approaches should be participatory and link across policy domains and scales, bridging bottom-up and top-down perspectives, and with spatial planning critical to balancing land system objectives. Specifically, we stress that the ZBNF transition needs to be better aligned with state-level conservation strategies to maximise biodiversity benefits. Top priority knowledge needs include quantifying the multidimensional performance and scaling-potential of agroecological systems, the effectiveness of different conservation interventions, and how different land system objectives trade off against each other. Our work highlights a lack of data and capacity sharing, which can be addressed through intersectoral partnerships and collaborative programmes to create effective, research-based policies and land management strategies.

KEYWORDS

agroecology, biodiversity, food system sustainability, transformative change, policy coherence, land-use planning, zero budget natural farming

1 Introduction

1.1 Food-biodiversity nexus

Agriculture is the most dominant and widespread land use globally (Ramankutty et al., 2018), and a third of it occurs in areas of high biodiversity conservation priority (Hoang et al., 2023). The conversion of natural ecosystems to farmland and the intensification of existing agricultural systems are the leading drivers of global terrestrial biodiversity loss (Maxwell et al., 2016; IPBES, 2019; Jaureguiberry et al., 2022). Bending the curve of biodiversity loss necessitates tackling its root causes; thus, entailing major food system transformations that include both demand-and supply-side efforts (Díaz et al., 2019; Leclère et al., 2020; Williams et al., 2021).

The erosion of biodiversity within farmland can result in negative feedback on agricultural yields (Burian et al., 2024). The productivity, sustainability, and resilience of food production systems are underpinned by biodiversity and associated ecosystem services, such as pollination, natural pest suppression, and nutrient cycling (Dainese et al., 2019; IPBES, 2019). There is ample evidence to suggest that biodiversity loss in agricultural landscapes increases risks to food production and human well-being (Foley et al., 2011; Pretty, 2018; Garibaldi et al., 2021; Burian et al., 2024; Maney et al., 2024).

However, despite the inextricable, multifaceted link between providing food security for people and conserving and restoring biodiversity, the two challenges have historically been separated within academia, policy, and practice (Glamann et al., 2017; IPBES, 2024). This is particularly acute in India, where biodiversity features little at the food-water nexus (Martin et al., 2024). Food system and nature conservation programmes or policies are often poorly integrated, and by focussing on a singular aspect the potential for trade-offs and negative repercussions is high (Liu et al., 2018; Meyfroidt et al., 2022; IPBES, 2024).

At the global policy level, there have been increased efforts to better integrate the twin challenges. For example, addressing food production and consumption is central to the Kunming-Montreal Global Biodiversity Framework (GBF), biodiversity is acknowledged to play a key role in supporting the United Nations Sustainable Development Goals, and the interlinkages between food and biodiversity were recently assessed in the IPBES Nexus Assessment (IPBES, 2024). However, operationalising the integration of the two challenges and associated transformative change necessitates a far better understanding of the complexities of implementation in different socio-ecological and socio-political contexts (Delabre et al., 2021).

1.2 Andhra Pradesh, India, as a case study

Navigating conflicts between agriculture and conservation is particularly challenging in India, with agriculture representing the largest threat to terrestrial vertebrates (Chaudhary et al., 2022). India has an exceptionally high agricultural land use footprint (Roy et al., 2015), which has led to a low connectivity between natural ecosystems and mixed effectiveness of the national protected area network (Ghosh-Harihar et al., 2019; Sengupta et al., 2024).

Conversely, without careful planning, a drastic expansion of the protected area network could threaten food security (Mehrabi et al., 2018). India has the highest number of undernourished people globally, and if current trends continue, 60% of India's population is likely to experience severe calorie-, digestible protein-and fat deficits by 2050 (Ritchie et al., 2018). The excessive and non-targeted use of agrichemicals and extensive irrigation have been supported by government subsidies, reflecting powerful political-economic interests, including those of corporate agri-food industries (Pingali et al., 2019). This has not only led to a significant erosion of ecosystem services and to a heightened susceptibility to environmental shocks, but also to a pervasive agrarian crisis (Vasavi, 2009; Rahman, 2015; Veluguri et al., 2021; Chaudhary and Krishna, 2024).

In response, numerous grass-roots movements and government-led programmes have emerged across India to re-design agricultural systems for enhanced livelihoods, sustainability and equity. The largest of these is the Zero Budget Natural Farming (ZBNF) programme (also termed Andhra Pradesh Community Managed Natural Farming, APCNF; Supplementary Figure 1) in the southern state Andhra Pradesh. ZBNF entails regenerating biotic interactions underpinning yield-supporting ecosystem services, using locally available, non-synthetic ingredients to make bio-inoculants (Bharucha et al., 2020; Smith et al., 2020; Supplementary Figure 1a). Notably, ZBNF represents one of the largest agroecological transitions globally (Veluguri et al., 2021). The government of Andhra Pradesh is aiming to roll out ZBNF to all six million farmer households in the state, spread across almost 9 million hectares, by 2030 (RySS, 2024), with the hope of improving farmer well-being and the economic sustainability of farms. Despite the central role of biodiversity in ZBNF, and ZBNF being acknowledged as highly relevant to global biodiversity conservation (Sutherland et al., 2020), the relationship between ZBNF and biodiversity conservation has received almost no research or policy interest (but see Berger et al., 2024).

Andra Pradesh is one of India's major rice-producers, and over 60% of its population depends on agriculture for their livelihood (Department of Agriculture and Farmers Welfare, 2023). It also contains numerous sites of national conservation importance because they represent rare natural habitats, provide key ecosystem services, and/or have a high diversity of threatened species (Srivathsa et al., 2023). Consequently, Andhra Pradesh encompasses areas where agricultural commodities (in particular, rice) are grown in areas of high conservation priority (Hoang et al., 2023). Agricultural encroachment into natural ecosystems has continued over the last few decades (Hansen et al., 2013; Roy et al., 2015; Pendrill et al., 2022; Potapov et al., 2022; Department of Agriculture and Farmers Welfare, 2023; Meng et al., 2023). Despite this, agriculture and the need for transformative change in food systems features little in state-level biodiversity strategies (AP State Biodiversity Board Vision Plan, 2024).

Thus, food and biodiversity challenges are strongly interlinked in Andhra Pradesh, however, the research, management and governance of them has largely been separate. Finding pathways to overcome this demands stakeholder perspectives on the barriers and enablers within relevant sectors and institutions, such as government, farming, business, academia, and conservation organisations. Our study is built on a stakeholder consultation with the overarching goal of identifying how sufficient food for people can be obtained while conserving and restoring biodiversity in Andhra Pradesh. Specifically, we present policy-, practitioner-, and researcher-led visions of what this goal would look like, what the key knowledge gaps are that impede achieving this vision, and what the top priorities for policy and action are. This consultation is the first of its kind in this context and, given Andhra Pradesh's unique agricultural context, represents a globally highly relevant case study.

2 Methods—stakeholder workshop

As a group of stakeholders and scientists, working on sustainable food systems and/or biodiversity conservation in Andhra Pradesh and elsewhere in India, we convened in a two-day workshop in May 2024. We are associated with 23 different institutions, spanning national and international conservation non-governmental organisations (NGOs; 7 people), inter-governmental organisations (2 people), a membership union (1 person), sustainability standards certification bodies (2 people), universities (13 people), think-tanks (3 people), farmers (2 people), and *Rythu Sadhikara Samstha* (RySS; the Andhra Pradesh government-affiliated organisation facilitating the transition to ZBNF; 2 people). Workshop participants were recruited based on their, or their institution's, past and/or present relevant work in the region, where the aim was to have all types of institutions represented and to have a relatively equal representation of participants with a predominantly agronomy or agricultural economics background and of participants with a biodiversity conservation background (final ratio 14:16 participants). All workshop participants are co-authors of this paper. We engaged in a deliberative dialogue (Boyko et al., 2014) with an emphasis on tangible outcomes.

Firstly, we envisioned a sustainable food system for Andhra Pradesh for the year 2040 that produces good quality food for all, does not degrade landscapes, nor contributes to biodiversity loss. The exercise was set up to draw on ideas from a socio-ecological systems framework that allows self-organization efforts to achieve resilience and sustainability goals in agriculture (Ostrom, 2009). We identified features of this future system, how it will be different to current agricultural practices, and how biodiversity would be conserved in landscapes created by this altered scenario. It first entailed discussions in small groups, and each group's vision was then presented to all attendees, followed by an open facilitated discussion.

Secondly, again through facilitated group discussions, we identified the food and land use policies and actions that are needed to achieve this vision. In small groups, we devised a list of high-priority policy action items while cognisant of the main actors that would enforce and be exposed to such policy. Specific ideas were listed, following a nominal group technique (Hugé and Mukherjee, 2018), until no one had anything new to add to the list. Ideas of all groups were collated and, after removing duplicates, we each anonymously voted for the five policies that we considered as most important (unranked, not allowing for multiple votes per policy per person). This was followed by open discussions on the barriers and enablers of these policies, and the role different food system and conservation actors play.

Thirdly, we identified the key knowledge gaps that we believe need to be filled to achieve the envisioned future, i.e., achieving food system sustainability and reversing biodiversity loss in Andhra Pradesh. We identified the top knowledge gaps related to food systems and biodiversity, following the same procedures as above, where each of us was allowed five votes for the top knowledge gaps related to biodiversity, and five votes for the top knowledge gaps related to food systems.

3 Envisioning sustainable land and food systems for Andhra Pradesh

The consensus was that current land and food systems in Andhra Pradesh could currently not be categorised as sustainable, because the region is dominated by monocrops and agrichemical-intensive farming (despite the ZBNF programme), malnutrition and rural poverty are persistent, biodiversity loss is rampant, and natural ecosystems are being lost and degraded, all aggravated by the growing consequences of climate change, including extreme weather events. We agreed that current biodiversity loss undermines the foundation of agricultural productivity and thus the sustainability of Andhra Pradesh's food system. Additionally, there are substantial socioeconomic disparities and equity issues in the state (Kumar et al., 2016; Anand and Thampi, 2021; Petrikova, 2022)

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which must be addressed to reach food system sustainability by 2040.

Discussion groups varied in their approach to envisioning the ideal state of food and associated land systems in Andhra Pradesh. Some simply listed what they considered to be the key features of such systems, whereas one group worked along a timeline, specifically stating the area under ZBNF and natural forest cover they would like to see by 2040, delivered through yearly incremental increases. Another approach was spatially explicit, entailing spatial optimisation with land-use objectives tailored to the different socio-ecologies of Andhra Pradesh, and one group's approach involved engaging the human senses to imagine what they would see, hear, smell, touch, and taste in the envisioned future.

While the approaches diverged, the key features of the envisioned integrated food and land system for Andhra Pradesh were similar across groups, where we agreed that the envisioned future would entail three pillars: (1) biodiversity-friendly farming practices, (2) integrated, multifunctional land systems, and (3) equitable and inclusive food systems (Figure 1).

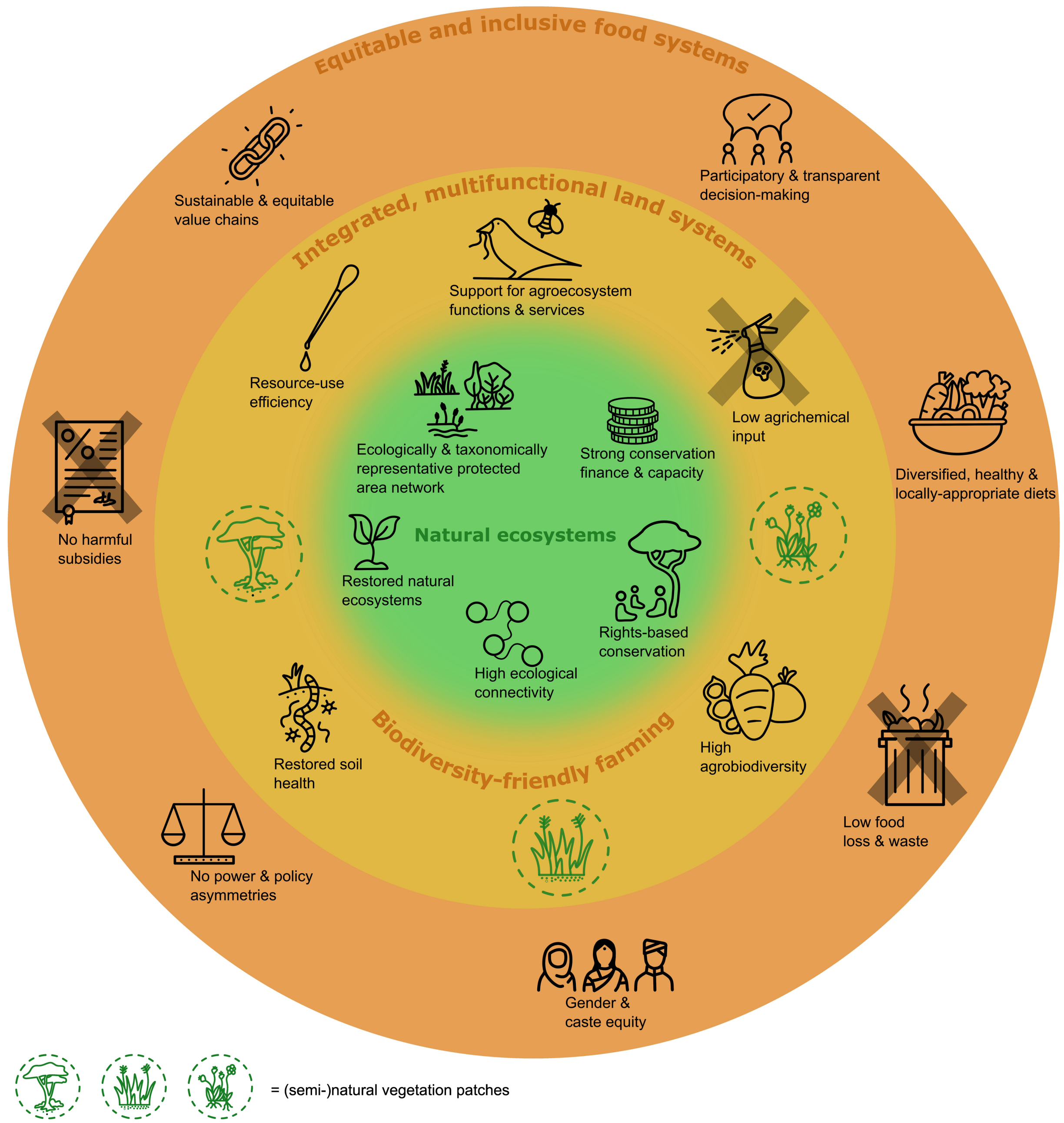

FIGURE 1
Conceptual figure illustrating our vision for sustainable food and land systems in Andhra Pradesh. Our vision entails three pillars: (i) agricultural systems managed using biodiversity-friendly practices, which are part of (ii) integrated, multifunctional land systems that also encompass well-managed natural ecosystems. These land systems are part of (iii) a wider food system that is centred around equity and inclusivity. Illustrations by Oli Broadhead.

3.1 Biodiversity-friendly farming

We agreed on a vision that entails a widespread adoption of farming practices that do not erode farmland biodiversity (i.e., diversity of wild species residing in and around agricultural land). This includes ZBNF, but more generally, we envisioned a few central principles and features, such as restored soil health, greater resource (including water and nitrogen use) efficiency without loss of agricultural yields, no or low levels of agrichemical inputs, and heightened ecological functioning. In line with the principles of agroecology (FAO, 2018; Barrios et al., 2020; Sietz et al., 2022) we envisaged a re-focus away from the singular objective of maximised yields to multifunctional agricultural systems that perform well along multiple dimensions. We stress the importance of strong support for and integration of biodiversity and associated ecosystem functions and services (such as pollination, nutrient cycling, and pest control) in food production systems, while acknowledging that not all species utilising agricultural landscapes contribute to food production and actions aimed to benefit those species should not compromise food security.

We also agreed that high levels of agrobiodiversity (i.e., a large variety of domesticated species used for food and agriculture; Jago et al., 2024) will be critical for a sustainable future (Supplementary Figure 1b), especially with regards to climate resilience and food security and sovereignty. We envisioned diversified cropping systems, especially those involving indigenous crop varieties, to play a central role in maintaining indigenous knowledge systems and overcoming undernutrition and micronutrient malnutrition in Andhra Pradesh, given that a high crop diversity frequently, albeit not necessarily, improves the dietary diversity of smallholders (Sibhatu et al., 2015).

Our visions slightly diverged regarding the role of emerging technologies and artificial intelligence. Whilst some envisioned that future food demand will purely be met through ZBNF and other agroecological farming practices, others had a more technocratic vision entailing new biotechnologies, including genetic modification, and precision agriculture. The latter harnesses the power of technologies such as drones, hyperspectral cameras, and thermal sensors to boost the productivity and sustainability of agriculture (Gebbers and Adamchuk, 2010; Cisternas et al., 2020). Nonetheless, we agreed that the future lies in finding the right balance, with measures tailored to each region's context.

Overall, given that agroecological approaches can facilitate transformative change of food systems and optimise interlinked ecological, socioeconomic, and political processes (Wezel et al., 2020), we agreed that ZBNF and other agroecological farming practices are essential elements for achieving the vision of sustainable food and agriculture in Andhra Pradesh by 2040.

3.2 Integrated, multifunctional land systems

We agreed on a vision that entails high landscape heterogeneity which fosters species persistence and ample ecological corridors connecting natural ecosystems, including those protected. The quality and permeability of agricultural landscapes tends to strongly influence the effectiveness of area-based conservation efforts (Fletcher et al., 2024). Hence, holistic, integrated landscape-scale conservation planning, where efforts to boost farmland biodiversity are aligned with conservation strategies focused on natural ecosystems, are needed in Andhra Pradesh. We agreed that identifying priority sites for wildlife movement, habitat potential for endangered and endemic species, and restoring natural vegetation patches within the agricultural matrix will be key to reaching the biodiversity goals of sustainable agriculture in the state. We stress that specific strategies must be attuned to local contexts, with different land system objectives carefully balanced. In some instances, identifying strategies that optimise ecosystem service provisioning will be at the forefront, whereas in other instances identifying ways of channelling wildlife through the matrix to minimise human-wildlife conflict will be critical. Moreover, we envisioned land-use planning to be a highly democratic, equity-focussed, transparent, and inclusive process, involving marginalised rural and forest-dependent people, including indigenous communities.

We also highlight that, in comparison to other Indian states, the forest restoration potential is high in Andhra Pradesh (Gopalakrishna et al., 2022) but stress that careful consideration must be given towards how competing demands for agriculture and forest restoration will best be met, envisioning, based on recent scenario-modelling (Mehrabi et al., 2018; Wolff et al., 2018), that this will likely involve mosaics of forests and agriculture. Nonetheless, Andhra Pradesh hosts a diverse set of natural vegetation types (Reddy, 2010) and which of these should be the focus of conservation efforts must vary by region. For example, in the Eastern Ghats of northern Andhra Pradesh moist deciduous forests must be better protected (Reddy, 2010), whereas in the South, open habitats, such as grasslands and shrublands, are predominant (Reddy, 2010), but these are currently neglected at the state and national level (Reddy, 2010; Sengupta et al., 2024). Efforts to restore natural ecosystems must be evidence-based. We stressed that timber plantations, especially when entailing single, non-native tree species, have extremely limited biodiversity value and should not contribute towards meeting area-based conservation targets. Overall, we envisaged a move away from poorly designed and executed tree-planting programmes and from a protected area network that undermines the rights of indigenous communities and is not ecologically representative.

Each of our perceptions of the adequacy and effectiveness of current area-based and species-centred conservation efforts in Andhra Pradesh dictated how we envisioned the idealised future for 2040. Some of us, predominantly those with an agronomy background, did not necessarily envision any changes from now, likely primarily valuing biodiversity for its contribution to food production. Those of us with an arguably more multidimensional view of nature and its relationships with people (see Mace, 2014), in particular conservation scientists and practitioners, considered current efforts wholly inadequate and envisioned a step-change in the quantity and quality of Andhra Pradesh's protected area network, the amount of funding for conservation and restoration efforts, and the training and support available to practitioners. We highlight that the biodiversity conservation capacity in Andhra Pradesh, especially of the Forest Department, is presently exceptionally low in comparison to other Indian states and regions.

3.3 Equitable and inclusive food systems

The third aspect of the vision was to achieve social equity, including gender and caste equity, with the existing economic, political, and sociocultural patterns that are driving ecological and social degradation disrupted. We envisioned a food system sitting within wider transformed economies, where structural barriers that promote unsustainable land systems are dismantled. This includes ending harmful agricultural subsidies such as those for agrichemical inputs, groundwater extraction, and seeds of climatically unsuitable crop varieties. Conversely, we envisaged enabling policies and initiatives to be nurtured, such as improvements in infrastructure, value chains, and social organisations. We also envisioned low levels of post-harvest crop losses and food waste, and behavioral change with respect to food consumption, health, and nutrition. Substantial dietary behavior changes are needed to deliver desirable human nutrition and environmental outcomes in Andhra Pradesh, where this entails lower intakes of foods such as rice, sugar, and poultry, and higher intakes of fruits, vegetables, and pulses (Chaudhary and Krishna, 2021). Thus, we imagined increased incentives for growing and consuming more diverse, locally appropriate, and nutrient-rich crops. Furthermore, we envisioned that power and policy asymmetries will be addressed, and participatory and transparent decision-making frameworks created, with the values and knowledge systems of a diverse set of actors (including tribal farmers, women, and youth) incorporated.

4 Priority policy solutions and actions

The group discussions led to a broad set of 27 policy recommendations (Supplementary Table 1), with five policy clusters receiving over 20 votes each, thus representing what we considered to be the most pressing policies and interventions. The five policies, presented in rank order, broadly relate to subsidies and payments, risk and insurance, post-harvest structural and marketing support, ecological connectivity and buffer zones, and locally-tailored land use planning (Table 1). Our other recommendations include, for example, more community-based (including indigenous) approaches to the conservation of natural ecosystems, strengthening of the science-policy-civil society interface, substantiating agricultural extension services, crop diversification in public distribution systems, and convergence of policies related to Nature-based Solutions (Supplementary Table 1). Nonetheless, we stress that systematic frameworks for assessing policy coherence and for identifying policy intervention points for transformative change should be employed in the future (e.g., following Nilsson et al., 2012 and Kanger et al., 2020 respectively).

4.1 Financial and infrastructural support to farmers

Agrichemicals, fossil fuel-based energy, and credits to conventional agriculture are still subsidised in Andhra Pradesh (Department of Fertilizers, 2024; Reddy, 2010). Phasing them out and redirecting finance to activities compatible with our vision will be critical through, for example, payment for ecosystem service (PES), certification, and agri-environment schemes. At present, the ZBNF programme does not involve financial support to farmers, and thus innovative financing mechanisms, such as sustainable certification schemes and carbon and biodiversity markets, could accelerate the transition and enhance the financial sustainability of the ZBNF programme.

Certification standards and PES schemes can be effective at delivering desirable ecological and social outcomes when carefully designed and implemented (Lambin et al., 2014; Tscharntke et al., 2014;

TABLE 1 Stakeholder policy recommendations.

Policy cluster	Main action points
Financial and infrastructural support	Rethink policy and taxes to redirect subsidies that directly and indirectly contribute to biodiversity harm, through existing policy instruments, such as payments for ecosystem services (PES) schemes and certification. Widen the umbrella of services under PES schemes to include all biodiversity-friendly practices assisted by transparent, clear measurement indicators
	Develop infrastructural support to agroecological farmers, such as increased access to and training in using appropriate inputs and equipment. Increased support to Primary Agricultural Societies, women and youth organisations.
Risk reduction and insurance	Develop robust social security policy, which centres on insurance against crop damage and yield loss due caused by abiotic and biotic risks, drought and precipitation volatility, and loss of human life due to human-wildlife conflicts, all for both anticipated and stochastic events. Create stable markets via purchase programmes and price guarantee policies
	Design policies that support resilience and risk reduction such as creating early warning systems, where such information is shared via effective digital public infrastructure customized for agriculture
Post-harvest structural support	Policy support and sustainable infrastructures to reduce food waste and food loss, including low-impact transportation, storage and cold-storage facilities, food banks, digital connectivity and information technology
	Value addition, involving innovation and accessibility of processing technologies and equipment, and enhanced marketing pathways, including, e.g., price premiums, coordinated marketing campaigns, and harmonisation with (sub-)national trading policies
Ecological buffers and corridors	Support science and practice of creating agroforestry models in farm-fringe areas that support ecologically functional corridors for wildlife to migrate and persist in mosaic landscapes
	Policy support to build non-negotiable transition buffers between agriculture and natural ecosystems through direct payments and payments for ecosystem services
Landscape-scale planning	Devise context-specific policy recommendations, sensitive to (agro-)ecological zones and socioecological settings
	Integrate biodiversity concerns into Gram Panchayat Development Plans (village-level administrative units) within regional scales of implementation, and spatial prioritisation to minimise trade-offs between food production and biodiversity conservation

DeFries et al., 2017). They require strong institutions, and we believe that the capacity in Andhra Pradesh to conduct detailed valuations of incremental changes in ecosystem services and biodiversity needs to be improved in order for these policy instruments to be effectively employed. Nonetheless, tools for evaluating ecosystem services (such as the TEEBAgriFood Evaluation Framework and TESSA - Toolkit for Ecosystem Services Site-based Assessment) are now widely accessible and relatively easy to implement, and technological advances in biodiversity monitoring hold promise (Besson et al., 2022).

PES and certification schemes themselves must be designed in a manner that does not reinforce existing power asymmetries and injustices. For example, farmers with small landholdings and/or without formalized tenure arrangements should not be excluded. Furthermore, small-scale enterprises, cooperatives, and grassroots community organisations (including Farmer Producer Organisations) play a central role in supporting farmers and in implementing PES schemes. They should thus be supported financially and via capacity building. Conversely, the disproportional political-economic power of agribusinesses creates lock-ins of current unsustainable conditions and must be dismantled.

4.2 Risk reduction and insurance

Andhra Pradesh's food systems are susceptible to numerous interacting shocks and stressors, and diversification along the entire value chain is important to improve their ecological, social, and economic resilience.

Global climatic changes are increasing the susceptibility, coverage, frequency, and severity of environmental hazards to food production. Climate change is likely to substantially alter land suitability for agriculture in the future, where currently productive areas might fail to produce enough food in the future (Jia et al., 2019). It is already having adverse effects on agriculture in Andhra Pradesh (Rao et al., 2017; Mishra and Aadhar, 2021), and numerous districts in the state are highly vulnerable to increasing temperatures, changes in rainfall patterns, and increased occurrence of extreme weather events (Rao et al., 2017). ZBNF and other diversification approaches likely reduce climate change vulnerability, however, a holistic approach for resilience and risk reduction is needed, ideally harmonised at the national level. While 80% of farms already have some form of insurance in India (GIZ, 2021), the system is beset with several problems and necessitates reforming (Mahul et al., 2012; Gulati et al., 2018). As a first step, cross-sectoral meetings convened by the public policy think-tank NITI Aayog, government ministries (Ministry of Agriculture and Farmers' Welfare, Ministry of Environment, Forest and Climate Change, and Ministry of Earth Sciences), the statutory insurance body (Insurance Regulatory and Development Authority), state governments, and other key stakeholders, such as insurance companies, will be key to developing a policy framework and operational guidelines for insurance schemes.

Adopting agroecological and biodiversity-friendly practices can pose a risk to farmers, with benefits frequently only materialising a few years post intervention and productivity outcomes being highly context-dependent (Tamburini et al., 2020; Rasmussen et al., 2024). The risk of transitional dynamics and unwanted outcomes due to context-dependency should not be borne by the farmers. RySS has conducted experiments on their own fields (Bharucha et al., 2020; Duddigan et al., 2023) and encourages farmers to initially adopt ZBNF on only part of their land, however, landholdings are small and many biophysical processes that drive yield benefits operate at larger scales (Ghazoul et al., 2009; Edwards and Laurance, 2012; Tscharntke et al., 2014). Thus, a more comprehensive de-risking framework, where farmers are compensated for yield losses in the early years, is needed. Social safety nets and household income diversification may additionally improve rural households' food security (Hertel et al., 2023).

Concentration of power in supply chains, including trade, and volatile market prices pose a threat to economic resilience (Naylor and Falcon, 2010). In general, purchase programmes and price guarantee policies hold promise, but given that each supply chain has unique characteristics, solutions must be locally-grounded, and commodity-specific.

4.3 Post-harvest support

At present, ZBNF produce does not universally fetch premium prices. There are some localised NGO-led efforts to create ZBNF-specific markets (e.g., by the Centre for Sustainable Agriculture, Jattu Trust, and Rainforest Alliance), but coordinated government and business support is urgently needed for this to scale at the state-level and to create a ZBNF brand value. Value-addition through processing would likely enhance ZBNF farmers' (and farmers employing other biodiversity-friendly practices) access to competitive regional and national markets. Tilting inter-state trade agreements in favour of ZBNF farmers will also be crucial, as will improved transparency in supply chains.

Furthermore, physical infrastructure needs to be improved to facilitate ZBNF farmers' access to markets, and, more fundamentally, to reduce post-harvest crop losses. Similarly, demand-side interventions tackling food waste will be critical since food losses as a whole represent a substantial sustainability challenge in Andhra Pradesh (Jha et al., 2015; Agarwal et al., 2021). However, devising evidence-based policies is hampered by a limited research base on the effectiveness of different interventions in India (Agarwal et al., 2021). A better understanding of the demographic and sociopolitical factors shaping food consumption is needed (Pandey et al., 2020) in order to identify crucial levers to reduce food waste and to transition to sustainable diets more broadly.

4.4 Ecological buffers and corridors

Agroforestry is regarded as a pivotal climate mitigation and adaptation strategy with positive livelihood outcomes that can also reduce deforestation (Teo et al., 2025). However, farmland and agroforestry trees are rapidly disappearing across India, including in Andhra Pradesh (Brandt et al., 2024; Supplementary Figure 1d). Reducing structural differences and increasing resource similarity between natural ecosystems and adjacent agricultural landscapes can increase species' effective area of habitat, ecological connectivity, and population sizes (Kremen and Merenlender, 2018; Fletcher et al., 2024). Agroforestry may be one strategy to deliver this in certain contexts (Ferreira et al., 2020), i.e., in regions that would be naturally tree-dense rather than grassland-dominated. Other strategies may include setting parcels of land aside for ecosystem restoration, but any such efforts must be community-led and extreme care must be taken to ensure that they do not result in land dispossession and are ecologically appropriate.

Conservation models focussed on private lands are in their infancy in India compared to other nations (Drescher and Brenner, 2018; Mariyam et al., 2021). However, OECMs ("other effective area-based conservation measures") being critical to meeting India's area-based conservation targets in line with GBF (Sengupta et al., 2024) represents an opportunity to up-scale private land conservation models (surrounding and connecting protected areas). To reduce conflict and transfer conservation benefits to local communities, innovative land system policies and incentive schemes are needed (Anand et al., 2010; Karanth and Karanth, 2012; Ghosh-Harihar et al., 2019). These must be co-designed with land-owners and managers to be effective, as the willingness to participate in such schemes varies by socioeconomic group (Mariyam et al., 2021).

4.5 Landscape-scale planning

Landscape-level zonation and prioritisation exercises can be useful tools for guiding land management and policymaking by highlighting the relative importance of different areas towards meeting biodiversity, ecosystem service, food security, human well-being, and other land system goals. However, priority mapping, especially at the global scale, has received ample criticism, both on ecological and equity grounds (Wyborn and Evans, 2021; Fleischman et al., 2022; Schultz et al., 2022). Nonetheless, we believe that priority maps for Andhra Pradesh would represent valuable, structured decision-support frameworks that can help identify where synergies as well as trade-offs between different land system objectives are likely to be particularly pronounced. A comparison to national priority maps may further guide activities in Andhra Pradesh (see Srivathsa et al., 2023). However, these maps must be locally-grounded, incorporating fine-scale (field) data, and involving organisations that represent farmers and other land managers in the process.

Building on these maps, context-specific policies should be devised that are harmonised at the state-level and are aligned with national strategies. At present, different institutions and government departments operate in silos, and local and decentralised forms of governance are not well-integrated (Bharucha et al., 2020). The public sector agricultural extension services, particularly those supported by the Andhra Pradesh Department of Agriculture, ensure continuity and convergence in programmes and facilitate adaptive governance (Singh and Burman, 2019; Raina et al., 2022). Thus, they must thus be strengthened. Furthermore, the footprint of individual conservation interventions is small, and in order for these to scale, greater collaboration in integration of programmes is needed between conservation organisations.

Landscape-scale policymaking and planning must be sensitive to the context-dependency of the effectiveness of agricultural and conservation interventions. For example, ZBNF's impact on agricultural yields appears to depend on the crop type, biophysical conditions, completeness of adoption, and the counterfactual farming system it aims to replace (Bharucha et al., 2020; Duddigan et al., 2023; GIST Impact Report, 2023; Duddigan et al., 2024; but see Berger et al., 2024). Furthermore, the impact of interventions frequently exceeds the direct local land footprint, with both positive and negative spillover effects being common. Thus, interventions are less likely to have unwanted outcomes and land-use planning is more effective when measured or conducted across scales, including at larger (e.g., state-wide) scales that can capture more complex land use dynamics (Meyfroidt et al., 2022; zu Ermgassen et al., 2024).

To transition to the shared vision through transformative, multi-scalar policy change, we considered the types of governance needed and how policy enforcement could be equitable and inclusive. We agreed on a widely shared notion of policy choices, action items, and the problems associated with ineffective governance, and we consequently suggest five policy actions (Table 2), under the governance and actors framing of environmental governance (Ostrom, 1999). Simply put they are: support farmers; incentivize reduction in agrichemical use; engage with industry and economy; promote investment in biodiversity-friendly farming; and promote interdisciplinary science and innovation. Each of these priorities together aids in a transition from the current high-agrichemical use to sustainable food production systems through environmental governance strategies that are a mix of regulatory, market and agent-focused instruments, community-based, and hybrid governance.

5 Key knowledge-gaps

Overall, we put forward 20 knowledge-gaps related to food systems (Supplementary Table 2), and 13 related to biodiversity conservation (Supplementary Table 3). The following ten, presented in rank order within each of the two categories, were voted to be of utmost priority to be addressed. Other knowledge needs include disentangling the gap between the outcomes of field-plot experiments versus real farm performance, identifying pathways to overcome the loss of consumer knowledge about regionally appropriate diets, and determining the impacts of invasive species.

5.1 Knowledge-gaps related to food system sustainability

5.1.1 Efficacy of agroecological farming to meet food demand

In response to concerns that agroecological approaches could have negative percussions on agricultural productivity, an increasingly large body of research is focussed on identifying if and how yields can be enhanced via better support for ecosystem services and minimising ecosystem disservices (Bommarco et al., 2013; Garnett et al., 2013; Seppelt et al., 2020). Whilst numerous agroecological interventions can have positive effects on crop yields and environmental and social outcomes, there is a high degree of context-dependency (Garbach et al., 2017; Kremen, 2020; Tamburini et al., 2020; Beillouin et al., 2021; Zemp et al., 2023; Rasmussen et al., 2024), highlighting the need for developing situated knowledge. There is now substantial evidence that ZBNF can maintain or potentially even improve crop yields in comparison to agrichemical-based farming in Andhra Pradesh (Bharucha et al., 2020; Duddigan et al., 2023; GIST Impact Report, 2023; Duddigan et al., 2024; Berger et al., 2024). However, these findings may not hold in other socio-ecologies (Koner and Laha, 2021) and/or over the long-term (Smith et al., 2020), and a far better understanding of the mechanisms by which ZBNF affects agroecosystem functioning and agricultural productivity is needed. Overall, our grasp of the impact of agroecological interventions on

TABLE 2 Proposed policy and governance strategies.

Policy action	Governance strategy
Support farmers with subsidies and low-cost inputs	Decentralization (strengthening of Panchayats), Community rights, Commoning and Collective Action
Incentivize reduction in agrichemical use	Market and Agent Focused Instruments, Regulatory, Hybrid: Private-Social Partnerships
Engage with industry and economy	Hybrid: Public-Private Partnerships
Promote investment in biodiversity-friendly farming	Regulatory; Hybrid: Co-management; Certification
Promote interdisciplinary science and innovation	Regulatory; Hybrid: Public-Private Partnerships; Co-management
Examples	
Andhra Pradesh State Action Plan for Climate Change	Hybrid: Farmers, Civil Society Groups, Government, NGOs.
Andhra Pradesh Biological Diversity Act (BDA) 2002	Decentralization, Community Groups
Strengthening JFMC (Joint Forest Management Committees) and Biodiversity Management Committees (BMCs).	Decentralization, Commoning, Co-production; Hybrid partnerships among Communities, Forest Department, NGOs.

yield and wider social and environmental outcomes in heterogenous settings is still in its infancy.

5.1.2 Evidence for scaling of sustainable food production systems

A few studies have compared the pathways of ZBNF adoption in Andhra Pradesh to that in other states, with the latter being initiated by communities and grassroots organisations (i.e., bottom-up) and the former being state government driven (i.e., top-down), albeit in partnership with numerous NGOs and women's self-help groups (Khadse et al., 2018; Münster, 2018; Khadse and Rosset, 2019; Bharucha et al., 2020; Veluguri et al., 2021). Government institutionalisation has been central to the large-scale adoption of ZBNF in Andhra Pradesh (Veluguri et al., 2021), however, this could imply some structural dependencies (Mier y Terán Giménez Cacho et al., 2018) and recent delays in payments to agricultural extension officers have highlighted the need for greater financial sustainability. Others have criticised the ZBNF programme for a lack of transparency, inconsistent implementation, and that ZBNF has not been as widely or rapidly adopted as intended (Saldanha, 2018; Rathore, 2019). Thus, further investigations of the pathway of ZBNF adoption in Andhra Pradesh are needed, as well as insights into how ZBNF could, or should, scale across India and other countries. This includes assessments of whether emerging carbon and biodiversity markets could represent a new sustainable financing avenue for ZBNF (embracing that both markets necessitate extremely strict regulation; Swinfield et al., 2024; Wauchope et al., 2024).

More generally, we need a far better understanding of the motivations for uptake and pathways for scaling in different socio-ecological contexts. A plethora of interacting factors affect the uptake of agroecological practices, including environmental change, market access and demand, new circumstances (e.g., irrigation support and knowledge access), and farmers psychosocial characteristics (Jacobi et al., 2020). However, to understand and foster adoption at scale, a multi-level transitions perspective, sensitive to the interplay of technical, cultural, policy and market forces, is needed (Moberg et al., 2021). Numerous key drivers for the process of taking agroecological practices to scale have been identified (Mier y Terán Giménez Cacho et al., 2018; Nicholls and Altieri, 2018), however, scaling is a highly context-dependent process, highlighting the importance of locally-grounded studies (Ferguson et al., 2019). Overall, existing regimes only allow for incremental changes, but transformative change, entailing fundamental structural and paradigm shifts, is needed to bring sustainable agricultural systems to scale (Kanger et al., 2020; Pascual et al., 2022; Garrett et al., 2024). However, we need a far better understanding of the efficacy of different transition pathways and relevant policy intervention points in Andhra Pradesh and elsewhere in India.

5.1.3 Loss of knowledge about processing traditional and indigenous foods

Numerous studies have examined the effect of dietary transitions on natural resource use and nutritional outcomes for people in India, generally highlighting the importance of shifting current consumption patterns, especially of refined wheat, rice and sugar, towards higher intakes of fruit, vegetables and nuts (Milner et al., 2017; Rao et al., 2018; Ritchie et al., 2018; Springmann et al., 2018; Davis et al., 2019; Damerau et al., 2020; Chaudhary and Krishna, 2021; Paul and Paul, 2023). The Green Revolution has led to the reduced production of many of these crops as well as the disappearance or underutilisation of indigenous crops and crop varieties, with the loss of associated knowledge of cultivation, processing, and preservation (Eliazer Nelson et al., 2019). Community-driven as well as state-led strategies to preserve seeds and foster bio-cultural heritage have emerged in Andhra Pradesh (Duthie-Kannikkatt et al., 2019; Kumar, 2023). However, we lack knowledge of how this can be effectively scaled, and how key inhibitors can best be overcome (Ghosh-Jerath et al., 2021).

5.1.4 Traceability of sustainable food sources

Globally, there have been ample supply chain transparency initiatives with the aim of rebalancing entrenched information asymmetries along the food system and demasking unsustainable production practices (Zyglidopoulos and Fleming, 2011; Mol, 2015; Gardner et al., 2019). Transparency pertains to which information is made apparent and accessible to certain actors (Gardner et al., 2019), and government interventions can help increase it (Lambin et al., 2014). There are general principles for developing well-designed transparency systems that have a positive transformative impact on interventions aimed to improve sustainability outcomes (see Gardner et al., 2019). However, transparency systems must be highly context-sensitive to be effective, and it is currently not known what this would look like in Andhra Pradesh. At present, the tracing of ZBNF produce, and other sustainably produced foods, is largely not possible. Fundamentally, with no separate markets for ZBNF produce, food items produced under ZBNF principles and those produced through agrichemical-farming are indistinguishable to the consumer.

5.1.5 Pesticide content of different foods

Chronic dietary exposure to pesticide residues can have negative health implications, with it being linked to a broad spectrum of medical problems such as cancer, neurotoxic effects, reproductive health concerns and endocrine disruption (Mnif et al., 2011; Costas et al., 2015; Nicolopoulou-Stamati et al., 2016; Petrakis et al., 2017). In Andhra Pradesh and elsewhere in India, relatively little is known about the pesticide content of different foods and consequently transfer of pesticides to the human diet (Soman et al., 2024), hindering consumers from making informed choices and decision-makers in devising policies with positive human health outcomes.

5.2 Knowledge-gaps related to biodiversity

5.2.1 Long-term, large-scale, and species-specific data are lacking

Land-use maps can be used to identity fundamental land-use sustainability challenges and track land-use dynamics over time, such as the expansion of cropland into natural ecosystems (including protected areas) and the disappearance of farmland trees (Baumann et al., 2022; Pendrill et al., 2022; Meng et al., 2023; Brandt et al., 2024). However, there are still prevailing spatial and temporal gaps in land-use data, especially for those features that cannot be directly mapped from satellites. For example, maps of agricultural intensity and the distribution of different crop types has remained partial and coarse (Newbold et al., 2015; Dullinger et al., 2021; Kuemmerle, 2024). The lack of reliable, time-series land-use data in Andhra Pradesh poses a challenge to mapping conservation targets and their threats, and for conservation and agricultural planning.

Furthermore, such maps are simple representations of land systems that do not capture the diversity of land-use actors and practices, where threats and benefits for biodiversity might easily be missed (Kuemmerle, 2024). Notably, data on biodiversity trends over time, in particular involving species-level density estimates (Balmford, 2021), are needed to ascertain how to limit (agriculture-driven) biodiversity loss in Andhra Pradesh. The advent of the revolution in biodiversity monitoring technologies represents an opportunity for coordinated monitoring efforts across Andhra Pradesh, including of taxa that are chronically underrepresented. However, these monitoring efforts must be specifically designed such that they can answer key conservation questions, including all other knowledge-gaps we outline here.

5.2.2 Trade-offs between biodiversity conservation and food production

Trade-offs between different land system objectives, including between food production and biodiversity, are the norm rather than the exception (Meyfroidt et al., 2022). Nonetheless, numerous strategies, from the field to the landscape-scale, have been shown to be effective at ameliorating trade-offs (Tamburini et al., 2020; Beillouin et al., 2021; Ricciardi et al., 2021; Wurz et al., 2022; Zemp et al., 2023). Notably, a recent study has shown that ZBNF is effective at reducing, and occasionally even neutralising, trade-offs between biodiversity outcomes and agricultural productivity and economic profit in northern Andhra Pradesh (Berger et al., 2024). However, such relationships, and thus the effectiveness of policies building on these, are likely to be highly context-dependent, and thus a step-change in the number of studies taking a similar approach is needed. We need a far greater understanding of what landscapes that minimise agriculture-biodiversity trade-offs look like in Andhra Pradesh and elsewhere in India. Approaches should employ causal inference techniques, link across scales, bridge bottom-up and top-down perspectives, and embrace the diversity of land-use actors and the factors influencing their behavior (Chaplin-Kramer et al., 2022; Kuemmerle, 2024).

5.2.3 Effectiveness of different conservation interventions

Interest in employing better methods for understanding causes and effects, and thus for assessing the effectiveness of interventions, has recently rapidly expanded in conservation science and practice (Jones and Shreedhar, 2024). Nonetheless, casual inference methods are still vastly underutilised, including at the food production-biodiversity conservation nexus. The positive impact of conservation programmes in Andhra Pradesh could likely be markedly enhanced if such methods were more commonly employed since, at present, our understanding of the effectiveness of different conservation interventions and policies, including those aimed at reducing human-wildlife conflict and those led by indigenous and local communities, is limited. Programmes must be designed with the aim of generating insights into cause and effect (Ferraro et al., 2023) which may be facilitated by greater collaborations between scientists, practitioners, and other actors. This extends to the ZBNF programme, where greater involvement by academics from the outset would have enabled a more rigorous study design to assess policy impact. Similarly, routine biodiversity monitoring programmes by the Andhra Pradesh Forest Department in protected areas and elsewhere should be streamlined for causal inference.

5.2.4 Incomplete data access and transparency

Biodiversity data are not only limited in Andhra Pradesh, but existing data and information on monitoring efforts are not always freely and easily accessible. Ensuring data accessibility and transparency is crucial for leveraging existing biodiversity information from government bodies (e.g., the Andhra Pradesh Biodiversity Board) and smaller data holders (e.g., research institutions and conservation NGOs). Improving access will facilitate the synthesis of available data and help identify critical gaps in knowledge about biodiversity in Andhra Pradesh's natural ecosystems and production landscapes.

5.2.5 Impacts of climate change on biodiversity and associated ecosystem services

Climate change is having an ever-increasing impact on biodiversity and ecosystem functions and services across India (Behera et al., 2019; Goswami et al., 2021; Srivathsa et al., 2023), exacerbating, often synergistically, other stressors including agricultural expansion and intensification (Ghosh-Harihar et al., 2019; Northrup et al., 2019; Hendershot et al., 2020; Outhwaite et al., 2022). In general, tropical species are more sensitive to climate change than temperate species (Deutsch et al., 2008; Perez et al., 2016; Newbold et al., 2020), and substantial negative repercussions for food security, through a decline in ecosystem service provisioning, are highly plausible (Mooney et al., 2009; Runting et al., 2017; Millard et al., 2023). However, it is largely unknown how future climate change is likely to impact biodiversity and associated ecosystem services in Andhra Pradesh.

Climate change-sensitive landscape planning and conservation management (that accounts for species range shifts, novel species assemblages, and evolutionary adaptations) can dampen some of the negative climate impacts (Heller and Zavaleta, 2009), where improving the quality and permeability of agricultural landscapes and retaining and restoring natural ecosystems are key (Littlefield et al., 2017; Northrup et al., 2019; Hendershot et al., 2020; Fletcher et al., 2024). However, it is uncertain what this would look like in Andhra Pradesh, and thus, detailed, multi-scalar studies addressing this are urgently needed.

6 Conclusion

Our study provided unique insights into how a diverse group of key stakeholders and actors envisions the reconciliation of food and biodiversity objectives in Andhra Pradesh. Despite the state-led ZBNF programme, the food system in Andhra Pradesh is currently largely unsustainable and inequitable, and biodiversity conservation efforts are inadequate in scale and ambition. Numerous knowledge-gaps remain, from fundamental science to the policy level. This includes incomplete knowledge of the multidimensional performance of agroecological systems, effectiveness of different conservation interventions, and how different land system objectives trade off against each other in varied contexts. Key barriers include the limited alignment of efforts across policy domains, institutions, and geographic scales, and there is a clear need to establish a science-policy-practitioner interface to facilitate data-and knowledge-sharing. We stress that the roll-out of ZBNF needs to be better aligned with state-level conservation strategies in order for biodiversity benefits to fully materialise. Notably, India has recently ratified the targets of the GBF (National Biodiversity Plan NBSAP, 2024), thus representing an impetus for Andhra Pradesh to update its biodiversity and agricultural strategies in line with national commitments. We stress the importance for integrated, adaptive planning, management and governance of food production and biodiversity in Andhra Pradesh and elsewhere.

Data availability statement

The original contributions presented in the study are included in the Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

IB: Validation, Resources, Funding acquisition, Writing – review & editing, Formal analysis, Methodology, Data curation, Writing – original draft, Investigation, Project administration, Conceptualization, Visualization. MB: Writing – review & editing, Writing – original draft. RB: Writing – original draft, Writing – review & editing, Project administration. AbC: Writing – original draft, Writing – review & editing. GM: Writing – review & editing, Writing – original draft. TN: Project administration, Writing – original draft, Writing – review & editing. ER: Writing – original draft, Writing – review & editing. RR: Writing – review & editing, Writing – original draft. VR: Writing – review & editing, Writing – original draft. ViS: Writing – review & editing, Writing – original draft. VaS: Writing – original draft, Writing – review & editing. AH: Project administration, Writing – review & editing. PB: Writing – review & editing, Supervision. BB: Writing – review & editing. CB: Writing – review & editing. ArC: Writing – review & editing. RD: Writing – review & editing. IE: Writing – review & editing. RG: Writing – review & editing. ViP: Writing – review & editing. BP: Writing – review & editing. VaP: Writing – review & editing. NR: Writing – review & editing. MR: Writing – review & editing. IS: Writing – review & editing. SV: Writing – review & editing. FT: Writing – review & editing. SU: Project administration, Writing – review & editing. TV: Writing – review & editing. LD: Funding acquisition, Conceptualization, Supervision, Methodology, Project administration, Validation, Writing – review & editing.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1594356/full#supplementary-material

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