Biological Conservation 284 (2023) 110165

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Perspective

Addressing agricultural labour issues is key to biodiversity-smart farming

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A R T I C L E I N F O

Keywords:
Biodiversity conservation
Agricultural development
Sustainability
Land-sharing
Trade-offs
Labour
Africa
Indonesia

A B S T R A C T

There is an urgent need for agricultural development strategies that reconcile agricultural production and biodiversity conservation. This is especially true in the Global South where population growth is rapid and much of the world's remaining biodiversity is located. Combining conceptual thoughts with empirical insights from case studies in Indonesia and Ethiopia, we argue that such strategies will have to pay more attention to agricultural labour dynamics. Farmers have a strong motivation to reduce the heavy toil associated with farming by adopting technologies that save labour but can negatively affect biodiversity. Labour constraints can also prevent farmers from adopting technologies that improve biodiversity but increase labour intensity. Without explicitly accounting for labour issues, conservation efforts can hardly be successful. We hence highlight the need for biodiversity-smart agriculture, that is farming practices or systems that reconcile biodiversity with land and labour productivity. Our empirical insights suggest that technological and institutional options to reconcile farmers' socio-economic goals and biodiversity conservation exist but that more needs to be done to implement such options at scale.

1. Introduction

Worldwide, biodiversity is declining faster than at any time in human history, with agriculture being considered one of the main causes (Laurance et al., 2014; Mehrabi et al., 2018; Pendrill et al., 2022; Sánchez-Bayo and Wyckhuys, 2019; Seibold et al., 2019). There is widespread evidence that trade-offs[1] between biodiversity conservation and agricultural development exist (e.g., Grass et al., 2020; McShane et al., 2011). Biodiversity loss occurs due to both agricultural expansion and intensification (e.g., Laurance et al., 2014; Zabel et al., 2019). Technology-driven productivity growth has curbed global agricultural land expansion (e.g., Villoria, 2019). However, agricultural intensification can undermine biodiversity on the farmland itself and in agricultural landscapes (e.g., Grass et al., 2021; Phalan et al., 2014). Moreover, there is increasing evidence on trade-offs between biodiversity conservation and human well-being arising from economic development (e.g., Henry et al., 2022; McShane et al., 2011; Mehrabi et al., 2018; Qaim et al., 2020). While there has been substantial research on trade-offs between agricultural land use and biodiversity, limited attention has been paid to trade-offs between agricultural labour and biodiversity, especially in regions where agricultural development competes with biodiversity conservation, as is true in much of the Global South today (Zabel et al., 2019). This is problematic because, next to land and capital, labour is a key factor of agricultural production, and strategies to increase labour productivity have far-reaching implications for the way agriculture is practiced.

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[1] "Trade-off" is a central concept in economics and other disciplines and implies that one goal can only be achieved at the expense of another goal. Trade-offs may involve active decisions or choices between alternatives, such as a farmer choosing between technologies that have different effects on labour and biodiversity. In this case, trade-offs occur when selecting one option over another. However, one can also define trade-offs more broadly as compromises that may not necessarily involve active decision-making by individuals. For example, societies (or farmers) may adopt technologies that increase labour productivity without considering impacts on biodiversity. This outcome is still considered a trade-off, even if there was no active and clear decision to prioritize labour productivity over biodiversity.

https://doi.org/10.1016/j.biocon.2023.110165
Received 28 February 2023; Received in revised form 10 May 2023; Accepted 10 June 2023
Available online 28 June 2023

Given the huge burden of labour on the daily life of the world's 550 million family farms (Lowder et al., 2021), addressing labour aspects is key for sustainable development. In developing countries, poverty is particularly widespread in rural areas and among farm households (World Bank, 2020), and poverty alleviation hinges on rising agricultural labour productivity as a key determinant of farmers' income (Fuglie et al., 2019). Labour productivity is low in many parts of the Global South, in particular in Africa (Fuglie et al., 2019), where around 80 % of farmland is cultivated manually (FAO and AUC, 2018). Agricultural labour is also linked to burdensome physical work, which can be detrimental to human health (Daum and Birner, 2021; Ogwuike et al., 2014). The labour burden will likely be exacerbated by climate change in tropical countries (Dasgupta et al., 2021). The need to allocate substantial amounts of time to manual agriculture can also lead to a neglect of food preparation, childcare and other household and schooling activities, affecting nutrition, education, and broader human development (Jackson and Palmer-Jones, 1999; Johnston et al., 2018). Seventy percent of child labour takes place in agriculture, affecting 112 million children globally (ILO, 2021). Furthermore, despite the common assumption that farm labour is abundant, labour shortages due to ageing rural populations, outmigration of (young) people, and structural transformation have become a significant barrier to agricultural development in parts of the Global South (e.g., Diao et al., 2020; Jansuwan and Zander, 2021; Ren et al., 2023; Silva et al., 2019). Hence, labour-saving agricultural innovations can be crucial for economic and social development in many situations.

Many technologies that reduce the burden of labour and increase labour productivity such as farm mechanization and herbicides can have downsides from an environmental perspective. They constitute threats to biodiversity, as further discussed below. Alleviating the labour constraints of current farming practices to enhance agricultural productivity and human welfare thus often comes at the expense of biodiversity in subtropical and tropical landscapes of the Global South, resulting in an important trade-off. In addition, practices that have the potential to contribute to biodiversity conservation on agricultural lands, such as intercropping and planting basins, are often more labour-intensive, which is an important obstacle to their adoption by farmers (Dahlin and Rusinamhodzi, 2019; Rusinamhodzi, 2015). In this paper, we therefore argue that more attention needs to be paid to the trade-offs between agricultural labour productivity and biodiversity conservation to identify agricultural development pathways that serve both people and nature. Based on existing literature, we develop a general conceptual framework of potential labour-biodiversity trade-offs, which we then use for the analysis of two case studies, one in Indonesia and the other in Ethiopia. Based on the conceptual and empirical insights, we also discuss technological and institutional options to reduce the trade-offs between agricultural labour productivity and biodiversity conservation. We establish the use of the term "biodiversity-smart agriculture" for farming practices or systems that reconcile biodiversity with land and labour productivity.

2. Conceptual considerations: trade-offs between agricultural labour and biodiversity

2.1. Pathways of labour-biodiversity trade-offs

Trade-offs between agricultural labour and biodiversity are conceptualized in Fig. 1. In this framework, agricultural labour is subject to the availability and costs of hired and family labour, including opportunity costs as well as physical burden and labour productivity considerations. For farmers who rely on hired labour, the availability and costs of labour strongly affect decision-making and technology use (e.g., Gallardo and Sauer, 2018; Hayami and Ruttan, 1970). Farmers who rely mostly on family labour do not typically place an explicit cost on their labour, but it is well established in the literature that time availability and the physical burden of labour nevertheless influence their decision making (e.g., Ellis, 1993; Moser and Barrett, 2006). In addition, the time that farmers allocate to agricultural activities has opportunity costs, which can be manifested in monetary or non-monetary terms. The concept of "opportunity costs" is an analytical tool that economists use to account for the fact that farmers consider – often implicitly – the benefits forgone when they allocate their time to one activity and not to another. Hence, opportunity costs of time must be considered when analyzing farmers' decision-making (e.g., Clayton, 1968; Ellis, 1993; Low, 1986; Moser and Barrett, 2006; White et al., 2005; Yujun et al., 2011). Smallholder farmers who pursue or could pursue non-farm income opportunities, which is increasingly the case in the Global South (Barrett et al., 2001; Dorward et al., 2009), typically have a good understanding of the potential income they lose during the time they spend on agricultural activities. This is also why labour-saving farming technologies are rapidly adopted in such situations while labour-intensive technologies are often not (Feike et al., 2012; Lee, 2005; Ruml and Qaim, 2021). Even where non-farm opportunities are limited, farmers typically still weigh the costs and benefits of different time use activities, such as agricultural work versus domestic or care work, leisure time, and – in case of children and adolescents - time to study and attend school (e.g., Daum et al., 2021; Johnston et al., 2018; Moser and Barrett, 2006). Nevertheless, while agricultural labour considerations play a key role in the decision-making of farmers, increasing agricultural productivity and reducing agricultural labour are certainly not the only goals that farmers pursue. Other socioeconomic and cultural factors also matter, and farming can also be a way of life (Wezel et al., 2020). Moreover, labour shortages can be mitigated not only by changing agricultural practices and technology, but also by other mechanisms, such as using informal exchange of labour (e.g., Tshotsho et al., 2023).

In agricultural landscapes, biodiversity consists of the planned biodiversity (crops/livestock) as well as the associated biodiversity of croplands and rangelands (e.g., weeds, pests and their natural enemies). Moreover, most agricultural landscapes of the Global South retain wild biodiversity, including wildlife and natural habitats. Biodiversity conservation has sometimes been criticized as a "top-down" approach driven by outsiders (Abrams et al., 2009). However, while smallholder farmers may not explicitly prioritize biodiversity conservation as a farming objective, preserving the local environment has often been a key goal of farming communities in the Global South (e.g., Abrams et al., 2009; Ostrom, 1990). Biodiversity can play a crucial role in supporting the productivity and resilience of farming systems by providing ecosystem services such as pollination, soil formation, nutrient cycling, climate regulation, maintenance of water supplies, and pest and disease control (Bélanger and Pilling, 2019; Bommarco et al., 2013; Renard and Tilman, 2021). Nevertheless, farmers may perceive and value different types of biodiversity differently, with some types seen as having little usefulness and potentially receiving lower motivation to conserve, in particular when undermining the opportunities for agricultural development (e.g., agricultural weeds, wildlife harming crops) whereas other types (e.g., insect pollinators, natural enemies of crop pests) being highly valued due to their usefulness for farming (e.g., Bardsley et al., 2019; Farmar-Bowers and Lane, 2009; Melvani et al., 2022). Even where farmers value biodiversity, this may not ensure its protection, particularly when collective action problems undermine conservation efforts. It is important to note that farmers' views may not necessarily reflect the actual utility of biodiversity for agriculture at the landscape or global level.

In this paper, we focus on two trade-off pathways, whose magnitudes depend on a range of socio-economic and agro-ecological factors. In the

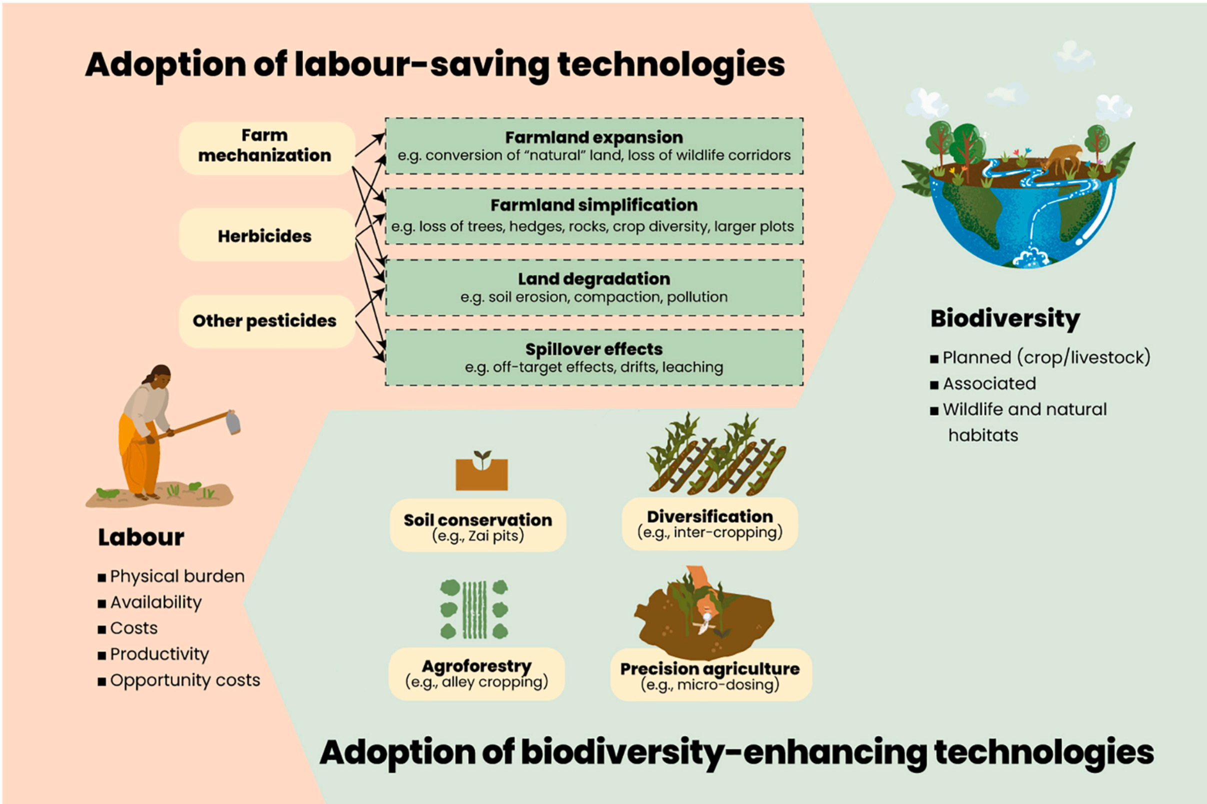

Fig. 1. Potential trade-offs between agricultural labour use and biodiversity conservation. The pink (top) pathway shows biodiversity trade-offs resulting from the adoption of labour-saving technologies. The green (bottom) pathway shows the labour trade-offs associated with the adoption of biodiversity-enhancing technologies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

first pathway, labour constraints trigger the adoption of labour-saving technologies, which can have negative effects on biodiversity (see Fig. 1).[2] In the second pathway, biodiversity-enhancing technologies can have negative effects on labour or are not adopted because of labour constraints (see Fig. 1).

Labour-saving technologies, such as mechanization and the use of herbicides and other pesticides, such as insecticides, are on the rise across the Global South (Daum, 2023; Diao et al., 2020; Gallardo and Sauer, 2018; FAO and AUC, 2018; Haggblade et al., 2017a; Tamru et al., 2017). Such technologies can greatly reduce the labour burden of farming (see also Table 1). One study conducted in Zambia showed that farming families who use tractors for land preparation used an average of 640 labour hours per ha per season in maize production, while non-mechanized families used more than 1100 labour hours (Adu-Baffour et al., 2019; see Fig. 2). Tractor use was associated with less unpaid family work from men, women, boys, and girls within the household (Adu-Baffour et al., 2019). In a cross-country study in Asia and Africa, Vos and Takeshima (2021) found that agricultural mechanization can significantly reduce child labour. Pesticides such as herbicides can also help to reduce labour burden (see also Table 1). For example, Haggblade et al. (2017b) find that herbicides reduce labour demand from 12 days per hectare, including 2 child days, to 1–2 days per hectare in total. Moseley and Pessereau (2022), in a study in Burkina Faso, describe a rapid increase of herbicides over the last years, which were referred to by female farmers as "mothers' little helpers". Fig. S1 in the appendix highlights the high labour burden associated with manual weeding in four African countries.

While appealing to farmers, labour-saving technologies can negatively affect biodiversity through farmland expansion, farmland simplification, land degradation, and spillover effects (Fig. 1). The adoption of labour-saving technologies can help farmers to address labour bottlenecks, providing an incentive to cultivate more land, which can lead to the conversion of biodiversity-rich rainforests and savanna (Adu-Baffour et al., 2019; Baudron et al., 2022; Chrisendo et al., 2021; Daum et al., 2020).[3] Conversely, mechanization, herbicides, and other pesticides may also help to limit farmland expansion by safeguarding or increasing yields in situations where labour bottlenecks hinder timely and optimal crop management (e.g., Silva et al., 2019). Farm mechanization is also often associated with farmland simplification. In many countries in the Global North, the rise of tractors and other big machinery has led to larger and more rectangular fields and the removal of farm trees and hedgerows, all of which is associated with lower biodiversity (e.g., Batáry et al., 2017; Fahrig et al., 2015; Macdonald and Johnson, 2000; Robinson and Sutherland, 2002). The same is now happening in parts of the Global South. Studies show that mechanization can lead to a removal of on-farm trees and hedges and the enlargement and re-shaping of plots to facilitate the use of tractors, leading to a loss of farm diversity and landscape mosaics (Daum et al., 2020; de Oliveira et al., 2017; Kansanga et al., 2020). Farm mechanization, herbicides, and other pesticides can be associated with land degradation, affecting

[2] Both historical and contemporary studies from different world regions show that labour constraints are the primary driver of labour-saving technologies such as agricultural mechanization and pesticides but other factors such as farming system evolution, market demand, technology costs, rural infrastructure, and policies also play a role (Binswanger, 1986; Daum, 2023; Diao et al., 2020; Gallardo and Sauer, 2018; Haggblade et al., 2017; Hayami and Ruttan, 1970).

[3] Similarly, farmers may shift to crops with lower labour intensity, such as palm oil, which can result in land expansion (e.g., Chrisendo et al., 2021).

Table 1
Labour and yield effects of labour-saving and biodiversity-enhancing agricultural technologies.

Types of technologies			Labour effects				Yield effects	Crops; country	Study
			Before (h/ha)	After (h/ha)	Change	Comments			
Labour-saving technologies	Agricultural mechanization	Land preparation	226	10	−96 %	Tractors versus manual; from 1133 to 645 h/ha (−45 %) overall labour use	Positive	Maize; Zambia	Adu-Baffour et al. (2019)
			500	60	−88 %	Draught power versus manual labour	N/A	Mix; cross-country	Sims and Kienzle (2016)
			N/A	N/A	−75 %	Draught power versus manual labour	N/A	Mix; cross-country	Pingali et al. (1987)
			776 (overall)	368 (overall)	−55 %	Tractors versus draught power and/or manual labour	Neutral	Mix, Ethiopia	Berhane et al. (2020)
			184	112	−38 %	Tractors versus manual labour[a]	Neutral	Mix, Ghana	Cossar (2019)
		Sowing	64	3	−95 %	Tractors versus manual labour	Positive	Sorghum, Mali	Aune et al. (2019)
		Land preparation and sowing	47 (112)	10 (10)	−79 % (−91 %)	Two wheeled tractors and conservation agriculture versus draught power and manual labour	Positive	Maize, Zimbabwe	Baudron et al. (2019c)
		Weeding	157	34	−78 %	Draught animals versus manual labour	Neutral	Sorghum, Uganda	Barton et al. (2002)
			184	47	−63 %	Tractors versus manual labour	Positive	Sorghum, Mali	Aune et al. (2019)
		Harvesting	624 (overall)	400 (overall)	−36 %	Combine harvesters versus manual labour	Positive	Wheat, Ethiopia	Berhane et al. (2020)
	Pesticides	Herbicides	96	8–16	−83–91 %	Knapsack spraying versus manual weeding	Positive or neutral	Mix, Mali	Haggblade et al. (2017b)
			N/A	N/A	−65 %	Knapsack spraying versus manual weeding (hired)	N/A	Mix, Malawi	Bouwman et al. (2021)
			N/A	N/A	−60 %	Knapsack spraying versus manual weeding (hired)	N/A	Sorghum, Nigeria	Ogungbile and Lagoke (1989)
			N/A	N/A	−51 %	Measured in value (Ethiopian birr) of weeding labour per hectare; compared to non-adopters	N/A	Mix, Ethiopia	Tamru et al. (2017)
	Agricultural mechanization and pesticides	Mechanized land preparation, chemical fertilizers, pesticides	1568 (overall)	432 (overall)	−72 %	Modern production package versus traditional production package (manual labour, no chemical inputs)	Positive	Rice, Côte d'Ivoire	Aihounton and Christiaensen (2023)
Biodiversity-enhancing technologies	Soil conservation	Zaï farming practices / basins	N/A	N/A	+702 %	Compared to manual tillage; +35 % for weeding	Mixed	Mix, cross country	Dahlin and Rusinamhodzi (2019)
			312 (overall)	680 (overall)	+118 %	Compared to manual tillage	Mixed	Maize, Zimbabwe	Nyamangara et al. (2014)
			104 (sorghum); 136 (millet)	256 (sorghum); 408 (millet)	+147 (sorghum)+200 % (millet)	Compared to manual tillage; reduction in overall labour	Positive	Sorghum, millet, Burkina Faso	Schuler et al. (2016)
		Integrated soil fertility management	472–776 (overall)	568–888 (overall)	+15–20 %	Compared to non-adoption of ISFM core components	N/A	Maize, wheat and teff, Ethiopia	Hörner and Wollni (2021)
	Diversification	Intercropping	141	146–211	+36 %	Weeding labour use	Positive	Maize, cowpea, Mozambique	Rusinamhodzi et al. (2012)
			322 (overall)	375 (overall)	+16 %	Conservation agriculture maize versus conservation agriculture maize-pigeon pea intercrop	Positive	Maize, pigeon pea, Malawi	Ngwira et al. (2012)
			N/A	N/A	+4 %	Weeding labour use	Mixed	Mix, cross country	Dahlin and Rusinamhodzi (2019)
	Agroforestry	Alley cropping	492 (overall)	751 (overall)	+53 %		Positive	Maize, Nigeria	Ngambeki (1985)
	Precision Agriculture	Microdosing	18	38	+108 %	Fertilizer application; compared to broadcasting	Positive	Sorghum, Sudan	Arbab and Dagash (2017)

Notes: Some studies reported labour days instead of hours. These were converted assuming 1 day = 8 h unless otherwise stated.
[a] Changes significant with Ordinary Least Square (OLS) but not Instrumental Variable approach.

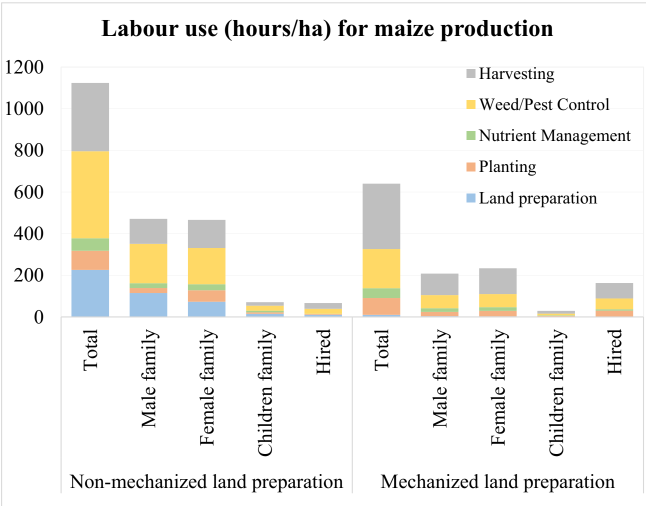

Fig. 2. Labour effects associated with mechanized land preparation in Zambia. Sample size: 121 mechanized and 129 non-mechanized farmers. Based on data from Adu-Baffour et al. (2019). Note: Mechanized land preparation also reduces labour use for weed/pest control as weeds are suppressed more efficiently with mechanized land preparation.

biodiversity on farmers' fields and in natural ecosystems downwind and downstream. For example, mechanized tillage can affect soil health and life, in particular, if not carried out according to good agricultural practices (Lal, 1984; Labiadh et al., 2013; Sims and Kienzle, 2017). The use of herbicides can affect insect populations, soil biota, groundwater, lakes, and rivers, in particular when management practices are poor (e. g., Mesnage and Zaller, 2021). Hence, labour-saving innovations are associated with certain risks for biodiversity conservation, although it is important to point out that such effects depend on various factors such as accompanying practices and policies, as further discussed below, and that not all labour-saving innovations negatively affect biodiversity.

The framework in Fig. 1 also shows that biodiversity-enhancing technologies are often not adopted by farmers because they have a high labour burden or lead to negative effects on human labour when adopted (Dahlin and Rusinamhodzi, 2019). Examples include cut and carry, green manure, integrated soil fertility management, crop diversity, intercropping, planting basins, and alley cropping (Dahlin and Rusinamhodzi, 2019; Grabowski and Kerr, 2014; Feike et al., 2012; Hoekstra, 1987; Hörner and Wollni, 2021; Nyamangara et al., 2014; Rusinamhodzi, 2015; Schuler et al., 2016). Such an increased labour burden can be particularly pronounced for women (e.g., Farnworth et al., 2016). Table 1 reviews the labour effects of some biodiversity-enhancing technologies.

2.2. *From labour-biodiversity trade-offs to synergies*

Labour considerations influence the adoption of farm technologies and hence the degree to which farming systems affect different biodiversity outcomes. Fig. 3 conceptualizes the trade-offs between labour and biodiversity in a three-dimensional matrix, showing that there can be both trade-offs and synergies. The matrix has four quadrants: low labour / low biodiversity, high labour / low biodiversity, high labour / high biodiversity, and low labour / high biodiversity. Of these four quadrants, only the last one is associated with low trade-offs, resulting in both positive social and environmental outcomes.

Fig. 3 also displays a third dimension: agricultural yields. The height of the columns in Fig. 3 illustrates the yield levels of different practices displayed in the matrix. Agricultural yields are a key dimension in the optimization matrix. Yields are not only important for farmers' income but also to produce food for the growing population. Moreover, the lower the yields, the larger the area required to meet any production target, which involves trade-offs with wild biodiversity. Therefore, the effects on yields need to be considered simultaneously when analyzing labour-biodiversity trade-offs. Many farming technologies and farming systems are associated with low labour input and high biodiversity, but they are also associated with low yields and are hence problematic. Biodiversity-smart technologies fall into the quadrant of low labour/ high biodiversity and achieve high yields. While yields and labour, alongside biodiversity, are regarded as the most important dimensions in our optimization matrix, it is crucial to remember that maximizing yields (and profits) and reducing labour are not the only goals of farmers. Other factors, such as cultural and social considerations, also play a significant role (Altieri et al., 2012; Wezel et al., 2020).

Fig. 3 shows that farmers can move between the different quadrants – and achieve higher or lower yields – by adopting different farming technologies for weed, pest, and nutrient management and different types of mechanization. This can be illustrated with the examples of land preparation and weed management.

- **Land preparation:** Manual land preparation, indicated as (1) in Fig. 3 is associated with a high labour burden of between around 100–500 h per hectare (see Table 1). Manual soil conservation practices (2b) can further increase this labour burden – by between around 120–700 % (see Table 1). In contract, mechanized land preparation (2a) can reduce the labour burden by around 40–100 %, resulting in a labour use of around 10–110 h per hectare. As discussed before, mechanization may reduce biodiversity at the same time, hence it was positioned in the low labour / low biodiversity quadrant. Scale appropriate mechanization solutions and mechanized conservation agriculture (3), among others, could help farmers to reach the quadrant with low labour/high biodiversity.
- **Weed/pest control:** Without weed management, labour requirements are low and the planned and associated biodiversity is high, but yields are limited, a position that is indicated with (1) in Fig. 3. Manual weed control (2) raises yields but also increases the labour burden: non-mechanized farmers spend 250–800 h per ha on manual weed/pest control, depending on the crop and weed pressure (Adu-Baffour et al., 2019; Baudron et al., 2019b; Haggblade et al., 2017b; Ogwuike et al., 2014; see also Fig. S1). Efficient manual weeding can also reduce planned and associated biodiversity. Conventional chemical weed management can greatly reduce the human labour burden – by 50 to 90 % to a few hours per ha (see Table 1) – and allow for higher yields but can undermine planned and associated biodiversity, leading to position (3) in the low labour / low biodiversity quadrant. Precision chemical weed management (threshold-based and ultra-low volume) and the use of mechanical and biological strategies for weeding (4) can bring the farmer back to the desirable quadrant (low labour and high biodiversity) – now with high yields. Advanced high-tech weed control may also involve robots that are programmed such as to leave certain weeds standing in the field for biodiversity purposes (Daum, 2021).

Agricultural development and economic transformation are often associated with predictable movements between the quadrants in Fig. 3, but these movements are not necessarily fully predetermined. Farmers may also leapfrog some of the steps, for example, by directly moving from manual weeding (1) to precision weed management with mechanical, biological and chemical tools (4). Just like single farms, entire farming systems can also be classified into the three-dimensional matrix and the four quadrants (Fig. S2). In this case, both farm-level changes, as well as landscape-level changes (e.g. from mosaic landscapes to simplified landscapes), determine biodiversity outcomes.

3. Empirical case studies from the Global South

In this section, the conceptual framework is applied to two empirical case studies to explore how labour use, biodiversity and yields are

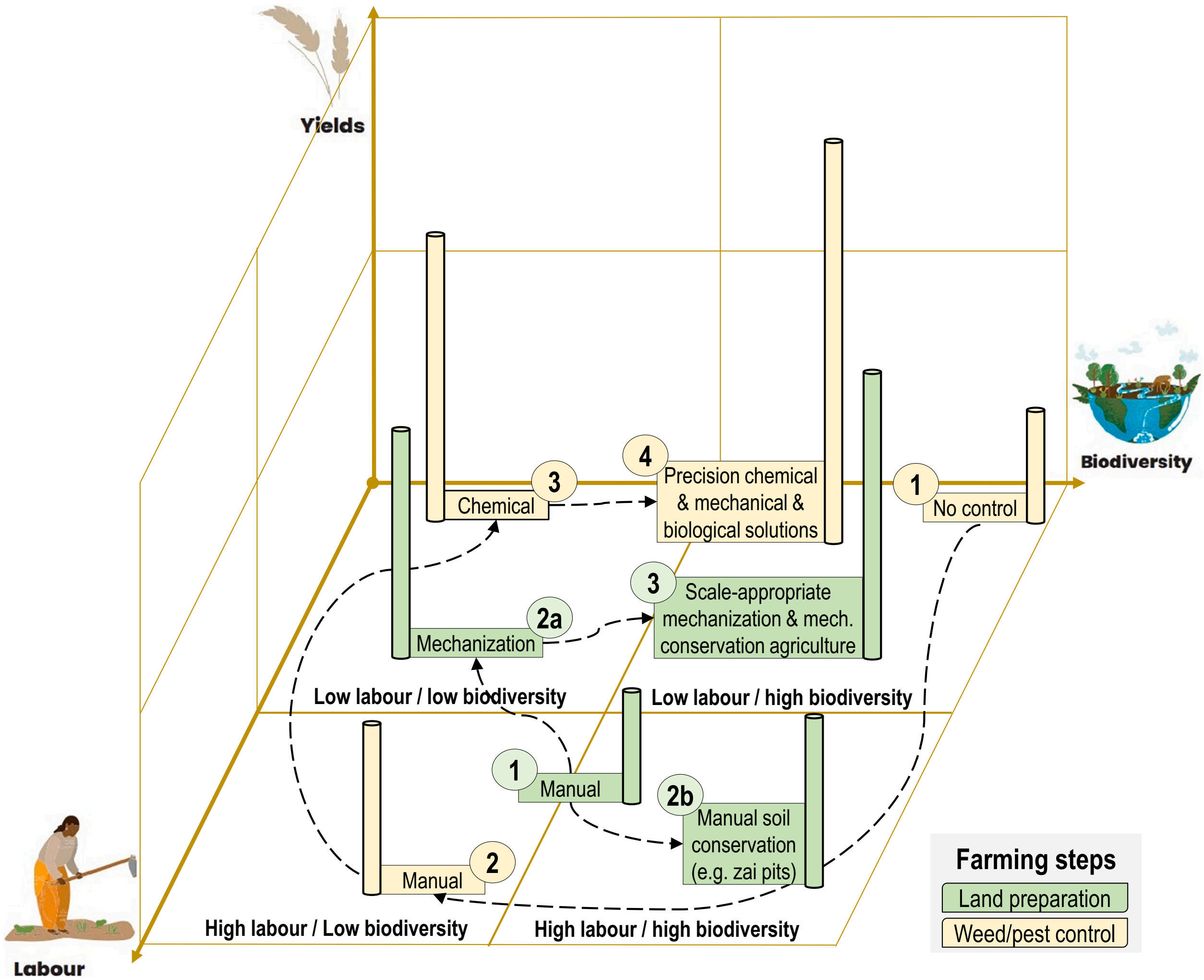

Fig. 3. Three-dimensional matrix of trade-offs between labour, biodiversity and yields, including hypothetical trajectories to move between quadrants. The figure focuses on farm activities related to land preparation and weed/pest control but the practices and technologies used for other farming activities such as planting, nutrient management and harvesting can also shape the location of farms in the matrix. Note that the placement of the farming steps in the three-dimensional matrix is only approximate.

related and what trade-offs can be observed. Subsections 3.1 and 3.2 present case studies on plantation agriculture in Sumatra, Indonesia and on annual crops in Ethiopia, respectively.

3.1. *Plantation agriculture on Sumatra, Indonesia*

The island of Sumatra is a mainstay of Indonesia's plantation agriculture, and human labour has been a long-driving force of changing agricultural practices. Jambi province on Sumatra showcases the changing Indonesian smallholder agriculture in the 20th century (Clough et al., 2016; Qaim et al., 2020). For much of the 20th century, Jambi was characterized by shifting cultivation and subsistence farming. Until the first half of the 20th century, rubber production in extensive agroforestry systems – also called jungle rubber – was an important economic activity of local farmers. Since the 1970s, the increasing global demand for rubber spurred the intensification of these agroforestry systems and their replacement with more intensively managed rubber monocultures; a process that continues up to today (Grass et al., 2020) (Fig. 4). In the 1980s, the Suharto regime and its transmigration program further promoted market-oriented crops and smallholder expansion on Sumatra (Euler et al., 2016). Smallholders received further financial and technical support from the so-called Nucleus Estate and Smallholder (NES) programs (Euler et al., 2016). These NES programs largely promoted the region's oil palm boom since the 1990s. While the majority of the first oil palm smallholders were contract farmers under the NES programs, today, over 95 % of smallholders grow oil palm independently without corporate contracts (Qaim et al., 2020).

A major reason for the widespread adoption of oil palm in Jambi is that its cultivation is much less labour-intensive than the traditional jungle rubber agroforestry and the modern rubber monocultures (see Figs. 4 and 5). Total labour costs per hectare and year are less than half for palm oil production as compared with rubber cultivation and in particular, the use of family labour is lower (Fig. S3). This goes along with the higher profitability of oil palm compared with rubber and jungle rubber, particularly because rubber prices have dropped in the past years (Grass et al., 2020). The reduced labour burden of oil palm increases farmers' profits, as demand for hired and family labour is reduced, and the resulting free labour capacity can be invested into other economic and non-economic activities (Chrisendo et al., 2021).

The rise of plantation agriculture has led to the conversion and loss of primary rainforest, which continues in the 21st century. Over the last 30–40 years, lowland rainforests and extensive agroforestry systems have largely disappeared, giving way to more intensively managed rubber and oil palm monocultures (Qaim et al., 2020) (Fig. 4). In 2013, only 30 % of Jambi province was still covered by rainforest (mainly in the mountainous regions), while 55 % had already been converted to

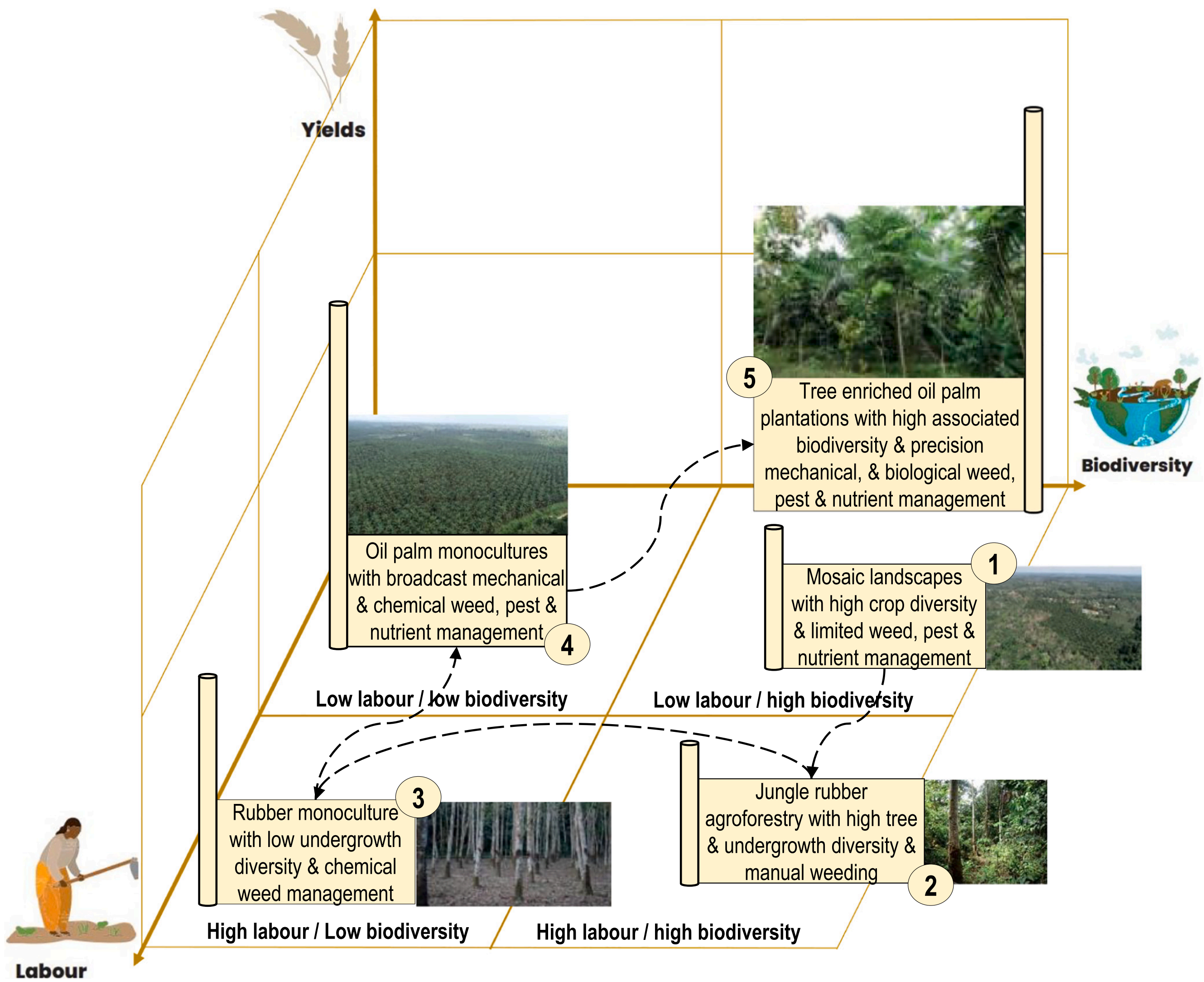

Fig. 4. Development of plantation agriculture in Jambi Province from the early 20th to the early 21st century. At the end of the 19th century, Jambi province was mainly characterized by slash-and-burn agriculture (1). From the beginning until the mid-20th century, extensive jungle rubber agroforestry was the dominant plantation system (2). Responding to the global rubber demand, agroforests were increasingly intensified by converting them to monocultures from the 1970s onwards (3). Governmental transmigration programs in the 1980s and 1990s spurred the oil palm boom (4). Dropping rubber prices, lower labour needs in oil palm and thus higher returns to labour in oil palm had the effect that this boom continues still today. A major challenge in the 21st century is to reconcile booming oil palm agriculture with the substantial biodiversity loss caused by it. One part of the solution may be oil palm plantations that are enriched with indigenous multipurpose trees, essentially transforming oil palm plantations into agroforestry systems (5). Note that this is an illustration of the trajectory, and the position on the axes as well as the yields are only rough estimates.

agricultural land and 10 % of the land was degraded or fallow, often awaiting conversion to monoculture.

Based on the conceptual framework displayed in Figs. 3 and 4, Fig. 5 displays the relationships between biodiversity, labour, and gross margins for a sample of 20 households. Biodiversity is measured as the number of leaflitter invertebrate species, which are a good proxy for the diversity of overall species diversity in the studied land uses (Grass et al., 2020). The coloured circles in Fig. 5 indicate the gross margins, as a measure of economic return, calculated by multiplying yields with the price of the product and then deducting all variable costs. The preferred option would be large circles in the upper right quadrant, indicating high economic returns combined with high biodiversity and low labour. Unfortunately, this specific combination is not realized.

As Fig. 5 indicates, while the lower labour burden and the higher profitability of oil palm systems make these economically appealing to many farmers, smallholder oil palm plantations – even when relatively small in size compared with corporate estates – harbour only low levels of biodiversity compared with the much more labourious jungle rubber agroforestry and monoculture systems (Fig. 5). Today, a major challenge is to reconcile the booming oil palm agriculture with the substantial biodiversity loss caused by it (Qaim et al., 2020; Grass et al., 2020).

Recently, several experiments have been launched that aim to mitigate the biodiversity trade-offs arising from the conversion of rainforests into intensively managed oil palm plantations. One set of experiments aims to improve the biodiversity value of oil palm plantations by adopting more environmentally-friendly management strategies (Darras et al., 2019). The main findings indicate that reducing fertilizer rates to avoid nutrient leaching and avoiding herbicides is possible without compromising oil palm yield and that gross margins are even higher under reduced fertilization because of reduced expenditures (Darras et al., 2019). The experiments also suggest that mechanical weeding increases the diversity of plants, arthropods, and belowground animals as compared with plots with herbicide application (Darras et al., 2019). While mechanical weeding also increases labour requirements, the increase in labour costs has been lower than the associated reduction in herbicide costs, increasing profitability (Iddris et al., 2023). Another set

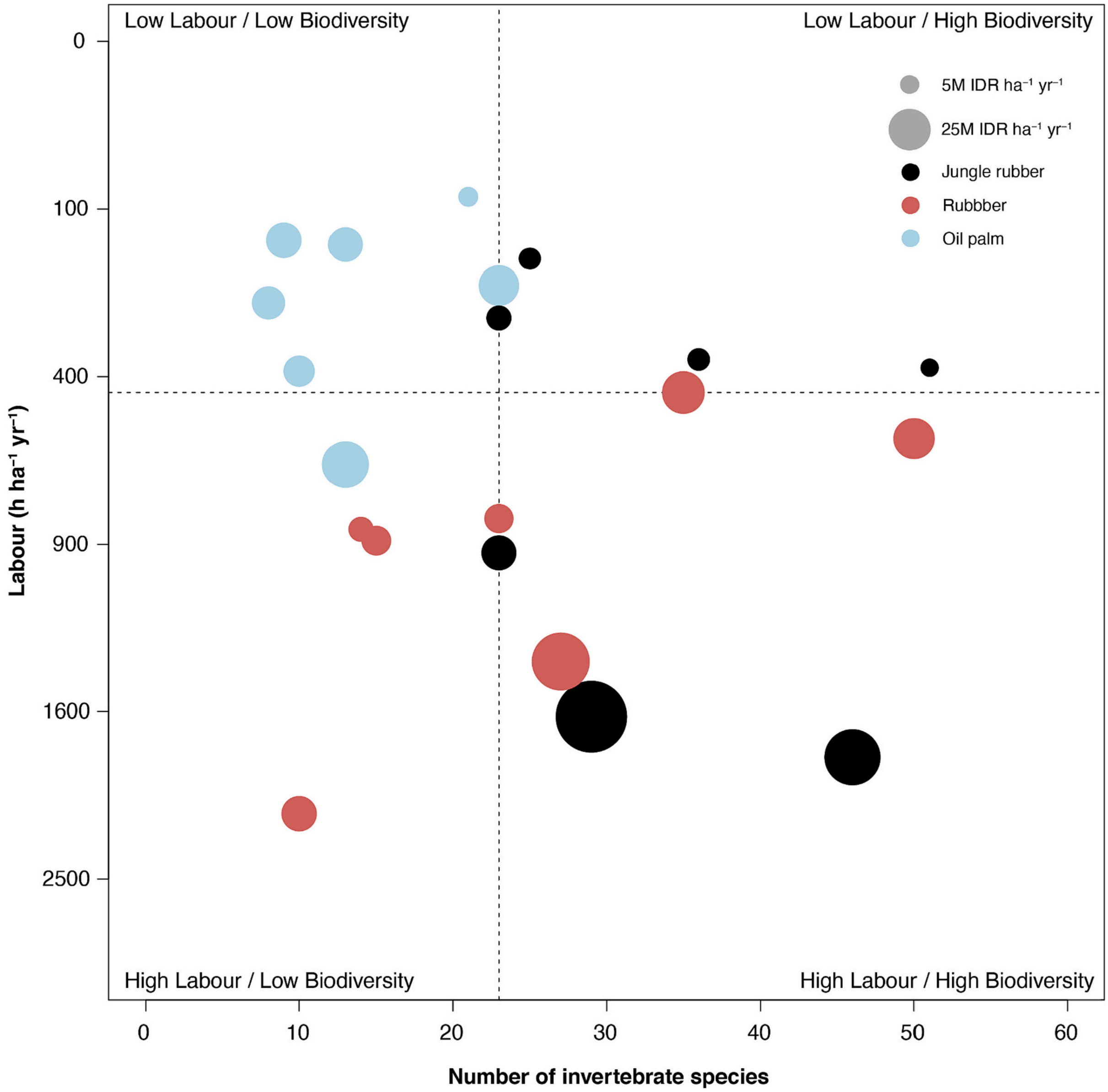

Fig. 5. Relationships between biodiversity, labour, and gross margins in jungle rubber (black), rubber (red), and oil palm (blue) smallholder systems in Jambi Province, Sumatra. Each circle displays data from one smallholder farm. The circle size is proportional to the gross margins. Data are based on biodiversity assessments of leaf litter invertebrates on 20 smallholder farms. Gross margins and labour input were calculated based on survey data collected from the respective households (both conducted in 2012; biodiversity data published in Grass et al., 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of experiments aims to increase the structural heterogeneity of oil palm monocultures by integrating native multipurpose trees into the plantation matrix (Fig. 5). This increases the diversity of trees, birds, and soil animals while reducing pathotrophic fungi (Zemp et al., in press). Importantly, increases in biodiversity and ecosystem functioning do not come at the expense of oil palm yields, as local trade-offs from thinning of oil palm for the planting of trees are compensated by positive effects of increased yields of the oil palms surrounding the forest islands (Zemp et al., unpublished data). These experiments show the great potential for making palm oil production more biodiversity-friendly. Yet, some of the measures make farm management more complex and/or increase the amount of labour required (e.g., for mechanical weeding instead of herbicide application; or for planting and maintenance of trees in agroforestry systems) (Susanti et al., 2020).

3.2. *Annual crop farming in Ethiopia*

The case study in Ethiopia was conducted in the Woreda (district) of Arsi-Negele, which is located in Southern Ethiopia and is characterized by a subhumid climate (Baudron et al., 2017). Until the agrarian reform, which started in 1974 and gave 'land to the tillers', the area was largely forested and mainly exploited by landlords for high-value timber (Duriaux-Chavarría et al., 2020). The population increased significantly after 1974, with forests being quickly converted to cropland, though at different times and rates depending on the distance to the main town of Arsi Negele (Duriaux-Chavarría et al., 2020). Deforestation slowed down in the mid-1980s and reforestation started in the late-1990s, again at different times and rates depending on the distance to the town of Arsi Negele (Duriaux-Chavarría et al., 2020). The resulting landscape can be described as a forest-agriculture gradient, along which three zones can be distinguished: (i) a diverse zone, with higher tree cover, and most remote from the town of Arsi Negele; (ii) an intermediate zone; and (iii) a simple zone, mostly transformed for agricultural production, with lower tree cover, and located closest to the town of Arsi Negele (Baudron et al., 2019a).

Fig. 6 displays the relations between labour, biodiversity and yields. In this case, yields are measured in kilograms of dry matter per hectare, and biodiversity is measured as the abundance of small-range birds (fruit/nectar eater bird species, invertebrate eater bird species, omnivore bird species and native tree species followed a similar trend, see Baudron et al., 2019a). As Fig. 6 shows, farming systems in the diverse zone are more labour-intensive than in the two other zones. This is because the corresponding farms manage a greater diversity of crop species and more livestock (Duriaux Chavarría et al., 2018). Farms in the diverse zone also recycle more biomass, in particular by importing fuel and feed from nearby forests and by using larger quantities of manure, compared with farms in the two other zones that mainly purchase their fuel and/or harvest it on-farm and depend more on inorganic fertilizers than manure for their crop production (Duriaux Chavarría et al., 2018).

Though being more labour-intensive, farming systems in the diverse zone are more productive when considering total – crop, feed and fuel – productivity (Baudron et al., 2019a). They are also more sustainable from an environmental perspective and more resilient (Duriaux Chavarría et al., 2018), provide more diverse diets (Baudron et al., 2017),

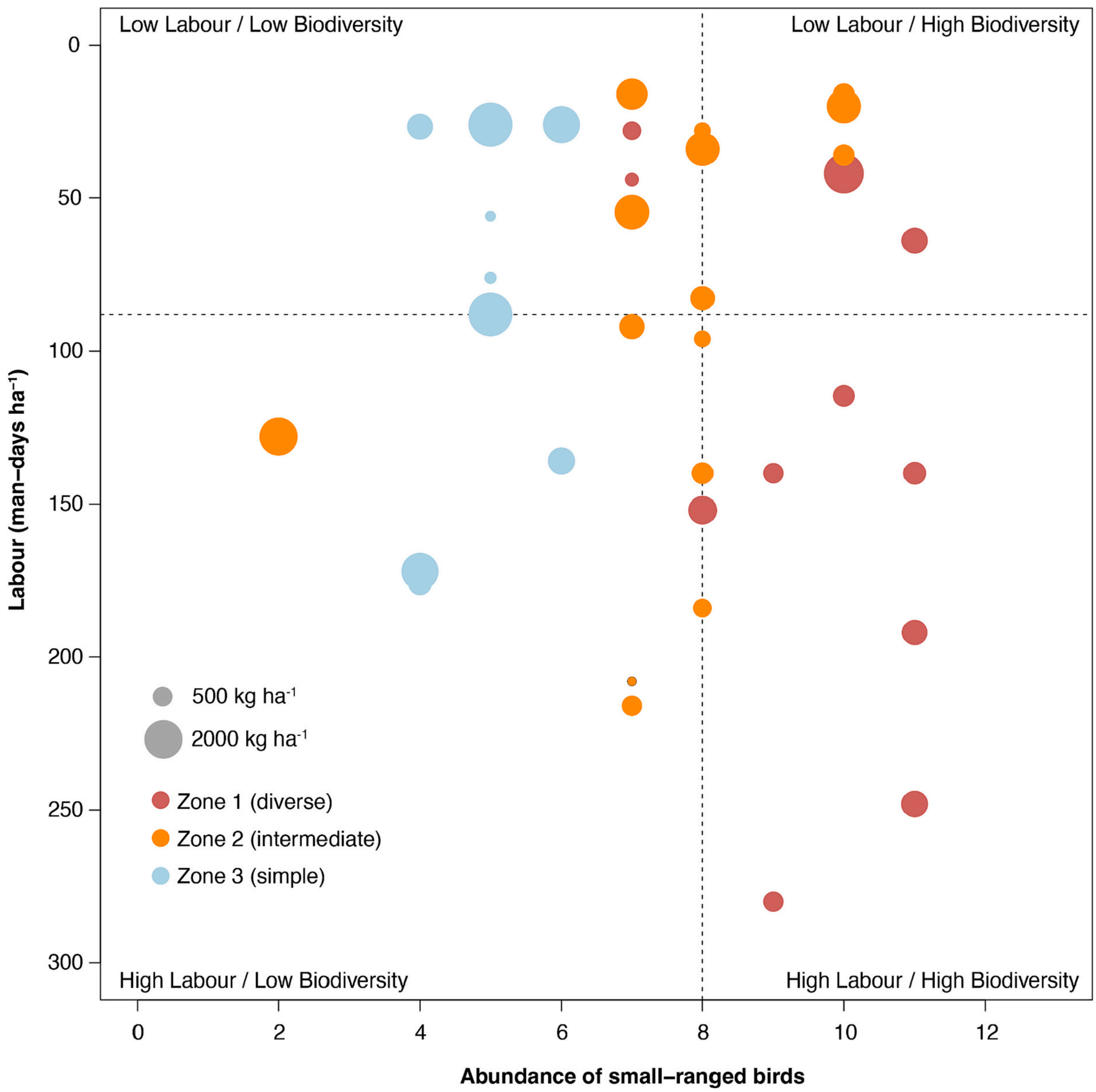

Fig. 6. Relationships between biodiversity, labour, and yields in diverse (red), intermediate (orange), and simple (blue) smallholder farming systems in Arsi Negele, Ethiopia. Each circle displays data from one smallholder field. The circle size is proportional to yields (kg DM ha^{-1}) of cereals (maize, wheat, teff, sorghum, and/or barley) and/or tuber (potato) of the corresponding field (to account for crop rotation within the same year, in particular, cereal-potato rotation). Crop productivity data are from fields of a stratified (stratification based on a farm typology) sample of 27 smallholder farms. Biodiversity data were recorded from point counts located in or nearby the above-mentioned fields that were visited in the morning (between 6 h00 and 10 h00) three times between April and May (dry season) and three times between August and September (wet season), with all birds within a 50 m radius recorded each time during a period of 10 min (data collected in 2015, biodiversity data published in Baudron et al., 2019a and farm data published in Duriaux Chavarría et al., 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and produce wheat – a major crop in the area – with higher nutritional content thanks to better soil health (Wood et al., 2018). The diverse zone also hosts a greater abundance of tree species and small-range bird species (Baudron et al., 2019a) (Fig. 6). Plant and seed-eating birds – potential pests which may consume crops – were also found to be more abundant in the simple zone, while invertebrate-eating birds – potential natural enemies which may consume insect pests – were found to be more abundant in the diverse zone (Baudron et al., 2019a).

Generally speaking, before the mid-1970s, farming systems in the area moved from a situation of low labour, high biodiversity, and low productivity towards low labour, low biodiversity, and high productivity until the mid-1980s. Since then, they have moved towards low labour, high biodiversity, and high productivity, through reforestation across the gradient to recover some of the ecosystem services lost during intensification (Duriaux-Chavarría et al., 2020). Labour-saving technologies compatible with high biodiversity (high tree cover and small plots) are being adopted (e.g., the use of small-scale combine harvesters), representing a possible move towards low labour, high biodiversity and high productivity.

4. Implications and ways forward

Protecting the world's remaining biodiversity, much of which is located in the Global South, requires biodiversity-smart agricultural development strategies, which reconcile agricultural production to meet the needs of the growing population and biodiversity conservation. Combining conceptual considerations with empirical examples from the Global South, this paper has shown that such strategies will have to pay more attention to agricultural labour dynamics to succeed. Adopting technologies that improve the productivity of labour helps farmers to achieve multiple socio-economic goals, including a reduction of economic poverty (Adu-Baffour et al., 2019), time poverty (i.e., lack of discretionary time) (Bergman Lodin et al., 2012), reducing labour drudgery (Daum and Birner, 2021; Ogwuike et al., 2014), and child labour (Vos and Takeshima, 2021). However, as shown in this paper, such technologies can have negative impacts on biodiversity. Conversely, technologies that promote biodiversity often increase the burden of labour, leading to limited adoption by farmers. Therefore, there is a need to develop biodiversity-smart agricultural development strategies, which address biodiversity conservation goals *and* socio-economic goals, specifically raising land and labour productivity. The empirical case studies presented above, which cover contrasting farming systems, suggest that such opportunities do exist but that more efforts are needed to implement them at scale.

Comparing the development options of farming systems in the Global South with the experience of the Global North provides some interesting insights. The farming systems in industrialized countries have evolved following a distinct pattern where labour productivity increased substantially, but biodiversity declined drastically in parallel (e.g., Robinson and Sutherland, 2002; Stoate et al., 2001). This pattern is also unfolding in the Global South, as shown in the case studies from Indonesia and Ethiopia. In terms of our conceptual framework, this process entails a move across the quadrants presented in Fig. 3 (see also Fig. S3). In a historical trajectory, traditional farming systems tend to move from the quadrant of "low labour, high biodiversity" to the quadrant of "high labour, high biodiversity", where population growth forces farmers to cultivate land more intensively in order to produce sufficient food, raising labour requirements (Boserup, 1965). Biodiversity remains relatively high, but the high labour requirements of this shift are a burden to men, women, and children. Hence, this quadrant is unsustainable from a social perspective, and it becomes infeasible when the process of economic transformation (i.e., the rise of industry and other sectors with new employment opportunities) starts to pull labour out of rural areas, which explains the rapid adoption of mechanization and pesticides and the dis-adoption of labour-intensive practices such as intercropping in Asia (Daum, 2023; Diao et al., 2020; Feike et al., 2012; Pingali, 2007). Industrialization drives the adoption of technologies such as mechanization and pesticides that save labour (and raise yields to some degree as they make farming more timely and efficient) but that can negatively affect biodiversity by leading to farmland expansion, simplification, degradation, and spillover effects as discussed above – causing a shift to the quadrant "low labour, low biodiversity". Many countries in the Global North are currently situated in this "low labour, low biodiversity" quadrant, whereas countries in the Global South are mostly situated in the "high labour, high biodiversity" quadrant or transitioning towards the "low labour, low biodiversity" quadrant. It is concerning that only very few farmers in the case studies are located in the "low labour, high biodiversity" quadrant, which maximizes social and environmental outcomes, and also achieves high yields (see Figs. 5 and 6).

Countries that are still in the "high labour, high biodiversity" quadrant face the unique opportunity to learn from the experiences and mistakes of industrialized countries and leap-frog the biodiversity-harming stage of agricultural development associated with the "low labour, low biodiversity" quadrant. This opportunity can help minimize the negative effects of farming on biodiversity and contribute to protecting some of the world's remaining biodiversity. Using this opportunity requires a paradigm shift that moves beyond the productivity paradigm, which is currently dominating policymaking and research and development (e.g., Baudron et al., 2021). Proponents of this paradigm argue that agricultural intensification meets environmental objectives by enabling land-sparing of natural land for wildlife, but such land-sparing rarely happens without strict enforcement of associated set-aside policies (e.g., Goulart et al., 2023; Grass et al., 2019). A pure land-sparing strategy also neglects the importance of planned and associated biodiversity, which has a value in itself and provides important agro-ecosystem functions (Baudron et al., 2021; Tscharntke et al., 2012). Hence, leap-frogging the biodiversity-harming "low labour, low biodiversity" quadrant requires a stronger emphasis on social and environmental objectives in agricultural policy-making as well as in research and development.

In research and development, paradigm shifts are needed among both conservation ecologists and agricultural scientists (Baudron et al., 2021). Conservation ecologists have to strive to not only enhance environmental but also economic and social sustainability, whereas agricultural scientists have to pay more attention to embracing multiple other goals beyond just yields (Baudron et al., 2021). Agricultural innovation systems have to be re-designed to foster technological and institutional innovations that maximize synergies and minimize trade-offs between multiple economic, social, and environmental objectives, for example by adapting research and development as well as extension priorities. Interdisciplinary research that simultaneously captures data on yield, biodiversity, and labour can help to identify positive deviants or bright spots, meaning farmers and farm areas that are already successfully minimizing trade-offs (see also e.g., Frei et al., 2018).

Unlike in the Global North, countries in the Global South have the opportunity to move from their farming systems, which are often still biodiversity-friendly, to systems with higher land and labour productivity without losing their biodiversity. At the farm level, this requires efforts to reduce the biodiversity trade-offs associated with farm mechanization and pesticides. One potential solution is scale-appropriate mechanization, where machines are adapted to farm size – and not the other way around – including draught animals as well as small tractors and two-wheeled tractors, which are already widespread in parts of Asia and some parts of Africa (Baudron et al., 2015; Baudron et al., 2019b; Daum, 2023; Diao et al., 2020). Such machinery may not only be better adapted to small plots with field elements such as trees and hedges but also easier to finance, run, and repair (e.g., Diao et al., 2020; Kahan et al., 2018). While desirable from a biodiversity perspective, such solutions may not be preferred by farmers in the long run given their still higher labour use and the economics of scale associated with mechanization unless accompanied with supportive policies (e.g., Daum, 2023).[4] Another option is sustainable practices that are mechanized, such as mechanized conservation agriculture (Baudron et al., 2015). In some countries, innovations such as agricultural robots, which smallholder farmers may access via Uber-type hire models, may play a role to reconcile yields, biodiversity, and labour (e.g. Daum, 2021; Ditzler and Driessen, 2022; Rose et al., 2021). In China, agricultural drones are already widespread in some areas, although they are not yet fully autonomous and mostly used for broadcasting inputs (Li et al., 2023). Simply refraining from the use of synthetic pesticides, as in the case of organic farming, can enhance local biodiversity (e.g., Tuck et al., 2014) but decrease yields and therefore cause biodiversity trade-offs due to larger global farmland requirements (Muller et al., 2017). A recent global review indicates that, on average, crop yields in organic farming are 19–25 % lower than in conventional agriculture (Meemken and Qaim, 2018). Organic farming is often also associated with higher labour requirements and costs (Crowder and Reganold, 2015; Orsini et al., 2018). Innovations such as precision sprayers that enable site-specific weed management reduce trade-offs between agricultural yields, agricultural labour, and biodiversity conservation (Gerhards et al., 2022). These and other practices, such as reducing field size and diversifying crop rotations, can significantly promote biodiversity and can also be applied in conventional agriculture (Tscharntke et al., 2021). Integrated pest management, which aims to substitute synthetic pesticides with mechanical and biological solutions, can lead to win-win outcomes between agricultural productivity and biodiversity conservation (Pretty and Bharucha, 2015), but clearly there is a need to pay more attention to reducing trade-offs regarding labour use (Beckmann and Wesseler, 2003).

Next to reducing the trade-offs associated with labour-saving technologies, biodiversity-preserving and -enhancing measures are needed, including both production-integrated measures (e.g., patch cropping, intercropping) and set-aside measures (e.g. trees, hedges) (Grass et al., 2019; Tscharntke et al., 2021). Research is needed on how such measures should be designed to reduce trade-offs between agricultural productivity and labour. The case study from Indonesia has shown that well-planned set-aside measures, in this case, the integration of islands of native tree species within plantations, can enhance biodiversity without compromising yield or labour-saving objectives, although it may make farm management more complex (Susanti et al., 2020). Farm-level solutions have to be accompanied by efforts at the landscape level, for example, careful land-use planning and monitoring to preserve biodiversity hotspots, habitat mosaics, and patch connectivity (Law et al., 2021; Pendrill et al., 2022; Tscharntke et al., 2021). The empirical case study from Ethiopia shows that multifunctional landscapes can be planned to "work for biodiversity and people" (Kremen and Merenlender, 2018). Biodiversity-smart technologies reduce the trade-offs between labour and biodiversity conservation for individual farmers. These solutions increase the likelihood of adoption, even in cases where farmers do not directly benefit from enhanced biodiversity, as they reduce the costs of biodiversity conservation. As such they reduce the need for external financial compensation. Where biodiversity conservation comes with higher costs than benefits for individual farmers, financial compensation is needed, for example, as part of certification schemes (Kubo et al., 2021) or public payments for ecosystem services schemes (e.g., Farmar-Bowers and Lane, 2009; Salzman et al., 2018).

Policymakers and researchers focusing on the Global South have the unique opportunity to avoid the mistakes of the Global North and to pursue biodiversity-smart agricultural development pathways that reconcile increasing land and labour productivity to feed the growing population with biodiversity conservation before it is too late. In the Global North, biodiversity-smart farming practices are equally important to address past mistakes. New types of technologies will help in both contexts if well adapted to local needs and conditions.

[4] Conventional agricultural mechanization is often associated with economies of scale effects (Takeshima et al., 2018). Combined with other factors of structural transformation, this can led to a "get big or get out" logic (Al-Amin et al., 2023) with increasing machinery sizes as well as land consolidation, growing field sizes and more rectangular fields. This is especially the case where machinery operators are expensive, as discussed above. Asset-sharing arrangements can reduce this effect to some degree by allowing machinery owners to spread the fix costs of machinery (e.g., Daum, 2023; Olmstead and Rhode, 1995). Given these economics of mechanization, scale-appropriate mechanization may not be adopted and used by farmers in the long run unless accompanied by the right policies, as further discussed below. Interestingly, recent research on the economics of agricultural robots suggests that autonomous crop machines may enable a return to smaller machinery (or fleets thereof), purely based on economic considerations since operators' costs no longer matter (e.g. Al-Amin et al., 2023).

Funding

Thomas Daum and Regina Birner are grateful for the financial support from the "Program of Accompanying Research for Agricultural Innovation" (PARI), which is funded by the German Federal Ministry of Economic Cooperation and Development (BMZ). Matin Qaim has received funding from Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under CRC 990 "EFForTS" and Germany's Excellence Strategy EXC-2070 – 390732324 "PhenoRob".

Declaration of competing interest

Thomas Daum and Regina Birner report financial support was provided by Federal Ministry of Economic Cooperation and Development (BMZ). Matin Qaim has received financial support from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation).

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2023.110165.

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