Opportunities and limitations to the irrigation-led sustainable intensification of mixed farming systems in Nepal's mid-hills

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The Sustainable Intensification of Mixed Farming Systems Initiative aims to provide equitable, transformative pathways for improved livelihoods of actors in mixed farming systems through sustainable intensification within target agroecologies and socio-economic settings.

Through action research and development partnerships, the Initiative will improve smallholder farmers' resilience to weather-induced shocks, provide a more stable income and significant benefits in welfare, and enhance social justice and inclusion for 13 million people by 2030.

Activities will be implemented in six focus countries globally representing diverse mixed farming systems as follows: Ghana (cereal–root crop mixed), Ethiopia (highland mixed), Malawi: (maize mixed), Bangladesh (rice mixed), Nepal (highland mixed), and Lao People's Democratic Republic (upland intensive mixed/ highland extensive mixed).

Contents

Abbreviations and acronyms

AC	AquaCrop simulation model
ADS	Agricultural Development Strategy of the Nepali government
BNF	Biological Nitrogen Fixation by leguminous crops
CC	Canopy Cover
CF	Chemical Fertilizer
CGIAR	Consultative Group for International Agricultural Research
CIMMYT	Centro Internacional de Mejoramiento de Maíz y Trigo, Mexico FAO
DE	Dietary Energy
DI	Deficit Irrigation
DM	Dry Matter
ET	Evapotranspiration
FAO	Food and Agricultural Organization of the United Nations
FD	FarmDESIGN whole farm bio-economic model
FGD	Focus Group Discussion
FYM	Farmyard Manure
IWMI	International Water Management Institute
KII	Key Informant Interviews
LER	Land Equivalent Ratio
ME	Metabolic Energy
MFS	Mixed Farming Systems
NARC	National Agricultural Research Center of the Nepali government
NI	Nitrogen Import
RAW	Readily available water in the root zone
RC	Relative Cover of weeds in total canopy cover
SI	Sustainable Intensification
SOM	Soil Organic Matter
TAW	Total Available Water in the root zone
WP	Water Productivity
WUE	Water Use Efficiency

Country background and research objective

Nepal is a landlocked country in South Asia characterized by a rugged hilly landscape stretching from east to west in between the Himalayan Mountain range in its north and the Indo-Gangetic Plains in its south. Food insecurity affects over half the population, and a quarter lives below the poverty line (NPC, 2021). Agricultural development has been slow, yet since the 1960's enhanced infrastructure (e.g. roads, communication, irrigation) and access to inputs (e.g. fertilizers, pesticides, mechanization) led to improvements in smallholder livelihoods with 44.7% of farming households shifting from subsistence to entrepreneurial farming. However, overall food grain self-sufficiency declines, reliance on imports increases, and poverty and food insecurity prevail (Khanal et al., 2020).

Irrigation-led intensification is considered key to closing yield gaps, mitigating water shortages, and extending the cropping season, thereby boosting agricultural productivity. Farmer-led initiatives have been promoted to develop cost-effective renewable energy-powered irrigation systems adapted to local conditions (Khadka et al. 2021; Nepal et al., 2021; Pradhan et al. 2017).

The sustainable intensification (SI) of smallholder mixed farming systems (MFS) has received considerable interest for its potential to improve the productivity as well as the resilience of production systems, mainly through the formulation of policy recommendations and the identification of technological interventions (FAO, 2011; Mabhaudhi et al., 2023). However, scientific evidence regarding how SI interventions influence farm management practices and ecosystem services has been limited, especially so in the context of Nepal's mid-hills (Krupnik et al., 2021). To evaluate the potential of irrigation-led and sustainable intensification, an analysis combining field and farm level assessment is required.

The objective of this research was to investigate the potential of irrigation and year-round cropping systems including legumes for the sustainable intensification (SI) of maize-based, mixed farming systems (MFS) in Nepal's mid-hills.

Methodology

Case study site

The study area, Halesi Tuwachung municipality, lies in the Khotang district located in the Koshi River Basin in the central-eastern mid-hills. The focus was on wards 6 (Mangaltar; ~1000 masl; Lat. 27.2097°N; Long. 86.5761°E) and 7 (Mahadevsthan; ~1500 masl; Lat. 27.1987 °N; Long. 86.63604 °E) (Figure 1). The subtropical climate features temperatures ranging from 9°C to 30°C (median 23°C) and an annual rainfall of 1450 mm. Halesi Tuwachung counts 6000 households, with approximately 70% of income derived from remittances and 15-30% from the sale of agricultural produce (i.e. cereals, pulses, goat and pig meat, milk and eggs mainly). Market integration is limited, local infrastructure for produce storage and transport is lacking, merely 8% of arable land is irrigated and up-hill water sources are depleting (Neupane et al., 2024).

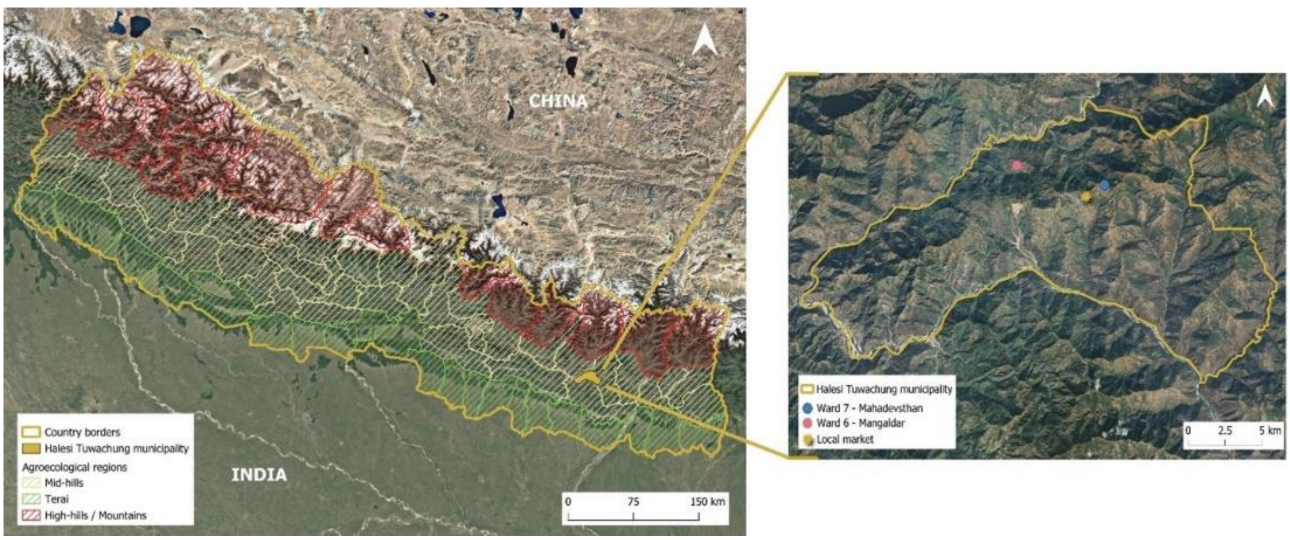

Figure 1. Map of Nepal depicting the three agroecological regions with a close-up of Halesi Tuwachung municipality depicting the geolocation of ward 6 Mangaltar, ward 7 Mahadevsthan and the nearest local market.

Research approach

This study took a semi-participatory, model-based approach to integrated farming systems analysis. Field observations, secondary data collection, and key informant interviews (KII) were conducted to quantify and validate MFS components. At field level, crop response to water was assessed for the main crops (maize, finger millet, ricebean, and potato) using AquaCrop (AC). AC was used to compute alternative sowing dates, evaluate irrigation and water-saving techniques, and inform feasible year-round crop rotations integrating leguminous fodders/green manures and cereal-legume intercrops. At the farm level, the bio-economic model FarmDESIGN (FD) was used to assess preferred crop rotations under rainfed and irrigated scenarios. Optimal farm reconfigurations were explored and achievable SI was quantified while identifying synergies and trade-offs between farm objectives. Focus Group Discussions (FGD) were held to evaluate farmer perspectives and to inform further research.

FAO's crop response to water model AquaCrop (AC; v7.1) was used to assess the yield, crop residue production, net irrigation requirements, and evapotranspiration water productivity of *current* crops maize, finger millet, ricebean, and potato in response to (deficit) irrigation strategies, and to quantify the performance of *novel* cropping systems to inform further farm level modelling. AC is a dynamic model integrating climate, crop, soil, and field management components and simulating daily crop growth in four main steps: canopy cover (CC; $m^2 m^{-2}$) increase, crop transpiration (Tr; mm day^{-1}), biomass production (B; kg DM ha^{-1}) and yield formation (Y; kg DM ha^{-1}) based on the harvest index (HI). AC concepts and equations are extensively explained by Raes et al. (2019, 2023), Steduto et al. (2009), and Vanuytrecht et al. (2014).

The year-round cropping systems with legumes were introduced in the whole-farm model FarmDESIGN (v5.12.1.0) to assess SI potential of field level interventions and explore optimal farm reconfigurations. FD is a static bio-economic model that quantifies flows between farming system components. FD enables the identification of Pareto-optimal solutions and the ex-ante assessment of synergies and trade-offs between multiple objectives arising from alternative farm management practices.

The study aimed to explore opportunities for sustainable intensification by integrating socio-economic and environmental dimensions. Socio-economic objectives focus on improving self-sufficiency in food, fertilizers, and feed (reducing market reliance and expenses) and boosting overall farm productivity (generating surplus for sale). Environmental objectives emphasize improving resource use efficiency, promoting on-farm recycling, enhancing soil health, and managing scarce resources, such as water. These considerations informed the development of objectives, decision variables, and constraints

Results

Crop response to water

The analysis of crop response to water showed that irrigation had the greatest impact on winter-grown potato, with yield potential (Yp) predicted to be 271% higher than the water-limited yield potential (Yw). Irrigated yield potential was higher compared to rainfed conditions by 22% for maize and 24% for finger millet, while yield remained unchanged for ricebean.

Relative water productivity (WP_{ET}) improvements were observed for all crops under deficit irrigation compared to full irrigation (0% RAW, reference) when weed and soil fertility were not limiting. Preferential deficit irrigation schemes differed per crop (purple marks, Figure 2) and would result in 86%, 55%, and 29%, water use reduction, while reducing yields by 7%, 0.1%, and 2%, and saving 97 mm, 72 mm and 88 mm of water compared to full irrigation for maize (75% RAW), finger millet (100% RAW) and potato (75% RAW), respectively. Reduced trade-offs between water savings and yield loss were reflected by improved WP_{ET}. Ricebean did not benefit from irrigation, the yield was unchanged and WP_{ET} was slightly lower when fully irrigating compared to rainfed conditions as with increased ET there were no yield gains, thus logically deficit irrigation saved water compared to full irrigation. Changes were more apparent for crops with higher absolute water requirements, mainly potato (winter) followed by maize (in part grown in spring) and finger millet (grown in winter).

Severe fertility stress limited the potential of irrigation on crop yields (Y) and water productivity (WP_{ET}), but also weakened crop responses to deficit irrigation. For potato grown in the dry winter season under weed and severe fertility stress, rainfed yields dropped by 46%, while the irrigated yields dropped by 79%

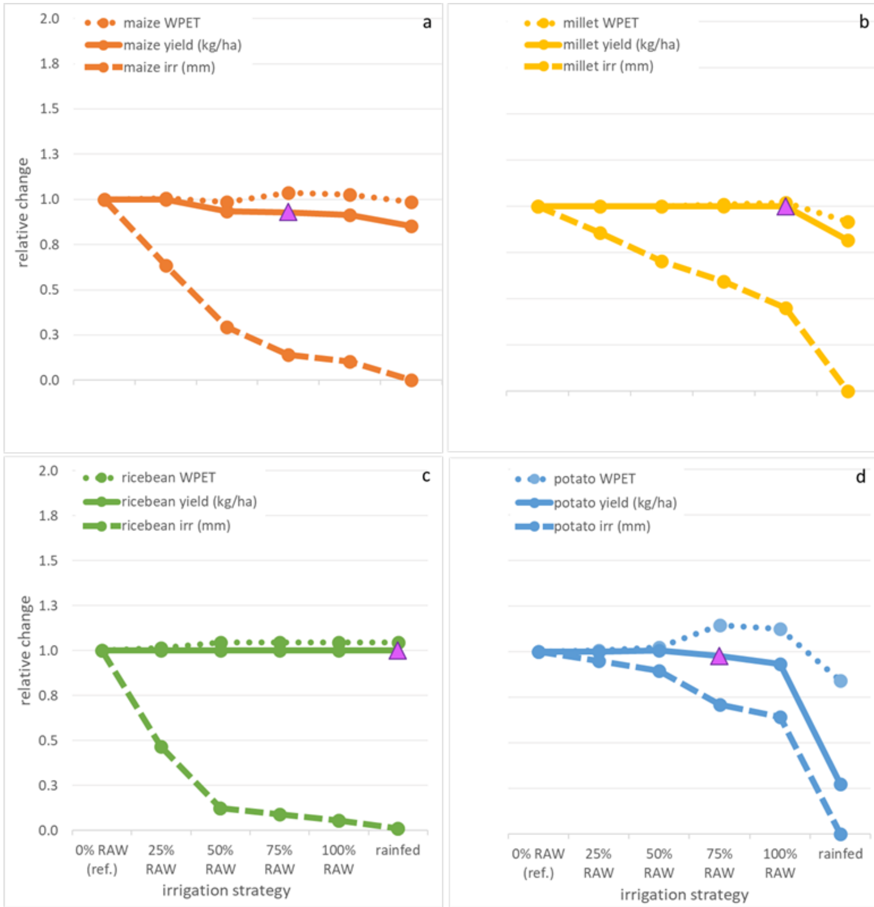

Figure 2. Relative changes in irrigation requirements (mm, dashed lines), (water-limited) yield potential (kg ha-1, solid lines) and water productivity (WPET , dotted lines) under deficit irrigation (25, 50, 75 and 100% of RAW depletion allowed) and rainfed conditions compared to full irrigation (0% RAW, reference) compared to full irrigation (0% RAW depletion, reference scenario) for maize sown April 16 (a, orange), finger millet sown July 16th (b. yellow), ricebean sown June 15th (c. green), and potato sown Nov 16th (d. blue). Weed and soil fertility stress not considered. Purple triangles mark the optimal irrigation scenario, highest WPET.

Year-round cropping systems

The analysis resulted in two cropping system reconfigurations with solely current crops and seven following a year-round cropping pattern including sole legumes and legume-cereal intercrops (Figure 3). Sowing maize on May 21st under rainfed conditions (rotations 3-7 in Figure 3) and on March 1st with irrigation (rotations 9-11) optimized yields compared to April 13th sowing (rotations 1 and 2). Rotations including potato (rotations 1 and 4), followed by rotations including wheat (rotations 7 and 10), yielded the largest quantity of dietary energy. The largest feed production was achieved by rotations that included maize grown in spring and lucerne in winter. Maize was identified as a larger feed contributor than lucerne with 70% of grain yields allocated to livestock. Wheat and lucerne exhibited higher water requirements than potato grown in winter following intercropped maize and rice bean, 3.2 times more for sole lucerne and 5.1 times for intercropped lucerne-wheat.

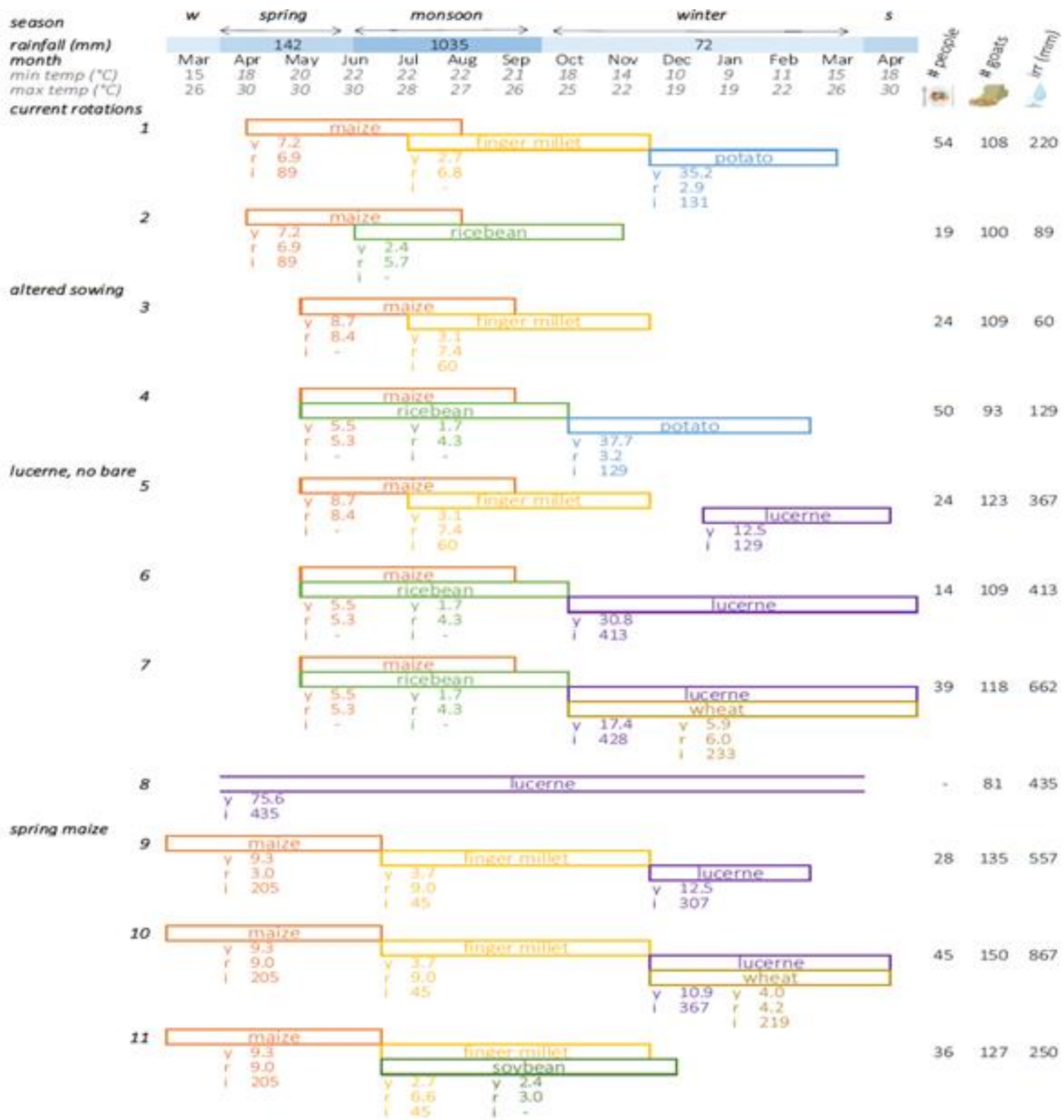

Figure 3. Performance of reconfigured maize-based cropping systems under irrigated conditions when soil fertility was not limiting. The number of people and goats feed from 1 ha cultivated land is derived from dietary energy yield (kcal ha-1) and metabolic energy (MJ ha-1) of 70% of maize grains, crops residues, and lucerne. Fixed-interval irrigation (weekly 15 mm) was initiated before critical soil moisture thresholds for crop development, as calibrated in AquaCrop. Under the crops: y = fresh yield (kg ha-1), r = dry crop residue (kg ha-1), i = irrigation requirements (mm).

Farm-level implications

The exploration of Pareto-optimal farm reconfigurations (Figure 4) depicted solutions spaces with synergies and trade-offs between farm objectives. Trade-offs were identified between increasing dietary energy yield (DE) and minimizing water requirements (WR) (Figure 4a), increasing DE and reducing nitrogen fertilizer imports (NI) (Figure 4d), increasing the organic matter balance (OM) and minimizing NI (Figure 4f), and between increasing OM and minimizing WR (Figure 4c). A synergy was found between increasing DE and increasing OM (Figure 4b). The influence of the opportunity to increase the area of cultivated land to 1 ha (light green area) revealed to be greater than that of irrigation only on 0.5 ha (dark blue areas) on the solution space for farm optimization (i.e. more people nourished with less NI and WR). When the cropping area remained restricted to 0.5 ha, limited opportunities for increasing DE production arose. Allowing the opportunity to increase farm size (up to doubling) led to 77%, 110% and 151% increase in DE produced compared to the baseline scenario (red dot) under rainfed (light green), irrigated (light blue), and irrigated without water saving objective (light yellow) scenarios, respectively. Preferential farm management strategies for achieving SI of MFS depicted in Figure 4.

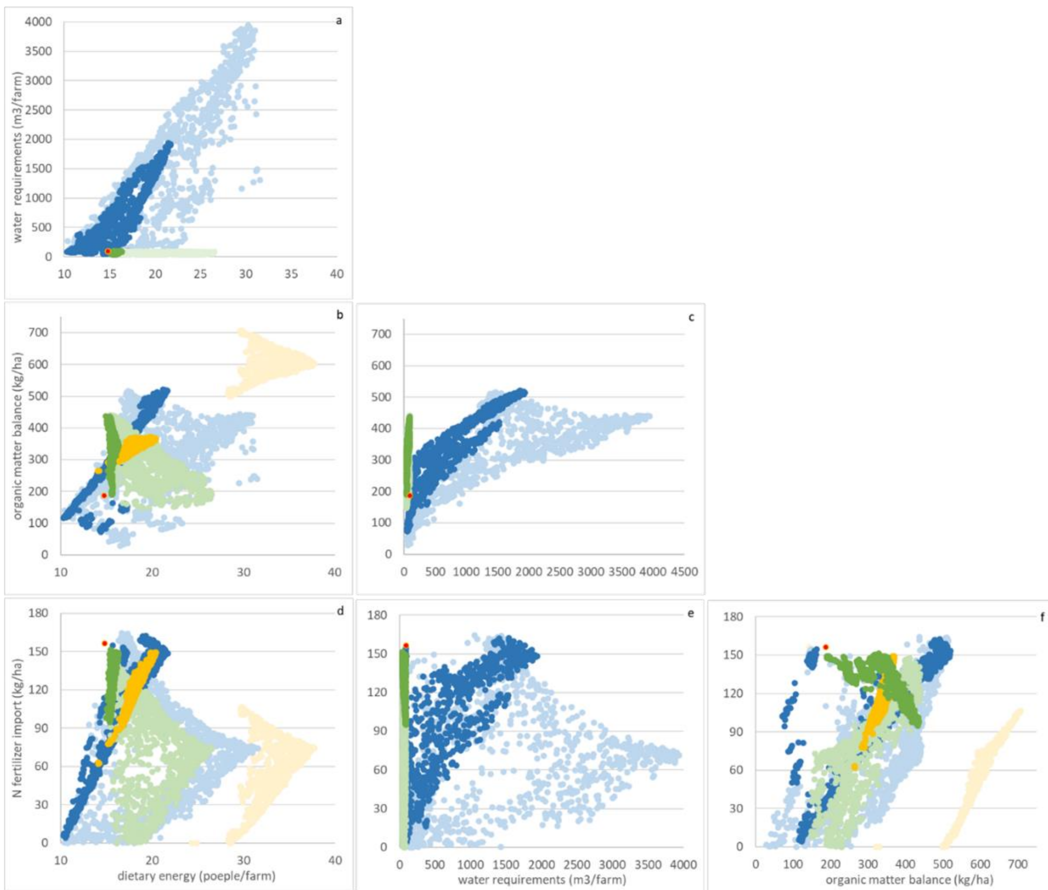

Figure 4. Farm reconfiguration solution space for multi-objective pareto-optimisation under rainfed (green), irrigated (blue) and irrigated without water minimization objective (yellow) scenarios with 0.5 ha (dark shades) or between 0.5-1 ha (light shades) available arable land. The dietary energy yield (number of people nourished from farm produce) and the organic matter balance (kg OM ha^{-1}) were set to maximize. The import of nitrogen fertilizer (kg N ha^{-1}) and the total water requirements (m^3 $farm^{-1}$) were set to minimize. Constraints were set on soil nitrogen losses (15-30 kg N ha^{-1}), maximum nitrogen import (170 kg N ha^{-1}) and on feed requirements (allowed deviation (%) of energy (-5 - +5), protein (0-30), structure (0 -∞), dry matter (∞ -0) relative to requirements for energy, protein and structure or intake capacity for the dry matter). Selected decision variables were the number of goats kept (0-60), the area of land allocated to a crop rotation (0-0.5, 0-1), and the crop products destination (fraction used as manure, feed, or food).

Farmer perspectives

When asked about the feasibility of integrating cereal-legume intercrops into the maize-based crop rotation to enhance food and feed production, participants of the FGDs largely deemed this strategy as suitable under irrigated conditions. Doubts were raised if under rainfed conditions the modelled yields would be achieved due to water scarcity. Further concerns were voiced regarding the shading effect of fully intercropped cereals and legumes as well as for the suitability of lucerne, novel in the area. Concerns regarding the increased nutrient requirements for cereal production off-season (e.g. wheat) were raised, suggesting a preference for sole legumes to avoid compromising nutrient availability for maize during the main cropping season. Perceptions of feed shortages varied among farmers, but both wards reported shortages and all farmers expressed an interest in increasing livestock numbers with sufficient access to feed. Farmers expressed a preference for cultivating a legume fodder or cover crop rather than leaving the land bare, even if yields would be low. Increased labor requirements were not identified as a major concern, as farmers tend to organize collectively to address the workload. Intensified cereal-legume production was acknowledged as beneficial for farm income, but not considered a preferred strategy. Discussion arose regarding the use of irrigation water for cereal-legume intercrops, with farmers arguing that under scarce conditions water resources might be better allocated to vegetables and cash crops. Additionally, farmers have expressed interest in water-saving techniques, if not compromising crop yields.

Implications

The results modelled in this study highlighted that irrigation alone is an unfeasible strategy to sustainably intensify production. Findings add evidence to the literature arguing that without addressing underlying yield gaps, smallholder farmers could remain “trapped in poverty,” unable to reap the benefits of technological interventions (Tittonell & Giller, 2013). Prioritizing improved soil fertility management practices, weed control, and access to resources could be recommended. For example, improving FYM management (i.e. minimizing volatilization, leaching, and untimely decomposition) could lead to soil fertility and water retention gains (Bishwakarma et al., 2015), while combining chemical fertilizers with FYM could further improve yields and nutrient use efficiency compared to sole CF or FYM (Jilani et al., 2012). Only then the potential of deficit irrigation could also be harvested, yet its feasibility as a water-saving technique for smallholder MFS remains debatable. DI requires cultivar-specific understanding of crop phenology, adequate monitoring of biotic factors, and reliable irrigation access (Geerts & Raes, 2009). Smallholders often face resource constraints, limited training, and restricted access to technologies, while managing water resources and implementing adaptive technologies become increasingly challenging under growing climate unpredictability (e.g. Alomia-Hinojosa et al., 2018; Bastakoti et al. 2017).

The methods employed in this study highlighted the potential of the AquaCrop and FarmDESIGN models to move beyond research and development, toward implementation by agricultural extension officers fostering further site-specific calibration and validation. AC has indeed been demonstrated particularly effective as a field-level decision-support tool when used collaboratively with farmers and tailored to site-specific social, economic, and ecological factors (Biazin et al., 2021), and well-suited to inform the management of cropping systems of both rainfed and irrigated MFS (Alvar-Beltrán et al., 2023). FD has enabled to promote SI of MFS and stakeholder engagement through participative farm optimization scenario development (e.g. Prusty et al., 2022). However, data limitations are found to be a common challenge in the Global South for implementing model-based decision support systems, which are deemed essential for agricultural development efforts to enhance food productivity, sustainability, and livelihoods (Jones et al., 2017).

Conclusion

Although irrigation could improve yields in year-round cropping systems compared to rainfed systems, the modelling demonstrated that soil fertility and weed competition would constrain net gains. Deficit irrigation generally resulted in higher water productivity than full irrigation, yielding more per unit of water but requiring access to often unavailable technologies. Modelling results showed that timely sowing could optimize water-limited yields and that reconfiguring crop rotations could minimize irrigation requirements while maintaining productivity. Extending rotations with legumes and cereal-legume intercrops could enhance overall farm productivity but might introduce trade-offs with water use. Expanding rainfed cropping to 1 ha could enhance achievable SI more than irrigating 0.5 ha, though irrigated systems expanded the solution space for same-sized landholdings. Incorporating leguminous green manures could mitigate trade-offs between intensified food production, soil organic matter (SOM) improvement, and reduced reliance on external fertilizers. Cereal production could contribute more than livestock intensification to the overall dietary energy yield. However, livestock intensification required less water and was critical for the SOM balance. The dual use of leguminous crops as feed and as green manure revealed competition between these uses. Relatively small changes in farm resource endowment and objectives led to the identification of different crop rotations, livestock herd sizes, and water usage in optimized farm reconfigurations. This underscores the relevance of model-based decision support tools for developing and evaluating field level interventions and their farm level implications. While irrigation and year-round cropping could be promising strategies for mixed farming systems, modelling outcomes showed that sustainable intensification requires consideration of socio-economic and environmental dimensions. Farmer-led technological development trajectories and enabling research and policy environments remain invaluable.

Literature

Alomia-Hinojosa, V., Speelman, E. N., Thapa, A., Wei, H. E., McDonald, A. J., Tittonell, P., & Groot, J. C. J. (2018). Exploring farmer perceptions of agricultural innovations for maize-legume intensification in the mid-hills region of Nepal. *International Journal of Agricultural Sustainability*, *16*(1), 74–93. https://doi.org/10.1080/14735903.2018.1423723

Alvar-Beltrán, J., Soldan, R., Vanuytrecht, E., Heureux, A., Shrestha, N., Manzanas, R., Prasad Pant, K., & Franceschini, G. (2023). An FAO model comparison: Python Agroecological Zoning (PyAEZ) and AquaCrop to assess climate change impacts on crop yields in Nepal. *Environmental Development*, *47*, 100882. https://doi.org/10.1016/J.ENVDEV.2023.100882

Bastakoti, R. C., Bharati, L., Bhattarai, U., & Wahid, S. M. (2017). Agriculture under changing climate conditions and adaptation options in the Koshi Basin. *Climate and Development*, *9*(7), 634-648.

Biazin, B., Wondatir, S., Tilahun, G., Asaro, N., & Amede, T. (2021). Using AquaCrop as a decision-support tool for small-scale irrigation systems was dictated by the institutional and market incentives in ethiopia. *Frontiers in Water*, *3*, 664127. https://doi.org/10.3389/frwa.2021.664127

FAO (2011). *Save and grow: A policymaker's guide to the sustainable intensification of smallholder crop production*. FAO.

Geerts, S., & Raes, D. (2009). Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management*, *96*(9), 1275–1284. https://doi.org/10.1016/J.AGWAT.2009.04.009

Jilani, G., Sarwar, M., Rafique, E., Akhtar, M. E., & Chaudhry, A. N. (2012). Impact of Integrated Nutrient Management on Yield and Nutrient Uptake by Maize under Rain-Fed Conditions. *Pakistan Journal of Nutrition*, *11*(1), 27–33.

Jones, J. W., Antle, J. M., Basso, B., Boote, K. J., Conant, R. T., Foster, I., Godfray, H. C. J., Herrero, M., Howitt, R. E., Janssen, S., Keating, B. A., Munoz-Carpena, R., Porter, C. H., Rosenzweig, C., & Wheeler, T. R. (2017). Toward a new generation of agricultural system data, models, and knowledge products: State of agricultural systems science. *Agricultural Systems*, *155*, 269–288. https://doi.org/10.1016/j.agsy.2016.09.021

Khadka, M., Uprety, L., Shrestha, G., Minh, T. T., Nepal, S., Raut, M., Dhungana, S., Shahrin, S., Krupnik, T. J., & Schmitter, P. (2021). *Understanding barriers and opportunities for scaling sustainable and inclusive farmer-led irrigation development in Nepal.*

Khanal, N. R., Nepal, P., Zhang, Y., Nepal, G., Paudel, B., Liu, L., & Rai, R. (2020). Policy provisions for agricultural development in Nepal: A review. *Journal of Cleaner Production*, *261*, 121241. https://doi.org/10.1016/j.jclepro.2020.121241Get rights and content

Krupnik, T. J., Timsina, J., Devkota, K. P., Tripathi, B. P., Karki, T. B., Urfels, A., Gaihre, Y. K., Choudhary, D., Beshir, A. R., Pandey, V. P., Brown, B., Gartaula, H., Shahrin, S., & Ghimire, Y. N. (2021). Agronomic, socio-economic, and environmental challenges and opportunities in Nepal's cereal-based farming systems. *Advances in Agronomy*, *170*, 155–287. https://doi.org/10.1016/bs.agron.2021.06.004

Mabhaudhi, T., Chibarabada, T. P., & Sikka, A. (2023). Status of integrated crop-livestock research in the mixed farming systems of the Global South: a scoping study. In *Frontiers in Sustainable Food Systems* (Vol. 7). Frontiers Media SA. https://doi.org/10.3389/fsufs.2023.1241675

Nepal, S., Neupane, N., Belbase, D., Pandey, V. P., & Mukherji, A. (2021). Achieving water security in Nepal through unravelling the water-energy-agriculture nexus. *International Journal of Water Resources Development*, *37*(1), 67-93. https://doi.org/10.1080/07900627.2019.1694867

Neupane, N., Shakya, S., Koirala, S., & Khadka, M. (2024). *Identifying Market Challenges and Opportunities in Mixed Farming System Piloted Sites of Mid-hills of Nepal: The Khotang Case*.

NPC (2021). *Nepal's food systems transformation: Context, pathways and actions. Outcomes of the national and provincial food systems dialogues as a part of the UN Food Systems Summit 2021*. National Planning Commission.

Pradhan, P., Costa, L., Rybski, D., Lucht, W., & Kropp, J. P. (2017). A systematic study of sustainable development goal (SDG) interactions. *Earth's Future*, *5*(11), 1169-1179.

Prusty, A. K., Natesan, R., Panwar, A. S., Jat, M. L., Tetarwal, J. P., López-Ridaura, S., Toorop, R. A., van den Akker, J., Kaur, J., Ghasal, P. C., Groot, J. C. J., Barba-Escoto, L., Kashyap, P., Ansari, M. A., & Shamim, M. (2022). Redesigning of Farming Systems Using a Multi-Criterion Assessment Tool for Sustainable Intensification and Nutritional Security in Northwestern India. *Sustainability (Switzerland)*, *14*(7). https://doi.org/10.3390/su14073892

Tittonell, P., & Giller, K. E. (2013). When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Research*, *143*, 76–90. https://doi.org/10.1016/J.FCR.2012.10.007

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