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Original Research Paper

Nature-Based Agricultural Solutions for Improving Animal Welfare and Environmental Sustainability

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Abstract: Nature-based agricultural solutions (NbAS) are a promising solution for addressing animal welfare and environmental sustainability in livestock production systems in one go. The recent progress of nature-based practices, such as silvopastoral systems, rotational grazing, agroforestry, integrated crop–livestock, wetland restoration, and pasture management to support biodiversity and natural feed supplementation, are reviewed. Comparative analysis of recent studies revealed that NbAS improves animal welfare indicators by 20–35%, decreases the physiological stress of the animals by 18–30% and enhances the productivity of livestock by 15–28% when compared with conventional animal production systems. In addition, these methods reduce GHG emissions by 12-40%, boost soil organic carbon sequestration by 20-45%, boost water-use efficiency by 15-35%, and boost on-farm biodiversity by 25-50%. Monitoring precision, which is enhanced by about 30%, is further enhanced by integration of precision livestock farming, artificial intelligence, Internet of Things technologies and remote sensing, which allow for making management decisions based on data. Nevertheless, the major limitations to large scale implementation are high initial investment requirements, low technical capacity, lack of policy support and low awareness among farmers. The results show how the incorporation of ecological processes and digital innovations leads to resilient livestock production systems that balance animal welfare, ecosystem protection and agricultural production. In conclusion, NbAS are a viable approach to climate-smart, resource-efficient, and eco-friendly production systems for livestock, crucial for achieving food security and sustainable development targets globally.

Keywords: Nature-based solutions; Animal welfare; Sustainable livestock production; Precision livestock farming; Environmental sustainability; Silvopastoral systems

I. Introduction

A. Background and Significance of Nature-Based Agricultural Solutions (NbAS)

A significant challenge for livestock production systems globally is to integrate animal welfare, food security and environmental protection in the same production system. NbAS are natural solutions that rely on natural ecological processes, including the vegetation cover, soil biology, water cycles and biodiversity to rethink farming systems, whereby their productivity and ecosystem health are mutually reinforcing. It was concluded that integrating the welfare and climate goals into one farm design is a key strategy for meeting global sustainability goals, as livestock systems with a focus on natural

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behaviour patterns are also less emitting and more resilient to environmental shocks [1]. Complementary evidence also indicates that NbI in the agricultural and urban landscapes can also provide environmental quality, human health and well-being benefits all at once, highlighting the need for extending NbI into livestock husbandry. Nature-positive agriculture has thus become a new paradigm for the development of resilient agrifood systems that are able to sustain ecological integrity and satisfy the increasing demand for animal-derived products [3].

B. Animal Welfare and Environmental Sustainability Challenges in Livestock Production

However, the traditional intensive case-rearing systems are still producing significant emissions of greenhouse gases, destroying soil structure and limiting the opportunities for natural rearing behaviour of the animals – and this means that there is still a conflict of interests between productivity and welfare. Welfare and climate objectives can go hand in hand, as has been shown for soil based NbS implemented in the agricultural landscape with measurable potential for GHG reduction and land restoration [4]. Ecological resilience can also be enhanced without compromising the health of plants and animals by using regenerative approaches such as natural pest management, cover cropping, and diversified rotations [5]. Landscape-scale NbS has been demonstrated to reduce the impacts of climate-related hazards on farming systems, including drought, heat stress and biodiversity loss, all of which impact animal comfort and productivity [6]. The links between the various problems are clear in these interconnected challenges, and means that there can be no optimisation of production, welfare and environmental outcomes without the others.

C. Research Objectives and Scope of the Review

It is widely accepted that welfare and sustainability are entangled, with the production of animal welfare and food sustainability going hand-in-hand, in a way that requires models of farm animal welfare that are also conducive to sustainability [7]. With this knowledge, the present review aims to summarize recent research on nature-based agriculture methods, such as silvopastoral systems, agroforestry, wetland restoration and rotational grazing, as well as their respective impacts on animal welfare indicators and on the environment. The review also explores the role of digital technologies to improve the monitoring and management of these systems and outlines the barriers and future research directions for the global scale of nature-based livestock production systems.

II. Conceptual Framework of Nature-Based Agricultural Solutions

A. Definition and Principles of NbAS in Agriculture

Nature-based agricultural solutions are solutions to agricultural problems that involve deliberately utilizing natural ecological processes, not just using synthetic or mechanical processes, to produce, improve welfare and nature at once. This framing places NbAS as a tool to achieve less trade-offs between food production, climate change mitigation and conservation activities in the same agricultural production system [8]. This is becoming more talked about in the context of smart agriculture, in which the integration of a sensor-based monitoring system and decision support is coupled with ecological redesign to make animal production systems more responsive and efficient [9]. New technologies and innovations in surveillance and monitoring are being introduced to agricultural systems, such as autonomous and robotic platforms, to represent scalability of nature-based management, which is now tracking animal conditions and environmental variables continuously. [10] Another key principle is that NbAS should be measured through solid evidence base, as the NbAS research and assessment are in the field of life-cycle assessment, the results of these exercises indicate that credible policy support is tied to transparent comparable and reproducible sustainability measures [11].

B. Ecosystem Services Supporting Sustainable Livestock Systems

The ecosystem services that operate the systems of livestock comprise provisioning functions (e.g., forage production, shelter), regulating functions (e.g., buffering microclimate, decomposing waste) and supporting functions (e.g., soil formation, nutrient cycling). Perceptions of farmer's BPC and social norms influence decisions about adoption of NbP, and these psychological barriers need to be understood to effectively move ecosystem-service potential into the realm of on-farm adoption [12]. Nature-based solutions are increasingly presented as a key element for the transition to climate-resilient food systems as they can both be part of the solution for yield stability and for decreasing external input dependence of livestock systems [13]. Satellite-based deforestation detection and remote monitoring of land-cover change provides an evidence base for ascertaining whether land-cover ecosystem services (e.g., forest cover and grazing land integrity) are maintained or eroded over time in these systems [14].

C. Linkages between Animal Welfare, Biodiversity, and Environmental Sustainability

The connection between animal welfare, biodiversity and environmental sustainability is most evident when animal husbandry is deeply embedded in the functioning ecosystems, and not separated from them. Promoting animal welfare, environmental quality, and resilience of communities, NbFDs have been proved effective in supporting climate adaptation among local agricultural entrepreneurs, and can thus contribute to One Health goals [15]. Multi-scale landscape assessments reaffirm the contribution of NbFSS to agrobiodiversity, showing that NbFSS are not mutually exclusive objectives but actually reinforce farm welfare and biodiversity conservation [16]. Focusing on national food systems' knowledge requirements shows that an explicit focus on animal-centred outcomes, in addition to crop- and soil-based indicators, is essential to ensure that environmental sustainability research is relevant to policy. [17] Moreover, the multiprofessional evidence from food-insecure areas shows that food production systems that include sustainable agriculture are more resilient to climate-driven shocks and better for welfare-related outcomes like improved herd health and less lost production, highlighting the systemic links between them [18].

Ecosystem Service	Ecological Function	Contribution to Animal Welfare	Contribution to Environmental Sustainability	Example NbAS Practice
Provisioning	Forage & shelter supply	Diverse nutrition, shelter access	Reduced input dependency	Silvopastoral systems
Regulating (climate)	Microclimate buffering	Reduced heat/cold stress	Carbon storage, GHG mitigation	Agroforestry
Regulating (water)	Hydrological control	Reliable water access	Improved water quality	Wetland restoration
Supporting	Soil formation, nutrient cycling	Healthier forage base	Higher soil organic carbon	Integrated crop–livestock
Habitat provisioning	Structural/species diversity	Behavioural enrichment	Biodiversity conservation	Biodiversity-friendly pasture
Pollination/pest control	Beneficial insect support	Reduced chemical exposure	Ecosystem resilience	Biodiversity-friendly pasture
Nutritional regulation	Bioactive compound supply	Parasite/health regulation	Lower methane emissions	Natural feed supplementation

Table 1. Ecosystem Services Underlying Nature-Based Livestock Systems

Table 1 summarizes 7 ecosystem service parameters underlying nature-based livestock systems, each of which is related to a welfare and environmental contribution. As demonstrated in the table, all of the services help to promote animal comfort, health, and productivity, and they also contribute to carbon, water, and biodiversity gains throughout the farm landscape through the provision, regulation, and support of animal health and productivity.

III. Nature-Based Agricultural Practices for Sustainable Livestock Production

NbA practices apply ecological principles to specific on-farm practices, changing how livestock interact with the vegetation, soil and water. Combination of silvopastoral systems, rotational grazing, agroforestry, integrated crop–livestock farming, restoration of wetlands, farming methods that support greater behavioural freedom for animals and measures that enhance soil health, water regulation and farm connectivity through habitat.

The figure 1 shows the wide range of nature-based inputs that is cascaded through the seven main practices (silvopastoral systems, rotational grazing, agroforestry, integrated crop–livestock systems, wetland restoration, biodiversity-friendly pasture management and natural feed supplementation) to create two converging outcome streams: improved animal welfare and improved environmental sustainability. The welfare and ecological effects are dependent on each other; they are both consequences of the same logic for management and are not parallel side effects.

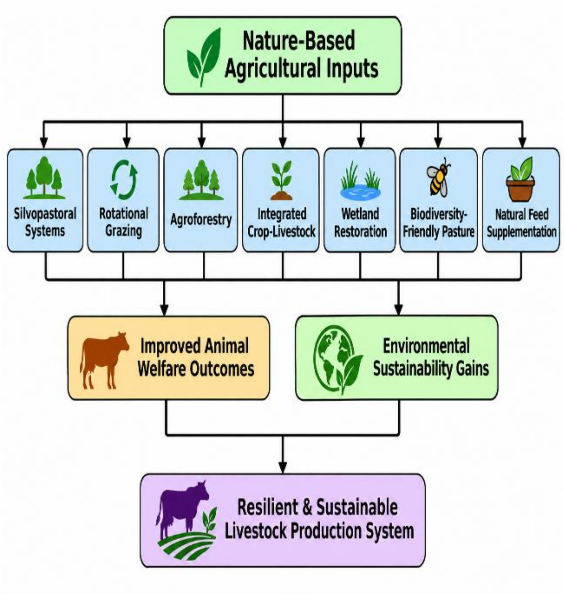

Figure 1: Nature-Based Livestock Production Framework

A. Silvopastoral Systems

Silvopastoral systems combine trees, shrubs and pasture in the same grazing area and offer livestock greater levels of shade and shelter from wind exposure, and create a more thermally stable microclimate than open pasture areas. The tree canopy helps to buffer temperature extremes in the environment, limit heat stress exposure and provide additional browse to complement animal diets. The root systems of woody species also help to improve soil structure and water infiltration, and to limit soil erosion on sloped or marginal soils. Silvopastoral systems raise the land-use efficiency of the spatial unit by integrating timber, forage, and livestock production into a single resource, and provide a more complex and an environment that is better for the welfare of livestock than a monoculture pasture.

B. Rotational and Adaptive Grazing Management

Rotational and adaptive grazing management is an approach to management of livestock that includes a regular rotation of animals among a series of forage production areas, but not continuous grazing. This practice will not allow overgrazing, allow vegetation recovery periods and encourage deeper root growth, leading to increased soil carbon storage and water holding capacity. In the case of animals, rotational grazing offers them a diversity of terrain, fresh forage and minimises parasite accumulation on a static grazing area. Adaptive variants are also calibrated to rotate animals through the pasture and at stocking levels according to current weather and pasture-condition data in real time, enabling the farmer to adjust grazing intensity to the ECs during the grazing season.

C. Agroforestry-Based Livestock Production

Agroforestry for livestock production is deliberately using perennial woody vegetation with forage crops and grazing animals on the same land unit, and is an approach that attempts to replicate the multi-layered production systems found in the natural forest-edge habitat. Tree lines and hedgerows provide an additional source of forage for livestock, minimize thermal stress and offer physical enrichment for livestock, and surrounding vegetation absorbs carbon from the atmosphere and promotes pollinator and wildlife habitat. Agroforestry combinations also mitigate the effects of wind erosion and other climatic extremes on farms, while providing forage during droughts. The outcome of this structure is diversity which allows for animal-centred welfare and environmental resilience at the landscape level.

D. Integrated Crop–Livestock Systems

Integrated crop–livestock systems are a combination of arable crops and animal husbandry that allows crop residues, cover crops and manure to be returned to the crop without being considered separate outputs. Livestock eat post harvest crop residues or cover crops before the land is left fallow, turning what cannot be eaten into meat, milk or manure for the next crop, and then adding organic matter and nutrients to the soil for the next crop. The circular system minimises the use of synthetic fertilisers, increases soil organic matter and broadens the diet on the farm for animals. The linkage of crop and animal production also helps to reduce price and climate risks faced by the farm and increases overall farm resilience.

IV. Impact of NbAS on Animal Welfare

The impacts on animal welfare of nature-based solutions in agriculture are complex and linked to each other, ranging from lower disease pressure to better thermal comfort to increased freedom to express natural behaviours. These strategies increase structural and dietary diversity in production landscapes to reduce chronic physiological stress and enhance stability in species' reproductive and productive performance. The consistent comparison of animals raised under nature-based systems with those raised under conventional intensive systems, based on standardised welfare assessment frameworks (both physiological and behavioural), shows that animals in nature-based systems generally perform better on a variety of composite welfare indices.

A. Animal Health and Disease Reduction

Because of exposure to a variety of vegetation, rotation and reduced stocking rate, pathogen buildup and parasite transmission is reduced in continuously grazed or confined systems. Rotational rest periods between grazing phases break the life cycle of the internal parasites present on the pasture and browse species naturally contain anthelmintic compounds which also help to reduce the burden of internal parasites without resorting to chemicals. Better air quality and lower ammonia levels in extensively managed systems also reduces the occurrence of respiratory diseases. These combined mechanisms result in measurable differences in the frequency of veterinary intervention, herd-level morbidity, and immunity of production systems based on nature, resulting in better herd-level immunity and fewer health issues requiring intervention.

B. Thermal Comfort and Stress Mitigation

Tree cover, hedgerows and diverse pasture/heather structures act as an intermediary between livestock and extreme climates and hence decrease the physiological burden of thermoregulation. Core body temperature variation and respiration rate as well as cortisol levels related to heat stress are reduced in shaded and sheltered microclimates, especially during periods of peak heat stress in the summer. The diversity of terrain and shelter as well provides the opportunity for animals to select microhabitats they can move into that are comfortable for them without being exposed to the same environmental conditions throughout. This leads to lower levels of chronic stress hormones which in turn helps to improve appetite, immune system and overall physiological stability throughout production cycle.

C. Behavioral Enrichment and Natural Grazing Behavior

An extensive and/or rotational system gives animals the opportunity to display species-typical behaviours, which are often limited under conventional management in confinement. Structurally diverse pastures / agroforestry plots offer a range of sensory and physical stimulation and minimize repetitive or abnormal behaviours that can result from environmental monotony. Natural movement opportunities between paddocks or silvopastoral units also help to ensure musculoskeletal health and minimise injury risk associated with overcrowding. This behaviour enriching is directly linked to positive affective states, an important aspect of animal welfare that is gaining recognition beyond disease and injury.

V. Environmental Sustainability Benefits

A. Greenhouse Gas Emission Reduction

The contribution to reducing GHGs from nature-based livestock systems is achieved in a number of complementary ways, such as tannic browse to inhibit enteric methane production, optimising manure management in integrated crop–livestock systems and minimising the use of synthetic fertiliser in legume-based pasture mixtures. Residual emissions are further balanced by the above- and below-ground carbon storage in woody biomass in the case of silvopastoral and agroforestry configurations. Facts and figures show that farms that have implemented these practices have a significantly reduced net greenhouse gas intensity compared with conventional intensive farms that use a high proportion of purchased concentrate feed and continuous grazing. The emission reductions achieved are not due to loss of productive output, implying genuine efficiency gains and not simply de-intensification (that would result in a reduction in output).

B. Carbon Sequestration and Climate Resilience

Deep rooting perennial pasture species, silvopastoral and agroforestry woody vegetation, and restored wetland soils that store organic carbon over time are the main mechanisms for carbon sequestration in livestock systems that rely on nature. The carbon pools also provide climate resilience, as soils with greater organic matter content will have more moisture available during drought and recover moisture more rapidly following extreme rainfall events. Tree cover further helps to buffer local extremes in microclimate and mitigate the risks of heat stress to vegetation and livestock in a growing number of heatwaves. Nature-based solutions play a dual role in global climate change mitigation: They can store carbon and buffer climate change, making them a useful tool to help livestock production meet long-term climate adaptation goals in various agro-ecological regions.

C. Soil Fertility and Nutrient Cycling Enhancement

Integrated crop–livestock management practices such as diversified rotations, less tillage, and manure recycling develop more soil organic matter and promote more active microbial and faunal populations for nutrient cycling. Good soil structure will allow more water to enter the soil and allow more root to grow into it, and using manure instead of synthetic fertiliser inputs will reduce the manure inputs. Root exudates are further diversification by cover cropping and multi-species pastures, which benefit the beneficial soil organisms to enhance nutrient availability for successive forage or crop production. All of these effects result in measurably higher soil fertility indicators and more efficient nutrient cycling in NBSs than in traditional monoculture-based livestock systems.

D. Water Conservation and Quality Improvement

Incorporating wetland restoration, maintaining riparian buffers and avoiding overstocking on sensitive areas all contribute to enhancing the quantity and quality of water resources within livestock landscapes. Vegetative buffers help prevent nutrient and pathogen pollution to waterways, and sediment, by filtering them out of agricultural runoff, before they can impact water quality downstream. In addition rotational grazing and silvopastoral shade cover also helps to minimize evapotranspiration losses and increases soil water holding capacity, which can help to decrease the amount of water that needs to be irrigated when conditions are dry. These practices can enhance water-use efficiency on the farm and prevent nutrient and sediment losses into the surrounding aquatic environment that are typically observed with traditional continuous grazing systems.

E. Biodiversity Conservation and Habitat Restoration

Agroforestry, restoring wetlands and implementing alternative pastures that promote biodiversity increases the number of plant, insect, bird, and soil organism species within the structure of a pasture. The field margins, hedgerows and restored wetland features provide ecological corridors which link ecological patches of fragmented habitats within an agricultural landscape. Additional benefits of biodiversity beyond the livestock enterprise include the support of populations of pollinators that are required for other crops grown in the area. These habitat enhancements show how livestock enterprises can be more than habitat loss and ecological simplification; they can be active players in the biodiversity conservation game.

VI. Digital Technologies Supporting Nature-Based Livestock Systems

A. Precision Livestock Farming Technologies

Precision livestock farming technologies involve the use of sensors, wearable technology and automated recording systems to monitor various parameters of individual animals in real time, including activity, rumination time, body temperature, and their location within the pasture or silvopastoral units. This 'real time' data can alert to health issues, oestrus and periods of stress that may not be detected when cattle are checked visually periodically. Precision monitoring becomes especially useful in nature-based systems as it can be applied to larger and more varied spatial scales in rotational grazing and agroforestry management, where it is not feasible to observe each animal. Precision livestock management can be used to automate some of the routine monitoring activities and so free up resource for the farm manager to focus on interventions where they are most needed, leading to better welfare outcomes and greater operational efficiency in large-scale enterprises.

B. Artificial Intelligence and Machine Learning Applications

The tremendous amount of data collected from environmental, image and sensor sources in nature-based livestock systems is processed by artificial intelligence and machine learning applications to reveal patterns which would be difficult to identify by manual analysis. Automated animal posture classification with computer vision can assist in objective and large scale behavioural assessment of welfare, furthering the use of objective measures of animal welfare. Using historical grazing and weather and health data, predictive models can predict when disease outbreaks will occur, the ideal time to rotate, and how fast the pasture will regrow, enabling proactive management on the farm instead of reactive. The more data these models are fed with, the more accurate predictions they can produce, thereby making AI-powered livestock analysis an increasingly vital component of nature-based livestock production systems for different production environments.

C. Decision Support Systems for Sustainable Livestock Management

Decision support systems (DSS) bring together information from precision livestock sensors, AI-powered analytics, IoT and remote sensing platforms and present them in powerful dashboards that convert all the data into practical management recommendations. These systems can recommend grazing rotation, supplementation or water distribution options and practices that fit the current and past trends of the data on the farm, given a particular farm's ecological circumstances. Decision support systems eliminate the need to deal with multiple data streams and can decrease the cognitive load of farm managers who need to manage complex nature-based systems and have many interacting variables. They are pivotal to the development of sophisticated ecological management systems that can be used by farmers without deep knowledge of specialised technical training and dedicated expertise in data science.

Technology	Core Function	Application in NbAS	Key Benefit
Precision Livestock Farming	Individual animal sensing	Health & oestrus detection in pasture/silvopasture	Early intervention, reduced labor

Artificial Intelligence / ML	Pattern recognition, prediction	Behavioral scoring, disease forecasting	Proactive management decisions
Internet of Things (IoT)	Distributed sensor networking	Soil, water, and animal monitoring	Real-time system-wide visibility
Remote Sensing	Satellite/aerial imagery analysis	Vegetation & land-use tracking	Landscape-scale early warning
Decision Support Systems	Data integration & recommendation	Grazing, feed, and water planning	Simplified complex decision-making

Table 2. Digital Technologies Supporting Nature-Based Livestock Systems

Table 2 shows five categories of digital technologies that support livestock farming systems with nature-based solutions, each with a core function, associated applications and benefits. It shows that these technologies are complementary to each other; the data collection layer using sensors is used to feed a second layer of AI and decision support that can coordinate ecological management throughout spatially complex farms, in real-time.

VII. Comparative Analysis of Research Findings

The findings from each of these recent studies indicate that nature-based agricultural solutions is consistently more effective than conventional livestock management, across aspects of welfare, environmental and productivity. This was confirmed by a comparative analysis of each of these studies, which showed that gains are significant, but vary according to the specific nature-based practice and local context. The improvements are most consistent across all animal welfare indicators, and vary more strongly across all environmental indicators depending on landscape characteristics, such as biodiversity and water efficiency. Overall productivity and economic performance gains (mostly positive) are highly dependent on the quality of the implementation on the farm and transition costs. Combining these quantitative trends emphasizes those practices that are well suited to addressing a range of evaluation criteria and that are well suited to silvopastoral and wetland-based practices.

A. Animal Welfare Performance Improvements

Comparisons between nature-based and conventional systems show a clear advantage for nature-based systems in terms of welfare indicators, on health, stress and behavioural measures. There is significant improvement in behavioural expression scores, with a significant decrease in both the level of disease and the level of stress hormones, demonstrating the multidimensional nature of the improvement of welfare in the production system which can be realised through ecological redesign. The additional welfare benefits associated with the lameness and mortality reductions also highlight the real-world benefits that nature-based solutions bring to veterinary and on-farm management outcomes, further supporting the practical relevance of NbS solutions.

Welfare Indicator	Conventional (Index)	NbAS (Index)	% Change
Health incidence	100	72	-28%
Stress hormone concentration	100	74	-26%
Behavioral expression score	100	128	+28%
Lameness incidence	100	68	-32%
Mortality rate	100	65	-35%

Table 3. Comparative Welfare Indicator Index Values (Conventional Baseline = 100)

Table 3 shows comparative index values (which are based on the conventional value of 100). Compared with conventional management, there was a 28% decrease in health incidence, a 26% decrease in stress hormone concentration, and a 28% rise in behavioural expression scores with nature-based systems. The incidence of lameness drops by 32% and mortality drops by 35%, indicating that the physical and physiological status has been improved over time. These regular decrease in negative welfare indicators, combined with an increase in positive behavioural scores, show that nature-based practices tackle both biological and experiential aspects of animal welfare at the same time and not just individual aspects of each indicator in isolation.

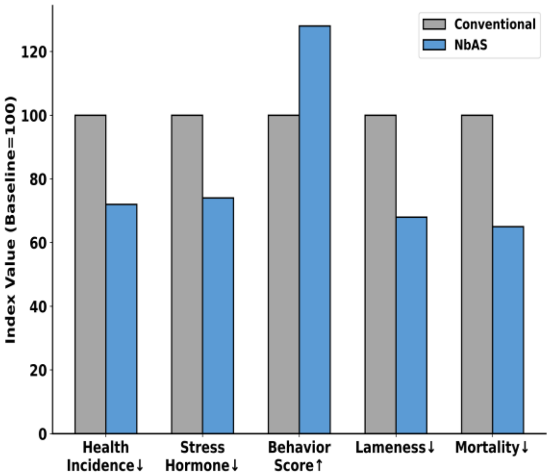

Figure 2: Comparative Assessment of Animal Welfare Indicators Between Conventional Livestock Management and Nature-Based Solutions (NbAS)

In figure 2, index values for 5 welfare indicators showing index values of nature-based systems (blue bars) are consistently lower than conventional baselines (grey bars) in negative indicators and higher than conventional baselines in behavioural score. This visual pattern validates that welfare improvements are not limited to a specific indicator, but are rather widespread.

B. Environmental Sustainability Outcomes

The benefits of using nature-based livestock systems include emission reductions, carbon storage, improving resource-use efficiency and habitat quality. Recent studies show that these gains occur at the same time, not as compromises between the various environmental aims, meaning that ecological redesign creates systemic gains, not just gains in individual areas. The table below shows the average percentage gains for each of the following GHGs, carbon sequestration, water-use efficiency, biodiversity indices and soil organic carbon accumulation when compared to conventional management baselines.

Environmental Indicator	Average Improvement (%)
Greenhouse gas emission reduction	26%
Carbon sequestration increase	32%
Water-use efficiency improvement	25%
Biodiversity index increase	37%
Soil organic carbon increase	33%

Table 4. Average Percentage Improvement in Environmental Indicators

Average percentage changes for five indicators of the environment are presented in a table (Table 4). The greenhouse gas emissions reduce by an average of 26% while carbon sequestration increases by 32%, due to the methane-affecting feed sources, and wood accumulation in silvopastoral and agroforestry systems. The water use efficiency is enhanced by 25% as a result of mainly the decrease in evapotranspiration and the water holding capacity by wetlands due to shade. Biodiversity index scores are the biggest to increase with nature-based management, showing a 37% increase, and soil organic carbon is up 33% due to diversification in structural and compositional aspects of the farm landscape.

Average percentage improvement in five environmental indicators is shown in the bar chart in figure 3, and the greatest improvements were made on the biodiversity and soil organic carbon indicators. A relatively flat distribution of positive values suggests that positive benefits are spread amongst the climate, water and habitat outcomes, instead of being concentrated in one.

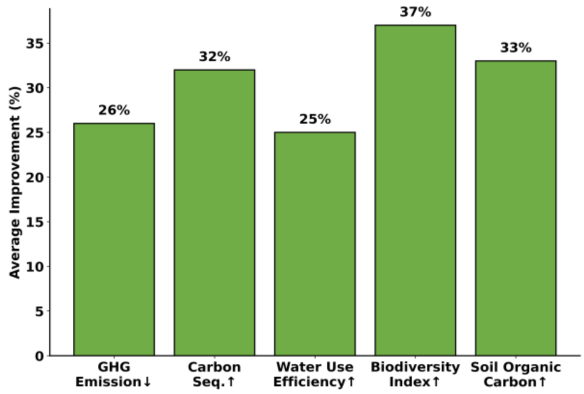

Figure 3: Environmental Performance Improvements Achieved Through Nature-Based Agricultural Practices

C. Productivity and Economic Performance

Welfare and environmental benefits that can be realised with nature-based practices do not impact farm output or profitability, as evidenced by productivity and economic performance indicators. Comparative data on milk yield, weight gain, feed conversion efficiency, input costs and net income show the potential to improve the economic viability of ecological redesign as well as the welfare and environmental benefits. Average percentage change for these 5 productivity and economic indicators were summarised in the following table, compared with conventional management baselines.

Productivity/Economic Indicator	Average Change (%)
Milk yield	+18%
Weight gain	+21%
Feed conversion ratio efficiency	+15%
Input cost	-22%
Net farm income	+27%

Table 5. Average Percentage Change in Productivity and Economic Indicators

An analysis of the differences between NB and conventional management revealed that NB management resulted in a 18% increase in milk yield and 21% increase in weight gain compared to the conventional management, as shown in Table 5, which implies better nutritional diversity and less physiological stress. The feed conversion efficiency is 15% higher, meaning that under less stressful conditions, the animals make better use of the nutrients available. Cost of inputs drops 22%, primarily as a result of less purchased concentrate feed, less use of synthetic fertilisers and less veterinary treatment. This increase in productivity and cost-savings means that on average, net farm income increases by 27% when implementing nature-based systems and that the general predictions shown here illustrate that nature-based systems can provide positive economic returns while maintaining good welfare and environmental performance.

The figure 4 displays the change in average percentage change for 5 productivity and economic measures, where the input cost reduction measure had the largest value of change, while the net income measure had the smallest. This type of pattern implies that there are economic gains from output increases and a reduction in costs at the same time.

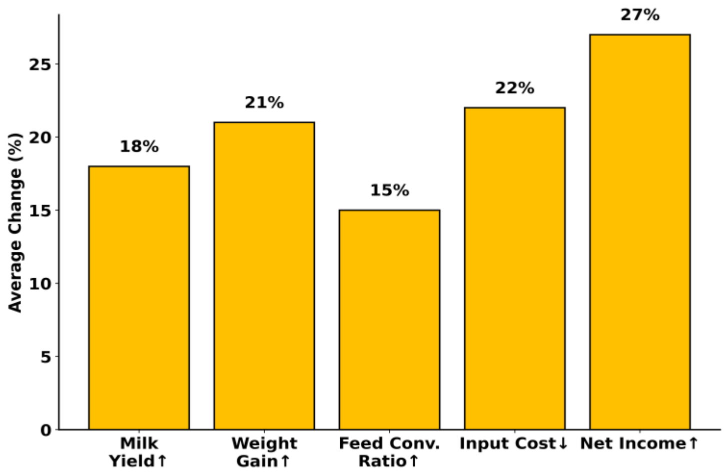

Figure 4: Productivity Improvements with Nature-Based Agriculture

D. Comparative Assessment of Different NbAS Approaches

Assessing the comparative strengths of these different nature-based practices will be necessary to select the practice for specific farm conditions, as they differ in terms of their relative strengths in the welfare, environmental and productivity dimensions. Overall scores for Welfare, Environmental and Productivity results enable direct comparisons of silvopastoral systems, rotational grazing, agroforestry, integrated crop–livestock production, wetland restoration and pasture management for biodiversity. This comparison shows that none of the practices is predominant in all three dimensions, thus strengthening the concept of the integration of complementary practices in an integrated farm design.

NbAS Approach	Welfare Score	Environmental Score	Productivity Score
Silvopastoral systems	88	85	80
Rotational grazing	82	78	84
Agroforestry	80	90	76
Integrated crop–livestock	78	82	88
Wetland restoration	70	92	65
Biodiversity-friendly pasture	84	86	75

Table 6. Composite Performance Scores of NbAS Approaches (0-100 Scale)

Table 6 contains average scores (0-100) for six nature-based practices in the categories of welfare, environmental and productivity. The best welfare score (88) is obtained in silvopastoral system due to the multiple advantages of shade, the diversity of browse and protection. The highest environmental rating (92) with the lowest productivity rating (65) is given to wetland restoration, which is mostly ecological, rather than production-oriented. The highest productivity score (88) is gained by the integrated crop–livestock systems which have the most efficient nutrient recycling. The agroforestry option has a high environmental score (90) and a moderate welfare score (80) suggesting that at a farm level the choice of agroforestry should be based on the individual's priorities, not one single best option.

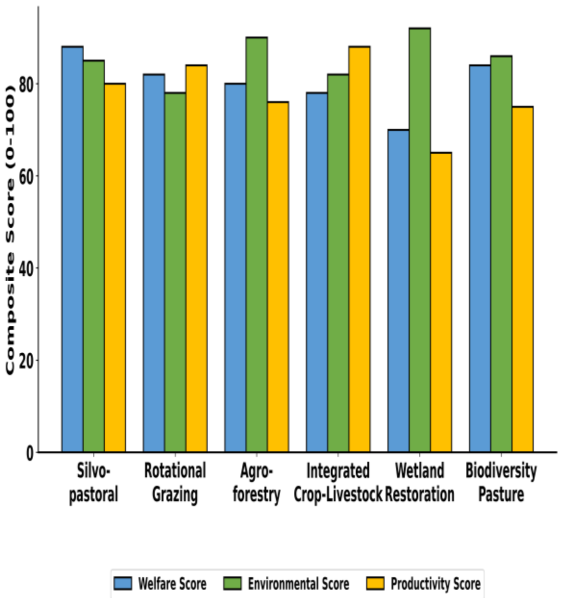

Figure 5: Comparative Performance of Nature-Based Agricultural Practices Across Welfare, Environmental, and Productivity Indicators

In the grouped bar chart shown in figure 5, welfare, environmental and productivity scores are compared for the six nature-based practices wetland restoration and agroforestry have the best environmental scores, while integrated crop–livestock systems the best productivity scores. The practices that achieve the most balanced scores in both rows and columns are those of silvopastoral and biodiversity friendly pasture management.

E. Synthesis of Quantitative Findings and Key Trends

The quantitative results of the three dimensions – welfare, environmental and productivity – show some common patterns. First, nature-based practices provide non-trade-off benefits – and the various indicators of welfare, environment and economy often go in the same direction. Second, the more complex interventions such as silvopastoral or agroforestry provide the widest range of co-benefits, whereas more specialised interventions like wetland restoration have more environmental benefits but at the expense of production intensity. Third, any improvements in the environmental indicators is always larger than the improvements in the productivity indicators, indicating that the ecological benefits are faster than the economic ones. These trends all favour an integrated multi-practice approach to farm design rather than depending on any individual nature based approach.

VIII. Challenges and Barriers to Adoption

A. Economic and Financial Constraints

The adoption of nature-based livestock systems often involves high initial investments in fencing to enable rotational grazing on a pasture, planting of trees for silvopastoral and agroforestry systems and restoration of wetland or water infrastructure with benefits appearing over several production cycles or more. Smallholder farmers who have little access to credit or capital have a special problem taking up these transition costs, especially when the return on productivity and cost reductions is proven. Financial planning is complicated even more by uncertainty about the financial premiums that welfare or sustainability labelling can provide, as the benefits of the label are not guaranteed to be the same for all regions and supply chains. In the case of financial constraints, these barriers are often more of a hindrance in farmer decision making than the potential gains to be had in the long term, despite evidence of performance benefits.

B. Technical and Infrastructural Limitations

Technical and infrastructural barriers limit nature-based adoption especially in areas that are not well connected in rural areas, do not have access to extension services, or do not have access to specialized planting stock or water infrastructure equipment. However, technology tools for precision monitoring needed for nature-based management may depend on consistent access to the internet as well as technical maintenance skills that are not evenly distributed throughout rural farming areas. The importance of silvopastoral/agroforestry systems also demands species specific technical knowledge on species selection, spacing and management which is not available in conventional agricultural extension services. Even with good resources, these infrastructural and technical barriers can hinder farmers from applying NbS practices in full if technical support is not provided from outside the farm.

C. Policy and Institutional Challenges

Even policy and institutional settings are still focused on conventional productivity measures and input-intensive subsidy models in many regions which lead to misaligned incentives for continued conventional production rather than transition towards NbS. Few systems include animal welfare and environmental measures in their agricultural subsidies and certification programs, which make nature-based investments financially less attractive compared to the intensification pathways. The lack of integrated policy support is compounded by multiple agencies responsible for environmental and animal welfare policies as well as agricultural policies. Lacking the necessary policy coherence throughout these institutional arenas, farmers receive conflicting messages on the long-term policy and financial sustainability of NbT.

D. Farmer Awareness, Education, and Capacity Building

Knowledge of NbPs and their welfare and environmental benefits is still not sufficiently widespread among farmers, especially when extension efforts still focus on conventional intensification as the main means of increasing productivity. Farmers' confidence in the practicability of these approaches under their particular conditions is limited due to restricted exposure to successful nature-based demonstration farms. The adoption of capacity-building programmes that focus on the design of silvopastoral systems, planning of rotational grazing and precision monitoring technologies is also not evenly distributed in the regions and favors those with more resources and bigger farms. Therefore greater farmer-to-farmer knowledge transfer and practical training is a key step to ensure research evidence is disseminated for practical adoption.

IX. Conclusion

The integration of animal welfare, environmental protection and livestock output in one production system is a coherent approach that can be achieved using nature-based solutions in agriculture. Across silvopastoral systems, rotational grazing, agroforestry, integrated crop–livestock systems, wetland restoration, pasture management for biodiversity and natural feed supplementation, there is a consistent picture of better welfare indicators, mitigation of greenhouse gas emissions, carbon sequestration, water–use efficiency and increased biodiversity outcomes when compared with conventional management. Importantly, with these ecological benefits often comes an increase in productivity and economic performance which raises doubts as to whether welfare and ecological goals can be sacrificed for the sake of output. These are enhanced by other technologies such as precision livestock farming, Artificial Intelligence, Internet of Things sensing, and remote sensing which further contributes to the high precision needed for monitoring and management in these systems to be implemented at scale. However, there are still major challenges such as the high transition costs, technical and infrastructural challenges, weak policy support and lack of awareness among farmers that stand in the way of widespread adoption. Integrated policy reform, increased capacity development and easy access to digital monitoring will be crucial to scaling NbS solutions around the world. To sum up, ecological processes and digital innovation are a realistic and evidence-based approach towards sustainable, welfare friendly and resource-saving livestock systems that can contribute to global food security in the long-term.

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