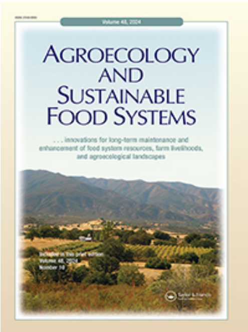

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Manure contribution to rural livelihoods at farm and landscape levels: a systemic approach in semi-arid Central Tunisia

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ABSTRACT

Manure valorization through on-farm use or market transactions is an ancient and widespread practice in the mixed crop-livestock systems of the semi-arid areas of North Africa. While research has long focused on the manure contribution to soil fertility at the plot level, little has been done concerning livelihood conditions. The present paper aims to assess the contribution of manure use and exchange on the livelihoods of rural communities using an original dataset collected in 2021 among 150 farmers in Central Tunisia. This analysis is carried out within the analytical agroecology framework combined with factor analysis methods. Results showed that manure use and valorization differ along the watershed, from a socioeconomic perspective in small farms operating under rainfed tree-pastoral systems, to an environmental and agronomic perspective in the mixed rainfed-irrigated systems downstream. Manure flow analysis confirmed that on-farm manure balance is positively correlated to economic wealth. However, the manure fluxes questioned the environmental sustainability of the vulnerable zones. Its use and management could significantly impact livelihood discrepancies in the future, with the increasing of demand and use of manure in more favorable zones such as irrigated lands at the detriment of the rainfed zones.

KEYWORDS

Manure management; Livelihood landscape; Farming system; Agroecology; Live on land

SUSTAINABLE DEVELOPMENT GOALS

SDG 1: No poverty

Introduction

The Southern Mediterranean landscape, spanning various biogeographic areas from the humid mountains in the North to the oasis or pastoral systems in the South, heavily relies on livestock activities that foster interactions between farms and the various agro-climatic landscapes (Alary et al. 2019; Moulin 2014). When this landscape is considered as a socio-ecosystem, livestock offer

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diverse functionalities and services, including meat and milk for food consumption and income generation, wool and skins, manure for soil preservation, recycling plant nutrients and carbon sequestration (*Ibid*). Livestock also heavily shapes the cultural, social, and economic pillars of societies living in the landscape. This Southern Mediterranean landscape is a representative socio-ecosystem of integrated crop-livestock systems around the world in which intra- and inter-farm interactions between crop and livestock components have demonstrated their importance in countering low productivity, drought, and other social and political shocks (Dumont et al. 2019; Herrero et al. 2013; Ryschawy et al. 2014; Sekaran et al. 2021; Thornton and Herrero 2014; Vall et al. 2023). The multifunctionality generated through the integration of the crop and livestock activities at the farm and landscape level allows us to reconsider the place and role of livestock within the agroecological framework. Notably, valorizing the livestock contribution, notably through manure management, by increasing synergies and recycling, and reducing the dependency on purchased inputs, could improve the overall socioeconomic and environmental viability of the integrated system from the perspective of an agroecological transition.

Agroecological practices, as defined by Wezel et al. (2014), are agricultural practices that seek to valorize in the best way ecological processes and ecosystem services. They are either new practices or traditional practices that have existed for a long time (Wezel et al. 2009). Ameur, Amichi, and Leauthaud (2020) recorded a dozen agroecological practices in North Africa of which the most important are mixed integrated crop-livestock farming (100% of the farmers interviewed using this system); the use of organic manure (90%); agroforestry (80%); and tillage reduction. In North African mixed farming systems, numerous agroecological practices related to crop-livestock integrated systems have been identified, including the use of compost, sheep manure, and manure teas in irrigated systems, as well as agroforestry with integrated olive-sheep production, or Barbary Figs in rainfed systems (Ameur, Amichi, and Leauthaud 2020; Akakpo et al., 2021; Hamamouche et al. 2020; Leauthaud et al. 2022; Mekki et al. 2021). These authors focused on rainfed or irrigated systems at the plot or farm scale. However, rainfed and irrigated systems are intertwined, especially in the case of livestock-related agroecological practices, because livestock are mobile in this semi-arid environment. Hence, there is a real interest in focusing on the territorial integration of livestock rearing and crop production. Here, we take the practice of manure management to illustrate this fact.

If manure management is an ancient practice in the Mediterranean region, soil fertility management remains one of the main challenges within the semi-arid zones of the basin (García-Ruiz et al. 2013; Lagacherie et al. 2018). Biomass is produced through livestock breeding and cropping activities. However, this biomass is poorly recycled on farm, leading to excessive use of chemical fertilizers and unsatisfying soil characteristics limiting the performance of both the agricultural and livestock feeding practices (Lal 2004; Powlson et al. 2014). With increasing social, scientific, and political interest in the development of enhanced agroecological systems (Altieri, Funes-Monzote, and Petersen 2012; HLPE 2019; Weber et al. 2009, 2014), manure use and management are evolving from a traditional practice to a niche activity that can significantly contribute to achieving agroecological transformations at multiple levels of the agroecological transition. This paper aims to provide an early assessment of the contribution of manure to agroecological transformation, particularly in the characterization and evaluation of the impact of various manure management patterns on livelihoods at farm and landscape level. Three main manure management types are most commonly used in Central Tunis: 1) the dry manure storage in mixed crop-livestock systems where manure is piled in open-air heaps or stored in dry and covered areas; 2) the fresh -or after a short period of storage-manure spreading onto cropland, usually practiced for rainfed cereal crops (like wheat and barley) or olive groves in rainfed zones; and 3) the grazing in pastoral systems where manure is naturally deposited and left to decompose in the field. Other types such as composting are rarely observed.

In the literature, manure use has mainly been studied regarding agronomic and environmental perspectives (Petz et al. 2014), but with few studies including economic, social, and gender-equity perspectives. Little is known about the income generated directly by manure or indirectly by manure transactions on the improvement of livelihoods at the farm and landscape levels. Moreover, from a farmers' perspective, but also from that of local development agencies, manure use is mainly considered a traditional practice and not an innovation to support sustainable agro-food transformation (Ayele et al. 2012; Rufino et al. 2007). This resource's social, economic, and environmental outcomes are often underestimated. In particular, the labor implications and considerations for gender equity are quasi-absent in the studies on manure management. These considerations are important as a balance between ecological, economic, and social benefits should be achieved through using manure.

The overall goal of the present paper was thus to assess the multiple and interlinked socioeconomic and environmental contributions of manure at both farm and landscape levels, using the multidimensional framework of agroecology. This research aimed to explore the monetary and non-monetary wealth creation in terms of socio-economic well-being and resource-use efficiency stemming from manure management that valorizes the interactions between livestock and resource use at the farm and landscape levels.

Conceptual framework

Previous research highlighted the economic and social contribution to rural livelihoods and diversification of household activities provided by manure use and management (Alary et al. 2021) and biodiversity preservation through grazing practices (Davis 2005). However, assessing manure management impacts on the agroecosystem at the farm level and food system at the landscape level involves the analysis of interactions and mutual influences between agroecological principles, as proposed in Figure 1. Manure management as an agroecological practice is aligned with several agroecological principles such as mineral fertilizer reduction, recycling, soil health, synergy with the ecological environment, and economic diversification. In parallel, given the transdisciplinary nature of agroecological principles and approaches, a multiscale approach incorporating off-farm effects is required.

Figure 1 depicts the relationship between enhanced manure management and agroecological principles at the agroecosystem and landscape levels. In mixed crop-livestock systems, manure constitutes an organic nutrient,

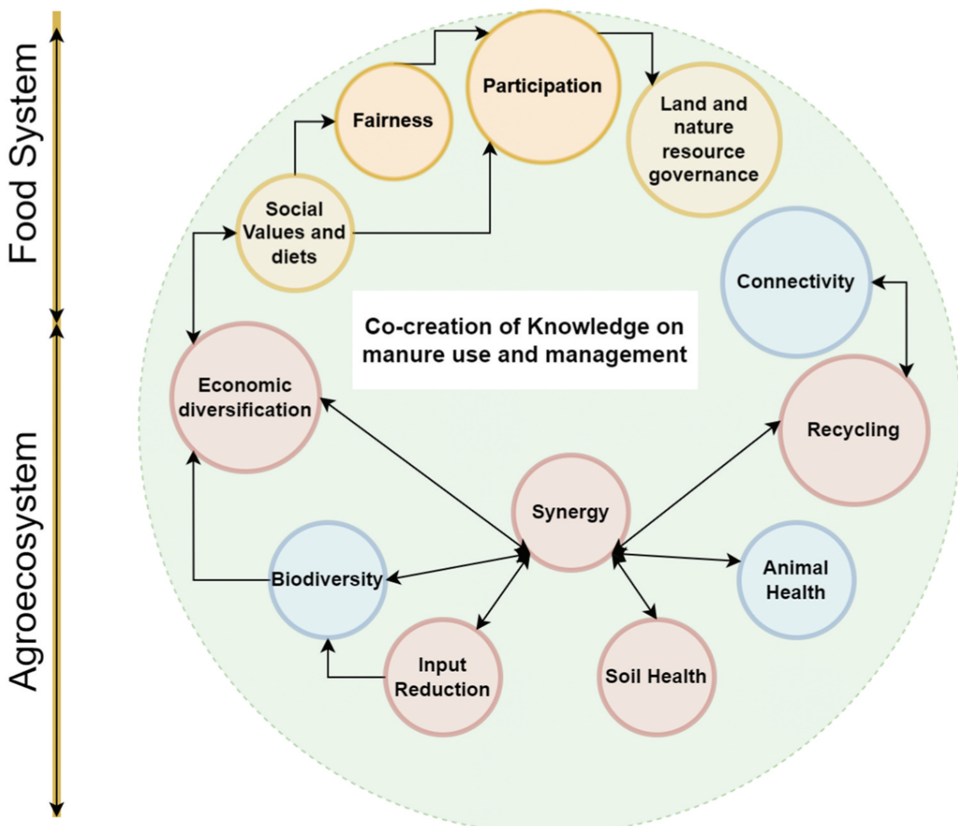

Figure 1. Manure as a core element of agroecological principles with connections to other agroecosystem and landscape-level practices note: red circles show agroecological principles to which manure is directly linked; blue circles show agroecological principles with which manure has some indirect effects; and orange circles show agroecological principles that will have effect through effects of cascade. The arrows show the cascading effects induced by manure management from one principle to another. Adapted from HLPE (2019) and Wezel et al. (2020).

a potential substitute for mineral fertilizers (input reduction), that enhances both physical and biological properties of the soil (soil health) while valorizing local, renewable resources issued from the farm system as a co-product of livestock systems (recycling) (Powell, Pearson, and Hiernaux 2004; Rufino et al. 2011). The "synergy" principle is usually related to the positive ecological interactions between agroecosystem elements (Wezel et al. 2020). We can cite multiple interactions related to livestock, such as livestock grazing for weeding and fertilization, as well as eating and pruning trees, use of shade of trees for livestock, and legumes for livestock feed, among others (Ben Salem and Smith 2008; Neffati, Ouled Belgacem, and Chaieb 2009). Manure-enriched fields can provide improved habitats for invertebrates, which are food for birds and other animals, thus indirectly promoting biodiversity. Moreover, reducing chemical inputs (such as synthetic fertilizers and pesticides) in crop production can have several positive consequences, both in terms of reducing environmental pollution and encouraging the adoption of more sustainable farming practices, such as manure application, choice of resistant varieties and mixes of varieties (legumes – grasses) to strengthen crop-livestock interactions (Altieri 2002; Bonaudo et al. 2014; Dumont et al. 2013; Wezel and Peeters 2014). However, the links between biodiversity and manure are not obvious, as they depend on how it is managed, particularly to limit nitrate pollution as it is observed in Europe (Wezel and Peeters 2014).

In this paper, we propose to analyze the "synergy" principle in terms of livelihood outcomes, resulting from input reduction, soil fertility management and crop yield increases, and economic diversification. Through the present agroecological framework, we propose highlighting the multiple contributions of manure as a renewable resource at farm and landscape levels. The main hypothesis is that the role of manure management and its benefits on soil fertility and livelihood enhancement is too often underestimated in the technical and policy agricultural programs and strategies in Tunisia.

Materials and methods

Case-study: literature review and delineation

The Governorate of Kairouan is located in Central Tunisia where agricultural and livestock farming are present with vulnerable natural resources and a limited access to inputs. More specifically, Kairouan has a semi-arid climate with a hot, dry summer and a cold, wet winter. Average annual rainfall varies from less than 200 mm to a maximum of over 400 mm, and around 70% of the territory is between 200- and 300-mm isohyets (ARC Atelier de Réalisation et de Conception 2011; Mougou et al. 2011). The topography of Kairouan includes flat, fertile plains in the East (100 m above sea level) and medium to high mountains in the West, reaching 700 m altitude, except for Jebel Serj, which reaches an altitude of 1,300 m (ARC Atelier de Réalisation et de Conception 2011). Agriculture remains one of the most important economic activities in the region employing around 30% of the workforce. The agricultural area covers over 614,000 ha, of which approximately 432,080 ha are arable, with 80% being cultivated (15% irrigated and the rest is rainfed) (*Ibid*). Around one-third of agricultural land is pastureland, and 6% is forest (Bureau d'étude 2011; CRDA 2011). Thanks to its geographical diversity, the Governorate of Kairouan is representative of two typical farming systems in the North African rainfed zone, i.e. (i) irrigated or rain-fed crops, forests, and pasturelands in the North-West; (ii) rainfed or irrigated crops, especially arboriculture (olive trees) and market gardening in the central plains (Marzin et al. 2016).

In the Kairouan Governorate, the downstream section of the Merguellil basin is characterized by irrigated agriculture. Market gardening, arboriculture, and cereals are the dominant crops, with small dairy cattle or small ruminant livestock production. The development of the irrigated agriculture depends mainly on access to water resources and the texture of the soil (Leduc and Virrion 2007; Leduc et al., 2004; Morel 2018). Still, it is also highly dependent on labor and manure from upstream in the basin, which is characterized by an extensive rainfed farming zone (*Ibid)*. In this zone, market gardening in small irrigated areas is mainly for household consumption (Du Buisson de Courson 2017). The foothills and mountainous areas are used for livestock grazing. Arboriculture, particularly such as olive and almond trees, is the predominant form of cultivated crop, while some annual crops, like mainly barley and wheat, are less common which are limited due to water scarcity and the complex arduous topography (*Ibid*).

Sampling approach

To take into account the diversity and complementarity between agro-ecosystemic environments in the landscape, notably in relation to manure and fertility management, we opted for a transect analysis along the Merguellil watershed that includes five delegations (administrative division at the local level) from East to West of the governorate (see Figure 1). The five delegations along the watershed represent the landscape unit in the present paper.

A farm survey was conducted in 2021 in the Merguellil upper catchment and downstream plain to assess the socioeconomic conditions of farmers, as well as the characteristics of their respective production systems and related input uses. Farm surveys were conducted using a semi-structured questionnaire composed of seven sections related, respectively, to: 1) Family characterization and workforce; 2) Agricultural assets and equipment; 3) Land and the cropping system; 4) Herd composition and management; 5) Agroecological practices; 6) Financial means; and 7) Household food security status. In complement to these seven sections, we added three specific sections related to manure production and use on farm, the manure transaction, and the workload due to manure management. The survey was conducted from June to September 2021 using Open Data Kit (ODK) software on a tablet for the seven general sections on farm structure and functioning and on paper for the three specific sections related to manure use and management. The approval and consent of the surveyed persons were systemically asked. All data were stored on an EXCEL database (2022).

To consider the diversity and complementarity between the different watershed zones relating to manure use and fertility management, we selected five administrative units (delegations) along the Merguellil watershed, comprising of plain areas (Chebika, Haffouz, Hajeb el Layoun) but also piedmont

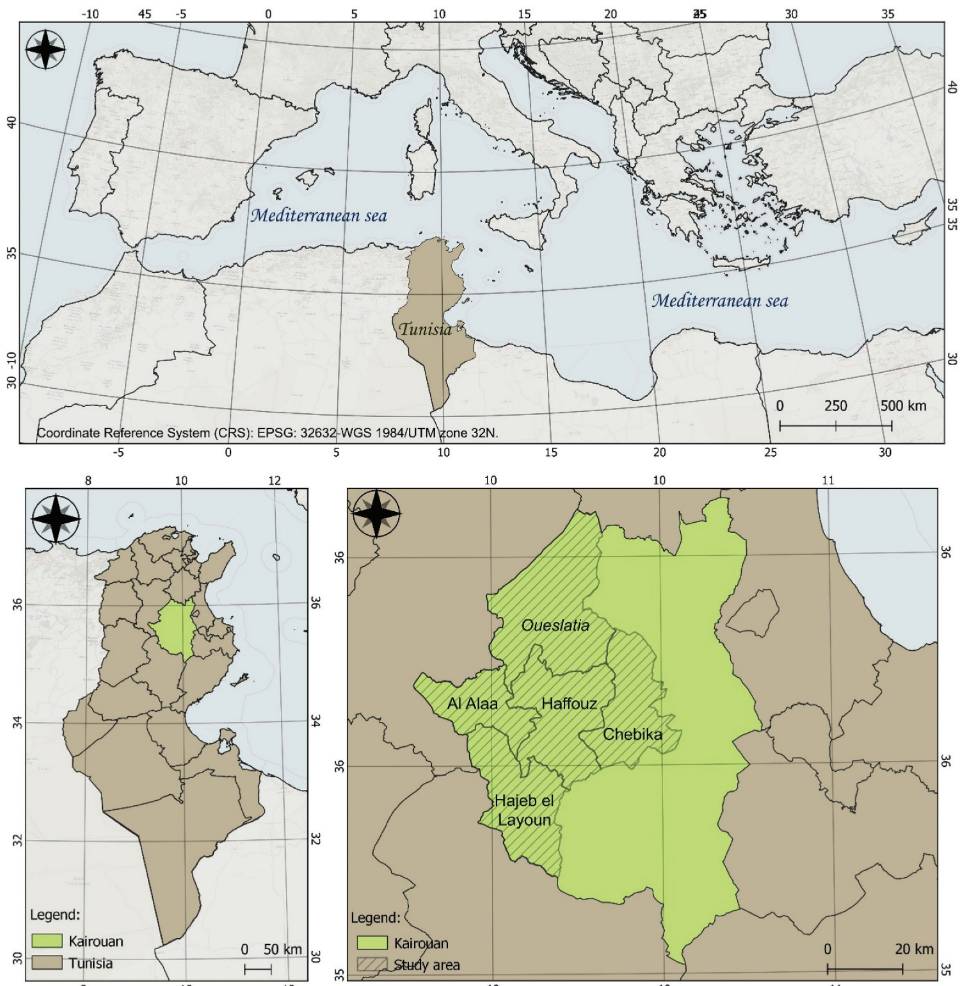

Figure 2. Location of the Kairouan Governorate in Tunisia (up and left) and the studied site with the five delegations of the farms surveyed in Kairouan Governorate (right down) (@ICARDA, 2023).

or mountainous zones (Oueslatia and El Alâa) (see Figure 2). Thirty farmers in each delegation were interviewed with regard to their livestock activity and manure use using a snowball sampling approach (Goodman 1961). In the upstream delegations, the first identified farmers were in partnership with the technical officers of the CTV ("Conseil technique et de vulgarisation"), while in the downstream delegations, the first farmers were identified in previous research projects in the zone. The criteria to identify the farmers were the type of farming system to cover the diversity of livestock, tree, and crop activities and also the land size. Over the 150 surveys, 147 farmers were retained for the results and analysis.

Table 1 summarizes the characteristics of the family farm systems in each delegation. The cropping pattern differs between upstream and downstream watershed according to irrigation facilities. Vegetable farming is the most dominant type of agricultural business in the downstream part of the watershed, while livestock activities with cereal crops are more developed in the upstream part. However, most systems were integrated crop-livestock along the watershed transect.

Legend: TLU (Tropical Livestock unit); Owned equipment refers to agricultural and watering equipment, including sprinklers, cisterns, motor pumps, wells, boreholes, drip irrigators for water management, mowers, harvester, sprayers, grinders, seeder, or tractors for crop cultivation and rework, or trailer for transportation.

Table 1. Characteristics of the farms surveyed by delegation in Kairouan ($n = 147$ farms, data represent means ± standard deviations).

	Downstream				Upstream					
Variables	Chebika		Haffouz		Hajeb Layoun		El Alâa		Oueslatia	
	31		31		28		30		27	
Sample size	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Age of the family head	50	16.9	51.4	16.7	44.3	12.8	53.2	16.5	48.7	17.0
Household size	3.7	1.7	4.7	1.4	4.2	1.3	3.8	1.9	4.5	2.1
Family members with secondary school level	2.8	1.6	3.6	1.1	2.5	1.3	2.2	1.6	2.9	2.0
Women members > 16 years old	0.7	0.9	1.5	1.0	1.4	0.7	1.6	1.3	1.8	1.2
Family members working on the farm (full-time)	2.4	1.4	2.6	1.3	2.2	1.0	2.1	1.1	2.2	1.5
Owned land area (ha)	8.5	8.6	4.1	7.3	2.3	1.6	1.8	3.1	6.1	11.5
Rented land area (ha)	4.3	6.0	0.4	1.4	0.4	1.4	0.0	0.0	2.7	7.0
Cereal area (ha)	3.9	6.4	0.2	0.6	0.4	1.2	0.4	1.0	7.4	13.6
Vegetable area (ha)	5.0	5.6	4.1	9.8	2.9	2.1	2.9	8.8	0.4	0.9
Forage area (ha)	0.3	0.9	0.4	1.6	0.1	0.4	0.4	1.0	0.2	0.6
Tree area (ha)	5.7	7.0	4.6	4.9	2.1	2.6	3.4	2.8	7.1	8.9
Cattle (number)	1.0	2.2	0.0	0.0	0.8	1.6	1.6	3.2	0.1	0.8
Goat (number)	3.0	5.9	2.3	3.8	0.3	1.1	0.9	2.5	6.8	12.3
Sheep (number)	37.7	41.6	30.7	29.2	9.0	12.7	12.2	11.9	37.7	37.4
TLU (units)	9.8	10.6	2.5	4.0	3.7	6.5	2.0	3.9	1.9	8.6
Owned equipment (number)	3.8	1.9	2.5	1.9	3.7	1.4	2.0	1.5	1.9	1.4

Method

In the present study, to assess the livelihoods of rural communities along a gradient of manure use, we applied a systemic approach based on factorial analyses at the farm level and a descriptive statistical analysis at the landscape level.

First, we identified indicators to characterize the household farming system. We selected 36 indicators, reflecting the physical assets (land, equipment, and livestock assets), human asset (based on the status of the family head and the family capacity in terms of education and work), and labor management strategies. The selection of indicators refers to previous research on the sustainable livelihood approach (Alary et al. 2021 etc.). The geographical location was a supplemental variable (Table 2).

Table 2. List of variables describing the farming systems.

Themes	Variable
Characteristic of the head of family (decision unit) (*K Human*)	Age of the family head (years)
	Sex of the family head
	Marital status of the family head
	Education of the family head
	Access to agricultural projects (yes/no)
	Number of family members who achieved primary level education.
	Number of family members > primary level
	Household size (members)
	Labor in non-farm activity (FTE/year)
	Labor in farm activity (FTE/year)
	Women count (> 16 years old)
Labor organisation (*K Labor*)	External labor on the farm (Full-time employment)
	Mutual labor contribution (% farm)
	Mutual labor benefit (% farm)
	Casual labor male (score 1 to 4 based on the number of days per year)
	Casual labor female (score 1 to 4 based on the number of days per year)
Land and cropping system (*K Land & Crops*)	Owned land (ha)
	Noncultivated land (ha)
	Rented land(ha)
	Vegetable area (ha)
	Cereal area (ha)
	Leguminous area (ha)
	Orchard area (ha)
Equipment[1] (*K Equipment*)	Rented equipment (av. number)
	Owned equipment (av. number)
	Borrowed equipment (av. number)
	Inherited equipment (av. number)
	Tractor equipment (av. number)
	Water equipment (av. number)
Livestock asset (*K Livestock*)	Cattle (count)
	Goat (count)
	Sheep (count)
	TLU[2]
	Grazing distance 10 km and under (% farmers)
	Grazing distance 10-50km (% farmers)
Location	Delegation

[1]The types of equipment are various, including sprinklers, cisterns, motor pumps, wells, boreholes, drip irrigators for water management, mowers, harvesters, sprayers, grinders, seeders, or tractors for crop cultivation, and rework or trailers for transportation ; [2] TLU (Tropical Livestock unit).

To characterize the diversity of manure management strategies, we identified and classified an indicator set (Table 3) into three dimensions: 1) The "manure balance" addresses the principle of "recycling" and includes the production, on-farm use, and the entry and exit flows of manure from the farm; 2) "Manure use" illustrates the contribution of manure use to soil nutrient management at the farm level for "soil health" and the reduction of dependence on chemical fertilizers ("input reduction"); and 3) The "manure labor" illustrates the "economic diversification" principle regarding family and external farm employment and focuses on the family and external workers involved in the manure collection and spreading (Table 3). The nitrogen (N) and phosphate (P) contents were estimated based on data references produced by Leclerc (2001) and used as a reference in Tunisia (Grissa 2017).

The livelihood outcomes resulting from the interactions at the agroecosystem level through manure management (related to the "synergy" principle) are mainly approached in terms of the source of income (external employment for occasional workers), the total monetary income at the household level (capturing both the input reduction and productivity increase), and, consequently, their relative contribution to overcome the poverty level at the household level. Here, we do not seek to isolate the effect of manure from other factors contributing to farm productivity, but rather the objective is to identify some correlations between manure management and household living conditions (Table 4).

To conjointly analyze the diversity of farm systems, manure management, and the impact on family farm livelihood, we crossed the farm typology with

Table 3. List of variables related to manure management.

Manure management dimensions	Variables	Unit
Manure balance « Recycling »	Manure production	Tons/TLU
	Manure on-farm use	Tons/TLU
	Purchased manure	%
	Sold manure	%
	Total on-farm manure balance (production+purchase-sold)	Tons/TLU
Manure use « input reduction » « soil health »	Mineral nitrogen use	kg/ha
	Mineral phosphate use	kg/ha
	Organic nitrogen use	kg/ha
	Organic phosphate use	kg/ha
	Organic nitrogen use over total nitrogen supply	%
	Organic phosphate use over total phosphate supply	%
	Sheep manure contribution over organic supply	%
	Crops fertilized with only manure	Number of crops
	Use of manure tea	Yes/no
Manure labor management « economic diversification »	Non-family workers for manure management	Month/ha
	Labor cost/ha	Local currency (TND)/ha
	Women's contribution to total labor need for manure management*	%
	Unit labor cost for manure management	Local currency (TND)/day

**Total labor for manure management include collecting, stocking, and spreading manure.*

Table 4. List of variables related to livelihood outcomes.

Variable	Description
Farm_income_FFW	Farm income per family farm workers (FFW)
Hh_Cash_poverty_threshold	The ratio between the cash flow and the household poverty level*
HH_Income_poverty_threshold	The ratio between the household net income (farm and off-farm income) and the household poverty level
Perc_Anl_Income	Percentage of the HH net income from livestock activity
Perc_Crop_Income	Percentage of the HH net income from crop and tree activity
Perc_Off-farm_Income	Percentage of the HH net income from off-farm activity

*Poverty level was fixed based on INS and World Bank (2020).

the three typologies addressing, respectively, the manure balance ("recycling"), manure use ("input reduction" and "soil health"), and the labor use for manure management (economic diversification) with a wealth typology based on variables of livelihood outcomes ("synergy" at the interaction of natural and social ecosystems). For this, we used five successive hierarchical clustering analyses (HCA) using the Ward method (Ward 1963) on the two first factors of both the multifactorial analysis (MFA), mixing quantitative and qualitative variables at the farm level and principal component analysis (PCA) for the three dimensions of manure management and the livelihood outcomes (Escofier and Pages 1994). The cross-analyses of the different classifications allowed us to characterize manure management by farm systems and the effect on livelihood outcomes.

Secondly, we performed a mapping characterization of nitrogen fluxes, i.e. the inflows and outflows between the 30 household farms surveyed in the five delegations representing our watershed landscape. This first descriptive approach allowed us to observe the dynamic of the flows of manure along the watershed with some potential impacts on livelihood with the monetary fluxes or soil fertility management with the physical fluxes. Then, we extrapolated the contribution of manure management to livelihoods at the landscape level, illustrating the studied watershed (the five delegations along the Merguellil basin) in relation to: (i) connectivity through the transactions of manure in and out of the studied zone; and, (ii) income and employment generation in terms of synergy and economic diversification. For this, we calculated the average quantities of manure sold and bought at the farm level by class of land size and by delegation in our sample. We suppose that the livestock structure and the manure management (in terms of on-farm use and transactions) are highly correlated to the land size type. For each land size type defined in official statistics (Institut National de la Statistique INS 2014a), we calculate the total out and in manure fluxes per farm in each delegation based on owned land repartition in the sample. Based on the official statistics of the number of farms in each land size class by delegation (Institut National de la Statistique INS 2014b), we can estimate the total manure fluxes that move in and out of each delegation along the watershed landscape. To approach the questions of fairness, or equity at the landscape system level, in relation to manure use and management, we proposed to

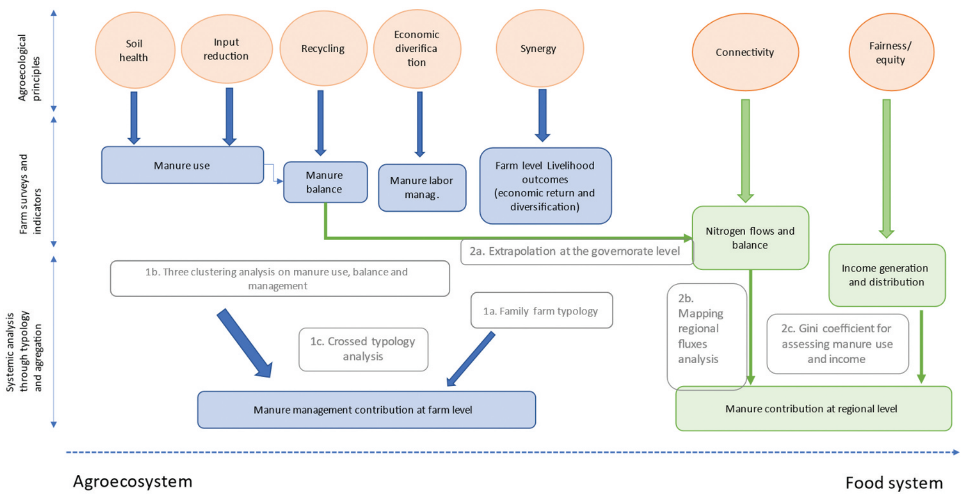

Figure 3. Representation of the conceptual methodological framework and sequential steps for analyzing contribution of manure to rural livelihoods at both the farm and landscape levels (light orange refer to the selected agroecological principles in part 2;; blue boxes refer to the different categories of indicators used in the manure management assessment at the farm level; green boxes refer to indicators evaluated at the landscape level; the white boxes mentioned the sequential steps followed in the present evaluation).

compare the inequality in terms of monetary wealth (estimated with the net income) and manure balance using the Lorenz curb.

Figure 3 provides the overall conceptual methodological framework and sequential steps used for analyzing manure contribution to rural livelihoods at farm and landscape levels, considering the diversity of manure production, exchange, trade, and use across varied production systems.

Figure 3 also shows that we are tackling different agroecological principles at different levels of the analysis. Principles such as soil health, recycling, input reduction, and economic diversification are captured at the agroecosystem level analysis, while other principles, such as connectivity and equity (or fairness), are rather explored when we conduct the landscape analysis by exploring nitrogen balance across delegations' income generation and distribution.

Results

Diversity of family farm systems in the studied landscape

The multiple factorial analysis allowed us to differentiate the household farms according to labor management and equipment assets in factor 1 and, secondly, on livestock assets in factor 2 (Figure 4). The two factors explain 25.8% of the variability in the sample. The "land and crop system" theme is positioned at the interaction of factors 1 and 2, differentiating the semi-intensive systems based on irrigated crops, motorized equipment, and external workers

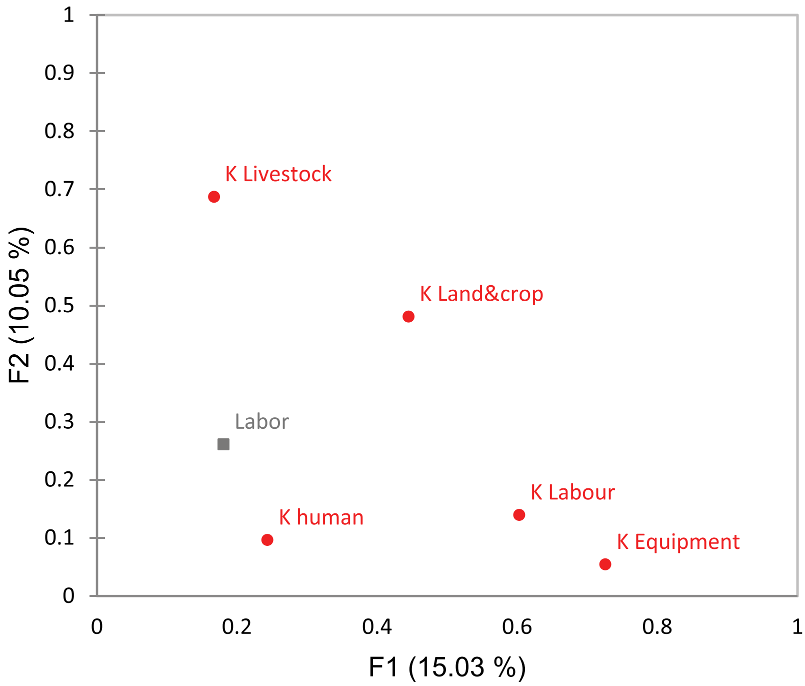

Figure 4. Projection of the eigenvalues of each theme on the factorial plan (F1*F2) of the MFA (Kairouan Governorate) (the active themes participating in the farm differentiation in red and the supplemental themes for illustration in grey).

on factor 1, and the mixed crop-livestock system mainly oriented to livestock systems in the rainfed zone, with little equipment and based on family labor on factor 2.

Three farm systems differentiated by the land farm size and the access to irrigation are identified (see Table 5).

Firstly, the "tree-pastoral system in the rainfed zone" (Type 1) clusters the oldest farmers (around 55 years old). The family counts around five people involved in farm activities (with two women of working age). The cropping system is based on traditional crops, i.e., cereals and orchards such as olive groves, on 1.5 ha in ownership. This type diversifies the herd composition with around 24 sheep, four goats, and rarely 1–2 cattle, when water is available for forage production. Sheep and goats are mainly raised on the grazing area around the farm (less than 10 km) and managed by women. The main sources of incomes and livelihood support are based on remittances and off-farm jobs.

Secondly, the "small-scale mixed crop-livestock system" (Type 2) clusters the smallholder farms managed by the youngest family heads (46 years old). The cropping system is based on cash crops (vegetables and orchards mainly composed of olive) on 4.3 ha, on average, and they keep a tiny flock of 15–20 sheep on average, mainly raised by women at home.

Table 5. Average characteristics of the three main farming systems in the Merguellil watershed (Kairouan) (147 farms).

Types	Type 1	Type 2	Type 3	All samples
	Tree-pastoral system in rainfed zone	Small-scale mixed crop-livestock system (mixed rainfed-irrigated)	Medium-to-large crop-livestock system in irrigated zones	
Number of farms per type	59	77	11	147
Age of the family head (years)	55.40	46.36	50.54	49.62
Household size (members)	5.13	3.76	3.62	4.18
Out-of-farm activities (FTE*)	0.18	0.12	0.37	0.16
Farm activities (FTE)	2.82	2.06	2.44	2.34
Total owned land area (ha)	1.47	4.30	17.46	4.56
Vegetable area (ha)	0.05	*3.47*	*12.23*	3.15
Cereal area (ha)	0.99	*1.58*	*12.85*	2.39
Leguminous area (ha)	0.23	0.33	0.00	0.27
Orchard area (ha)	*3.84*	*4.25*	*9.27*	4.57
Own Tractor (% owners)	0.30	0.79	1.54	0.70
Irrigation equipment (% owner)	0.09	1.02	1.54	0.77
Cattle (TLU**)	0.66	0.61	1.38	0.70
Goats (TLU)	0.38	0.11	0.7	0.26
Sheep (TLU**)	*2.43*	*1.80*	*8.0.5*	2.55

**Full-time equivalent; ** TLU (Total Livestock Unit).*

Finally, the "medium to large crop-livestock system" (Type 3) clusters middle-aged farmers (about 50 years old) who inherited around 15–20 ha of dry and irrigated land. The cropping system is based on cereal crops for food and feed requirements at the family farm, with vegetables and/or orchards (olive groves) for cash income. These are the most equipped farmers owning a tractor or lorry per farm. They also own a medium to large flock with an average of 80–90 heads of small ruminants (sheep and goats) and a few of them (less than one-quarter of the group) with 1–2 cattle raised indoors. Around 45% of these farmers practice grazing around the farm (less than 10 km).

Manure management contribution in the watershed agroecosystem

Manure use and the "soil health" principle at the landscape level

The relative contribution of cattle and sheep manure to the total nitrogen supply from mineral and organic fertilizers is illustrated in Table 6. We can see that organic manure intake remains the primary source of fertility in the rainfed zone, representing more than three-quarters of the nitrogen supply (79% in Oueslatia and 87% in Alaa), compared to the irrigated delegations where manure represents around one-third of the nitrogen supply.

If organic manure continues to be the primary source of soil nutrients in the rainfed zone, its adequacy becomes questionable. Table 7 underscores significant nitrogen and phosphate supply gaps across the three farming systems, comparing the two rainfed systems with the irrigated mixed system in

Table 6. The relative contribution of nitrogen from cattle and sheep manure related to the total nitrogen supply in the five delegations comprising the landscape level (%).

Classes of land size	Chebika	Haffouz	Hajeb Layoun	El Alâa	Oueslatia	N input from manure per land classes (% of the total N supply)
<10 ha	30%	39%	38%	80%	84%	41%
<20 ha	33%	42%	41%	69%	60%	46%
<5ha	35%	21%	24%	95%	100%	33%
≥20 ha	36%	25%	8%	100%	88%	45%
N input from manure by delegation (% of total N supply)	34%	29%	32%	87%	79%	42%

Table 7. Summary of manure use and flows by farm type (over 147 farmers).

	Tree-pastoral system in rainfed	Small crop-livestock system	Large crop-livestock system	in av.
Nos of farms	**59**	**77**	**11**	**147**
Manure production (Tons)	14,2	11,8	32,0	14,3
Manure on farm Use (Tons)	3,8	16,1	77,1	17,6
Manure bought (Tons)	0,6	12,2	48,4	11,7
Manure sold (Tons)	7,1	2,3	8,5	4,4
manure farm balance (Tons)	7,7	21,7	71,8	21,6
Total cropped area (ha)	*5,1*	*9,6*	*34,3*	*10,3*
Manure balance (Tons/ha)	*1,5*	*2,3*	*2,1*	*2,1*
Nitrogen use (in kg/ha)	**6,2**	**43,6**	**29,0**	**30,4**
Nitrogen supply from manure (in kg/ha)	**4,8**	**13,5**	**12,5**	**10,6**
Nitrogen supply from manure (% of total nitrogen)	**77%**	31%	43%	35%
Phosphate use (in kg/ga)	5,5	32,9	11,8	22,3
Phosphate supply from manure (in kg/ha)	3,4	9,4	8,5	7,4
Phosphate supply from manure (% of total phosphate)	**61%**	28%	72%	33%
External worker for manure management (in months/year)	0,0	0,2	0,5	0,1
Labor cost for manure (DT/year)	0,0	240,0	1196,9	253,2

Manure balance per ha = (manure production + manure bought-manure sold)/total crop area;

Tunisia's semi-arid zone. The nitrogen and phosphate supply per hectare is two to five times less important in rainfed than irrigated zones. Even if the rainfed crop system based on cereal is less demanding in minerals (like nitrogen or ammonia), the soil structure and hence soil health can be dramatically affected by the reduction of manure spreading as a soil amendment, especially in this rainfed zone affected by erosion.

Manure use and management and the principles of "recycling" and "input reduction"

We identified three groups based on the clustering analysis of manure use (noted U) (Table 8). The percentage of nitrogen with an organic origin (illustrating "input reduction") varies from almost zero percent for Type 1 (U1, "No manure use") to less than one-third for Type 2 (U2, "Mixed organic-mineral use") and almost two-thirds in Type 3 (U3, "manure intensive use").

Table 8. Crossed analysis of manure management with farm system.

Farming system	(T1) Tree-pastoral system in rainfed	(T2) Smallholder mixed crop-livestock system	(T3) Medium-to-large crop-livestock system	Total average
Nos of families	*59*	*77*	*11*	*147*
Manure use (« Input reduction »; « Soil health »)				
(U1) No manure use	**45%**	9%	8%	20%
(U2) Mixed org-mineral use	0%	**15%**	0%	9%
(U3) Manure intensive use	55%	76%	**92%**	71%
Manure balance (« recycling »)				
(B1) Low manure balance	**87%**	61%	**77%**	71%
(B2) Manure buyer	2%	**31%**	**23%**	21%
(B3) High manure balance	**11%**	8%	0%	8%

We can see two types in the rainfed zones: 55% declared using mainly manure, and 45% did not use manure. This last group corresponds primarily to grazing systems where manure is not stored. Let's note that the manure can be indirectly mobilized, but this is not accounted for here. Medium-to-large crop-livestock systems (Type 3) are the most intensive manure users compared to small-scale mixed crop-livestock systems (Type 2), which use mineral and organic fertilizers.

The clustering analysis related to manure balance (noted B) (and related to "recycling") in Table 8 differentiated three groups according to production and transaction. We can distinguish the type of manure buyers (B2, "Manure buyer"), corresponding to crop-oriented systems, the manure producers who are both buyers and sellers according to the cropped areas for the medium-to-large crop-livestock system or only sellers for tree pastoral systems in the rainfed area (B1, "low manure balance"), and the manure producers dedicated mainly to on-farm use (B3, "high manure balance").

Manure management and livelihood outcomes in relation to "economic diversification"

The clustering analysis on the work organization for manure management in Table 9 allows us to distinguish two main types of labor organization (noted L) around manure management according to holder size. We can see that the labor tasks around manure management are mainly realized by male family members in smallholder farms (L1) compared to medium-to-large crop-livestock systems where these tasks are handled primarily by female occasional workers (L2), with an increasing rate of time and daily cost for large farms (L3) (Table 9).

The livelihood outcome related to monetary wealth (noted W) allowed the differentiation of three wealth groups. The most vulnerable group

Table 9. Crossed analysis of manure management with household farm systems and wealth status.

Farming system	(T1) Tree-pastoral system in rainfed	(T2) Smallholder mixed system	(T3) Medium to large crop-livestock system	Total
Nos of families	*59*	*77*	*11*	*147*
Manure labor (« Economic diversification »)				
(L1) Family work based on men's work	**100%**	46%	38%	63%
(L2) Medium intensive work based on women workers	0%	45%	**46%**	31%
(L3) High-intensive labor based on women workers	0%	9%	15%	7%
Wealth (« Synergy »)				
Vulnerable W1	**77%**	18%	8%	36%
Medium wealth class W2	23%	**79%**	**69%**	61%
Rich wealth class W3	0%	2%	**23%**	3%

(W1) are farmers with the lowest monthly net family income, with a mean of 1170 DNT per month and around two-thirds of family income from livestock activities. The group (W2) records an average monthly net income three times higher than (W1), compared to 10 times higher for (W3) on average. Unsurprisingly, the majority of farmers in the types (W1) and (W3) are in the groups (T1) and (T3), respectively, revealing the weight of the structural factor in overall monetary wealth. However, we note that all farmers in the wealthiest category are highly intensive users of manure. 1

To assess the overall links between farm systems and manure management and livelihood outcomes, we implemented a multi-factorial analysis (MFA) with all the sets of variables. Figure 5 shows the projection of the variables related to farming systems, manure management, and livelihood outcomes on the two first factorial factors of a MFA. The first two factors represent 22.2% of the variability of the sample over 147 farmers. The first and second factors differentiate the farmers according to farm productivity and income (F1) and land and livestock assets (F2). We see that manure use and manure balance are at the interaction of these two dimensions, i.e., the physical assets (land and livestock) and the productivity. Labor organization around manure use is strongly linked to labor management at the farm level, which is linked with economic performance and assets. Usually, the use of external workers for manure management is mainly restricted to medium and large farms. Most of these workers are women, although family male workers mainly manage manure on small-scale farms.

Manure management contribution at the food system level

Regional fluxes of manure ("connectivity" principle)

Figure 6 illustrates the geographic distribution of the inflows and outflows of manure for the 147 studied farms in all delegations. The Oueslatia and Al Alaa

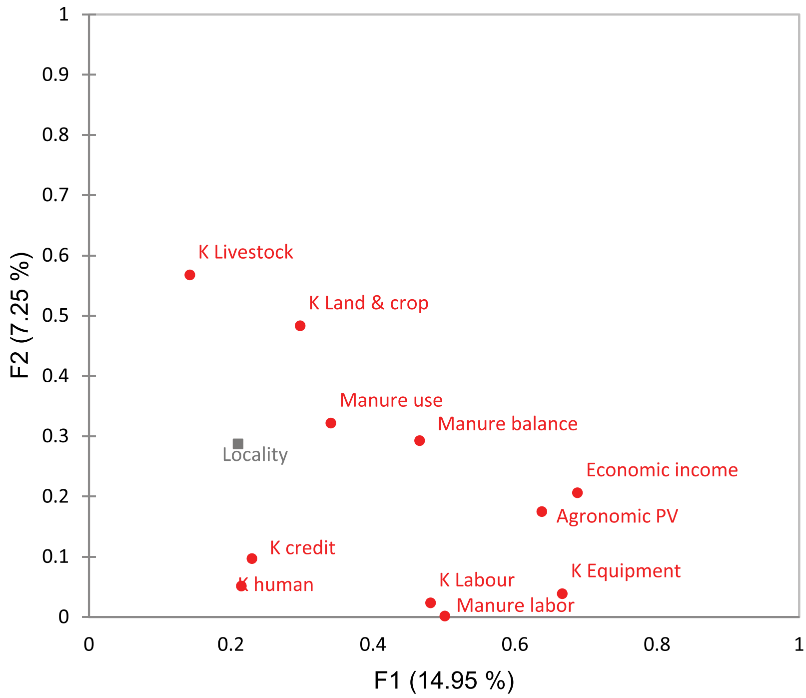

Figure 5. Projection of the groups of variables related to the farming system, manure management, and economic income on the two first axes of the multi-factorial analysis explaining 22.3% of the variability (in red the active themes considered in the MFA and in grey the supplementary theme only projected in the factorial plan).

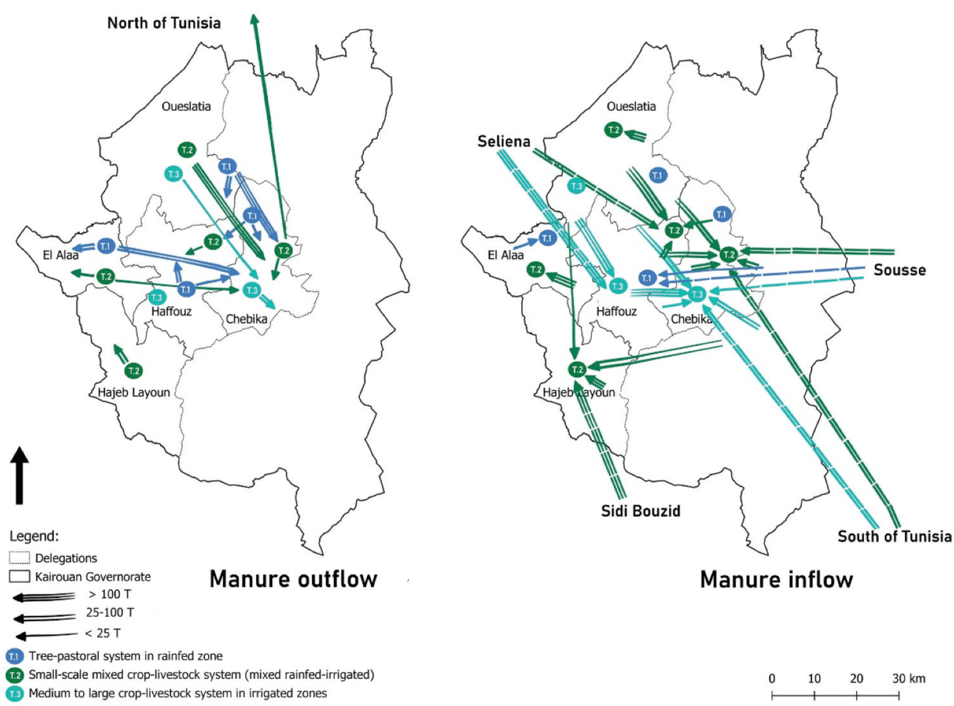

Figure 6. Geographical fluxes of manure with a) the outflow from the surveyed farms; and, b) inflow to the surveyed farms (authors) (the outflow arrow represents the transfer of manure from one farm type within a delegation to another delegation. In contrast, the inflow arrows signify the significant manure influx entering one type within a delegation from another delegation).

delegations, located in the upstream watershed, controlled 73% of the total organic manure transactions. These delegations are typically characterized by the dry cereal and small ruminant systems of the semi-arid zone of central Tunisia, represented in Type 1. Almost all the manure sales occurred in the studied Merguellil watershed (around 98.9%), with around 61% destined for the irrigated systems, mainly localized in the Chebika delegation. Thirty-two percent of the farmers were engaged in this economic activity of manure selling, with a peak of 59% of surveyed farmers in Oueslatia at the extreme upstream side of the landscape. The average quantity of manure sold was about 15.5 T per farm, ranging from 3.1 to 29 T per farm, on average, per delegation.

On the other hand, about 72.8% of manure purchases took place in the studied landscape, and more than one-third (about 37.3%) of this occurred in the same delegation. The remaining purchased manure (around 35.5%) came from the most vulnerable areas, i.e., from the Oueslatia and Al Alaa delegations. The delegations Chebika and Hajeb Layoun bought an average of 24.5 and 17.3 T of manure per year and per farm, respectively. Farmers complete their manure needs outside the study area in these two delegations, notably from neighboring governorates, i.e., Sousse for Chebika and Sidi Bouzid Governorate for Hajeb el Layoun. Besides, we noted a large difference between manure's average selling and buying price, revealing a relatively good margin of benefit for intermediaries such as transporters and traders in this value chain. On average, the selling price is around 39 DNT (Tunisian Dinar) per ton, ranging from 17 DNT to 43 DNT per ton. On the other hand, the purchasing price is more stable around 75–80 DNT.

From the analysis of the fluxes in the studied zone, manure appears to generate a very dynamic market at the landscape level but perhaps to the detriment of soil health in the rainfed zone.

Income generation from manure and equity at the landscape level

In addition to the supplemental monetary fluxes due to the manure marketing, manure management provided around a thousand supplemental jobs at the minimum wage at the landscape level (extrapolated data at the regional level comprising the five delegations), without including the intermediary activities along the value chain (transportation and trading) (Table 10). Additionally, the manure transaction (selling plus wage) generated a flux of cash flow of around 2.6 million DNT (or 822,000 € in 2021), which was not negligible in the total contribution of livestock to the studied area.

Negative trade-offs between the economic and environmental benefits of manure management are not to be neglected. The Gini coefficient issued from the Lorentz curb (Figure 7) confirms the high liaison between monetary wealth (expressed in net income) and nitrogen balance on the farm,

Table 10. Contribution of manure to income generation in the five delegations in euros for a total of 18,847 farms (1 € equivalent to 3.2 DNT in May 2021).

Delegation	Income from sheep manure sold (€)	Income from cattle manure sold (€)	Income generated from employment in manure management (€)	No. of people covered by the manure source of income
Chebika	34988,8	8462,0	22317,0	83.0
El Alâa	49643,3	73906,6	18838,5	179.7
Haffouz	76001,4	0,0	63432,3	175.9
Hajeb Layoun	0,0	3470,5	16343,4	25.0
Oueslatia	413965,2	24072,4	29845,0	590.4
Total in the studied region	574598,8	109911,5	150776.2	1054.0

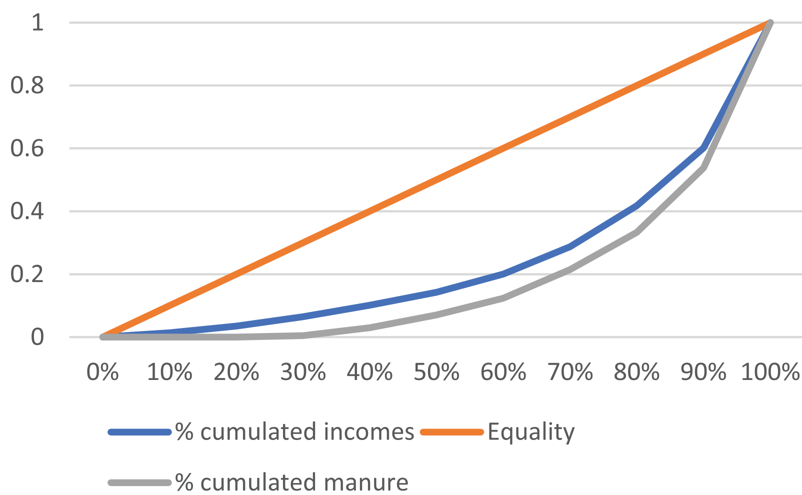

Figure 7. Lorentz curve applied to income and manure use distribution over the 147 farmers in Kairouan.

establishing around 0.43 for income distribution and 0.54 for manure balance. It also shows a higher inequality with regards to manure balance with the risk of long-term impoverishment of soil fertility in the rainfed zones.

Discussion

Manure contribution to livelihood at the farm and landscape level

Firstly, at the farm level, results highlighted the contribution of organic manure as a source of income generation for rainfed areas through employment and manure transactions and a source of soil and plant nutrients in irrigated zones, where cultivated crops require a relatively higher amount of fertilizers than annual crops in the rainfed zone. Although organic manure remains the primary source of soil nutrients in the rainfed zone (more than three-quarters of nitrogen and 60% of phosphate), the overall supply of nutrients (chemical and organic) remains lower than in irrigated zones. These results at the farm level immediately raised the risk of environmental impoverishment in the rainfed systems at the benefit of irrigated zones that benefit not only from the nutrients produced in the rainfed zones but also from a source of employment at low wages coming from the rainfed zone. In fact, we observed that manure spreading is a male's task when performed by family or permanent workers and a female's task when farmers use casual workers (daily rate is, on average, respectively, 14 DT/day and 23 DT for women and men). The gender difference of daily wage could be explained by the gap of physical capacity between men and women but also the status of the different tasks allocated to men and women as external workers. Spreading manure is not considered a technical and grateful task. Results showed that if organic manure remains the main source of soil nutrients in the rainfed zones, the total nutrient supply per cultivated land unit is low to the detriment of soil health (mainly soil structure) and food and feed production. The situation is often aggravated by the poor nutrient supply from manure due to the feeding system of animals with poor nutrient-enriched food sources and also the issues of manure collection and conservation. Moreover, the yield productivity gap may increase in the future in relation to the increasing demand for organic nutrients due to the expanding cost of chemical fertilizer and the recent encouragement for more agroecological products even if it is at the early stage.

These flows of manure from vulnerable zone to more favorable zones for cropping is observed in other parts of the African continent, like in Senegal, where multinational and large private farms have also started to buy large quantities of manure from the agro-pastoral zones (Audouin 2014; Dieye 2021). In traditional agro-pastoral livestock systems of West African countries, the herd mainly exploits fallow, marginal land (silvopastoral areas), and crop residues. In return, the ingested biomass is transformed into organic manure for fertilizing agricultural land (Dugué 1998; Vall et al. 2023). This fertility transfer from breeders to farmers was often formalized through manure contracts. So, the evolution of the pastoral livestock systems toward agro-pastoral systems tends to accelerate the benefits generated in agriculture-livestock integrated systems in which livestock provides manure and energy for the development of crop production but also constitutes a threat to the fertility of the pastoral zone compared to the agricultural zone. With the pressure of access to chemical fertilizers since 2022, this fertility transfer through herd mobility is increasingly replaced by manure mobility over significant distances raising more questions about manure management and the various losses at the different stages of production, storage, transportation, and spreading.

However, in contrast, manure constitutes a consequent source of added value and income in the vulnerable zone. With growing market potential, manure could ensure the perenniality of livestock activities in these vulnerable zones, where the rainfed crop production system has become vulnerable with the recent intensity and frequency of dry climatic events. The results highlight the multifunctional role of livestock at the landscape level, as shown by Krausmann (2004), and also of manure.

Our results show that manure use and valorization differ along the watershed, from a socioeconomic value in small farms operating under rainfed tree-pastoral systems to environmental and agronomic values in mixed rainfed-irrigated systems downstream. Manure flow analysis across farm types and along the watershed confirms that on-farm manure balance positively correlates to wealth. On-farm manure management practices, either based on dry manure storage or fresh manure spreading, often perceived as a traditional and old practice, are the most used in semi-intensive and intensive farm systems. This trend should raise the attention of policymakers and development agencies dealing with economic and environmental challenges in semi-arid zones. Moreover, the two Gini coefficients for net income and manure balance indicate a greater environmental inequity than economic that questions the overall environmental sustainability of the watershed landscape. This gap stresses the necessity to address the agroecological transition at the landscape level. Improving manure management practices, from livestock raising to its application on cropped areas, could significantly enhance the livelihood of the landscape. This approach takes into account both livestock-oriented systems in rainfed regions and crop-oriented systems in more favorable zones.

However, our typology in three types does not allow us to capture the complete diversity of farm systems in each agroecological zone, where De Buisson Du Buisson de Courson (2017) and Morel (2018) in the upstream identified around 10 to 20 types, respectively, in the upstream and downstream of the watershed. In particular, large crop farmers specializing in vegetable production are not well captured, although they are important buyers of manure coming from outside the landscape. From an agroecological outlook, it's important to capture these actors for their strong market linkage and opportunity to sell agroecological produce. So extending the approach to a larger diversity of farm systems could highlight the importance of the manure market and the added value generated through manure.

Manure contribution to the agroecological transition: synergy or inequity

As shown in the results, manure use is at the interaction of several agroecological principles contributing to "recycling" (renewal resource), "input reduction" (substitute to chemical fertilizer), "soil health" (thanks to the physical and biological nature of organic manure) that favor both the agroecological and socioeconomic interactions at the farm and landscape levels. The present study pointed out several contributions as the direct contribution to "economic diversification" through the sale of organic manure and the reinforcement of regional agroecologial interactions, notably between crop and livestock interactions ("synergy"), but also indirect contributions through both the productivity gains for the manure buyers and the labor requirement at the landscape level. The results showed that the medium-to-large crop-livestock systems with the highest livestock integration through manure use are the most efficient regarding the two principles of recycling and input reduction.

So using the agroecological framework, as presented in part 2, to approach a sustainable transition allowed us to capture the multiple dimensions of livestock contribution and its fundamental role as driver of a potential agroecological transition or at least a more environmentally friendly system in these widespread mixed crop-livestock systems, and at the farm and landscape levels. However, while the exchanges of matter (organic manure) and labor generate employment and income along the value chain, the spatial disconnection between crop and livestock may generate agro-environmental problems associated with nitrogen and phosphate use that we started to observe in the studied landscape. Moreover, this agro-environmental inequity can increase with the increased demand for organic manure and the tension in the manure market with the decrease in livestock numbers in rainfed zones. While the recent increase in demand for organic manure is due to the increasing price of chemical fertilizers, a trend that has been accentuated by the Ukrainian crisis (since 2022), this trend can also be exacerbated to answer the growing demand for agroecological products. Vice versa, official data in the studied governorate of Kairouan record a decreasing trend of livestock numbers in rainfed zones due to increased migration and repetitive dry years that constrain farmers from purchasing feeds. Generally, migration concerns mainly active young and middle-aged men who can manage grazing activities. With men migrating out of the rainfed zone to look for work, women are forced to reduce livestock activities in line with their domestic workload. This trend urgently requires more cooperation between agroecological areas defined as agroecosystems at the landscape level to improve local optimal manure allocation and to ensure a dynamic and virtuous agroecological transition.

From this agroecological perspective, we need to recall that manure management from a technical or social point of view, taking into account the agronomic practices and exchanges, is part of an extended traditional knowledge that preserves and improves natural resource use and ecological services, as shown by Berkes, Colding, and Folke (2000). In line with Berkes, Colding, and Folke (2000), we observe that this traditional practice is based on socially and locally enforced rules and generates a diversity of direct and indirect resources used for livelihood security. But, the parallel approach of agroecological principles through the livelihood approach at farm and landscape levels allowed us to see the complicated challenges between socioeconomic and agroecological sustainability at short- and long-term scales. Here, we consider the landscape as an agrarian unit in which people, through their agricultural practices and objectives, express at the natural landscape level (Agnoletti 2014; Sereni 1997), with the risk of marginalization processes of vulnerable zones as we have observed in our case study. Moreover, this landscape unit showed that the "synergy" principle, as defined by the HPLE (2019), appears very tricky to capture the complex and diverse interactions between human and natural processes that shape the rural landscape. This challenge calls for developing research and development activities at the farm and rural landscape levels and integrating environmental, social, and economic dimensions to understand the agroecological transformation. For that, livelihood landscape units, as we propose in the present paper, could be a more suitable social and geographic unit from the standpoint of agroecological transitions. As mentioned in Zaremba et al. (2021), the "synergy" principle should be addressed at the nexus between agroecological processes and economic diversification, not only at the interaction of soil-crop-livestock units.

Finally, this analysis of manure management practices at the farm and landscape levels through the agroecology framework showed some forms of power imbalances based on gender or, more generally, it allows the identification of the risks of marginalizing more vulnerable zones. These results highlight the need to link the two scales of farm and landscape together and to integrate social values and justice in synergy and connectivity approaches.

Conclusions and perspectives

With the increasing social, scientific, and political interest in developing agroecological systems, manure management has the potential to pass from a traditional practice to a niche activity to achieve an agroecological transition pathway. The results of this study showed that manure contribution to livelihoods constitutes an interesting way to address the principles of agroecological transition pathways. Manure valorization is a non-negligible economic benefit (on-farm use or transaction) at the farm level but with a risk of increasing environmental impoverishment of the rainfed zones to benefit the wealthier irrigated zones. This trend could accelerate livestock reduction in the rainfed zone, which may, in turn, pose a threat to the more favorable zones and potentially trigger an agroecological transition. These different dynamic risks and opportunities of complementarities between agroecological zones should challenge the attention of policymakers and development agencies dealing with both the economic and environmental challenges of the semi-arid zones. Considering organic manure not as a by-product but as a primary product of small ruminant activity (similar to milk for cattle) could be the first step toward a more integrated and sustainable approach for this semi-arid zone of North Africa.

Note

1. In 2021, a person is considered poor if their annual consumption expenditure is less than 2,536 TD (INS, Tunisia (http://www.ins.tn/publication/resultats-de-lenquete-nationale-sur-le-budget-la-consommation-et-le-niveau-de-vie-des#:~:text=En%202021%2C%20une%20personne%20est,23%2C1%25%20en%202005.).

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