REVIEW AND INTERPRETATION

Crop–Livestock Interactions in the West African Drylands

J. Mark Powell,* R. Anne Pearson, and Pierre H. Hiernaux

ABSTRACT

Many semiarid regions of Sub-Saharan Africa (SSA) are experiencing vast increases in human population pressure and urbanization. These augment the demand for agricultural products and have led to the expansion, intensification, and often closer integration of crop and livestock production systems. The transition of crop and livestock production from the current relatively extensive, low input/output modes of production to more intensive, higher input/output modes of production presents numerous challenges to the achievement of required long-term production increases from these farming systems. This paper provides an overview of the challenges facing agricultural production in semiarid SSA with a focus on West Africa. A description of mixed crop–livestock farming systems and their evolution is followed by an overview of the principal linkages between crops and livestock: income, animal power, feed, and manure. The most detailed discussions relate to nutrient cycling in these farming systems. Most livestock derive their feed almost exclusively from natural rangeland and crop residues, and livestock manure is a precious soil fertility amendment. However, most farmers have insufficient livestock and therefore manure to sustain food production. Nutrient harvests from cropland often exceed nutrient inputs, and soil nutrient depletion is a principal concern. The paper concludes with a discussion of strategies that may improve the productive capacity of these mixed farming systems.

MOST DRYLAND FARMING systems of SSA integrate crop and livestock production. Pearl millet [*Pennisetum glaucum* (L.) R. Br.], sorghum [*Sorghum bicolor* (L.) Moench], and maize (*Zea mays* L.) are the principal cereals, fonio [*Digitaria exilis* (Kippist) Stapf] is important in some areas, and rice (*Oryza* spp.) is cultivated in delta areas and along river and stream borders. The legumes cowpea [*Vigna unguiculata* (L.) Walp.] and groundnut (*Arachis hypogaea* L.) are both subsistence and cash crops; grain and hay may be sold. Household livestock holdings range from a few to hundreds of head per household with varying ratios of cattle, sheep, and goats (Wilson, 1986; Swinton, 1988). In some areas, especially associated with cash crop production, cattle, donkeys, horses, and camels provide draft power for tillage, crop planting, weeding, crop harvest, processing, and transport. Livestock also provide meat and milk for households and cash income that is often invested in crop production technologies. In many regions, livestock are also a means of storing capital, of buffering food shortages in years of poor crop production, and of meeting social and religious obligations of farmers.

In these systems, the productivities of livestock, rangelands, and croplands are inextricably linked. Although most agricultural products are used for subsistence purposes, some outputs of rangeland (wood, bush straw, and fruits), cropland (grains, crop residues, and legume hays), and livestock (animals, milk, meat, and skins) are sold. Crop residues are vital livestock feeds during the 6 to 8 mo dry season, and manure enhances soil fertility for crop production. Natural forages from rangelands and fallow lands provide important livestock feeds and, through manure, nutrients for cropland. Manure is obtained from either one's own livestock, from the livestock of other farmers, or through exchange relationships with pastoralists. Manure contracts between farmers and pastoralists are still important in many West African dryland areas, and farmers have developed a variety of ways to combine their own smaller herds to manure large cropland areas.

A principal challenge facing agriculture in many parts of SSA is how to achieve sustainable increases in crop and livestock production with limited use of fertilizers and feed supplements. Farmers continue to rely principally on organic matter recycling to maintain soil fertility. However, the harvest of N, P, and K exceeds the input of these nutrients, and yields appear to be declining. Low rural incomes and the high cost of fertilizer and feed supplements, among other factors, prevent the widespread use of these external nutrient sources. The use of fertilizer is limited to small land areas devoted to cash crops, and diet supplements for livestock are used scantly in semi-intensive livestock-fattening operations around urban areas and for fattening animals before religious and social festivals. Animal manure is currently perhaps the most important soil fertility amendment. As long as fertilizers and feed supplements are unavailable, the fertility of cropland will continue to depend on the nutrients supplied from rangeland in the form of manure.

The climatic and socioeconomic changes occurring in many parts of SSA are rapidly transforming traditional, extensive crop and livestock management practices, based on shifting cultivation and transhumance, to more sedentary forms of production. Problems common to these agricultural systems include inadequate feed resources, encroachment of cropping on grazing lands, reduced fallow periods (resulting in declining soil fertil-

J.M. Powell, U.S. Dairy Forage Res. Cent., USDA-ARS, 1925 Linden Drive West, Madison, WI 53706; R.A. Pearson, Cent. for Trop. Veterinary Medicine, Easter Bush, Roslin, Midlothian, EH25 9RG, UK; and P.H. Hiernaux, Int. Livestock Res. Inst., B.P. 12404, Niamey, Niger. Received 5 March 2003. *Corresponding author (jmpowel2@wisc.edu).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: SSA, Sub-Saharan Africa.

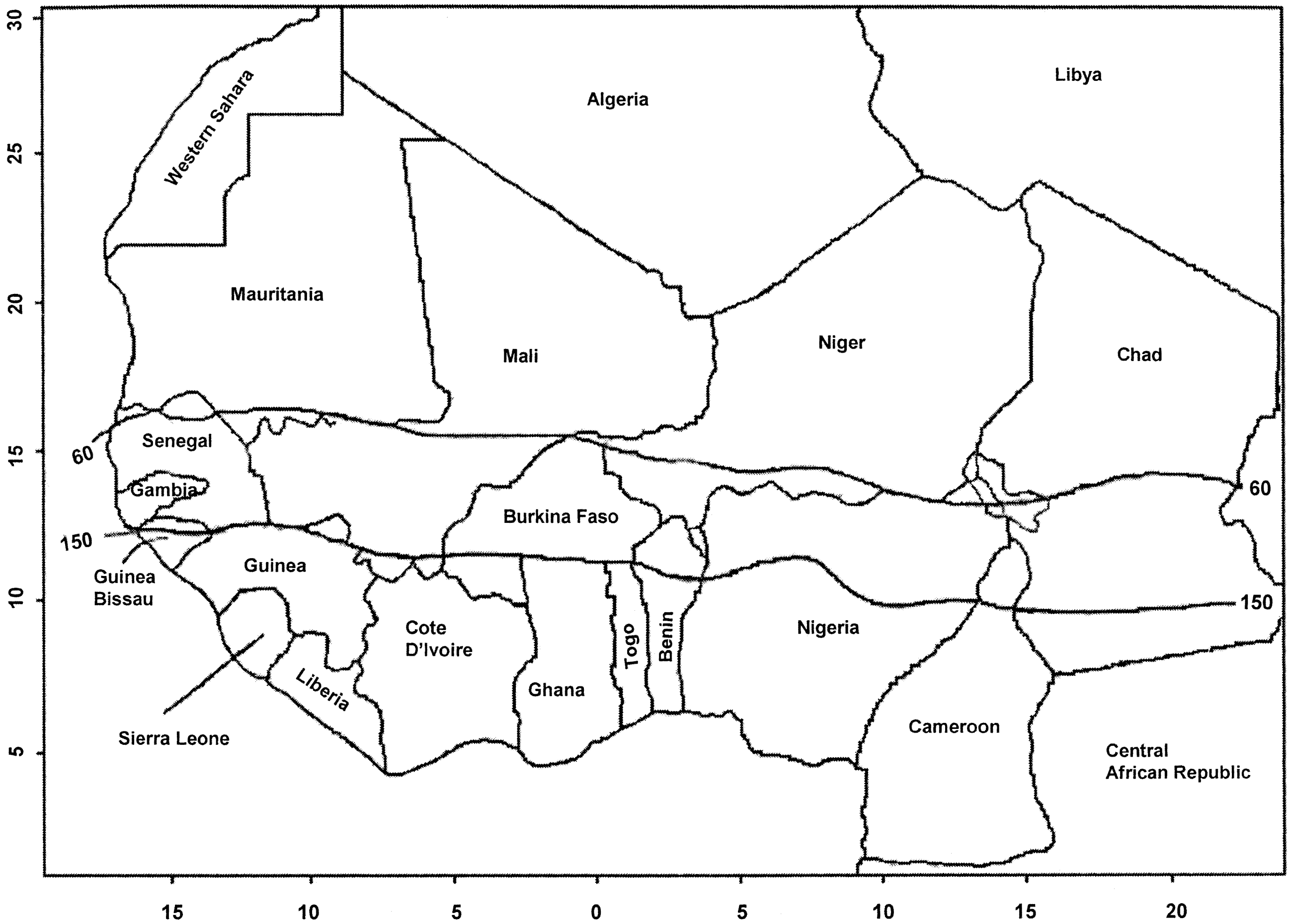

Fig. 1. The Sudano-Sahelian zone of West Africa. Growing season isolines of 60 to 150 d are shown. (Shivakumar and Wallace, 1991).

ity), lack of access to nutrient inputs, labor shortages during the cropping season, and inadequate market opportunities (Steinfield, 1998). The purpose of this review is to provide a synopsis of the principal biophysical and socioeconomic interactions between crops and livestock and strategies to improve the productive capacity of mixed farming systems in the Sudano-Sahelian zone of West Africa. This zone extends from Senegal and The Gambia in the west to Chad in the east and is characterized as having a growing season of 60 to 150 d (Fig. 1) and annual rainfall of 400 to 1000 mm. We refer to this zone as the West African drylands.

MIXED FARMING SYSTEMS

Seré and Steinfeld (1996) define mixed crop–livestock systems as those in which at least 10% of the feed comes from crops and/or crop by-products or more than 10% of the total agricultural production comes from nonlivestock farming activities. Mixed farming systems are further divided based on whether or not they rely on rainfall or irrigation to support crop and pasture production. The full integration of crop and livestock production into the same unit is an evolutionary process mediated principally by differences in climate, population densities, disease, economic opportunities, and cultural preferences (Powell and Williams, 1995). At low population densities, agricultural systems are extensive, and crop and livestock production are often operationally separate enterprises. As population densities increase, there is pressure to intensify agricultural production, which leads to an increase in the interactions between crop and livestock production (McIntire et al., 1992). As markets continue to develop and technical changes increase, a movement away from integration and a return to specialization may occur. This occurs when market conditions and public policies result in fertilizers being used instead of manure, when tractors replace animal power, and when cultivated forages and diet supplements are used instead of crop residues. At this point, the economic incentive for a mixed farm enterprise to provide its own inputs diminishes, and specialization becomes more profitable.

Evolution of Crop–Livestock Interactions

Traditionally across the West African drylands, crops and livestock have been ethnically and operationally separate but functionally linked enterprises. Exchanges of grain, crop residues, and water for manure between sedentary crop farmers and migratory pastoralists have linked crop and livestock production for years (van Raay, 1975; McCown et al., 1979; Toulmin, 1983; Powell, 1986; Mortimore, 1991). However, these specialized forms of agricultural production are under transition. Increasing human and livestock populations combined with

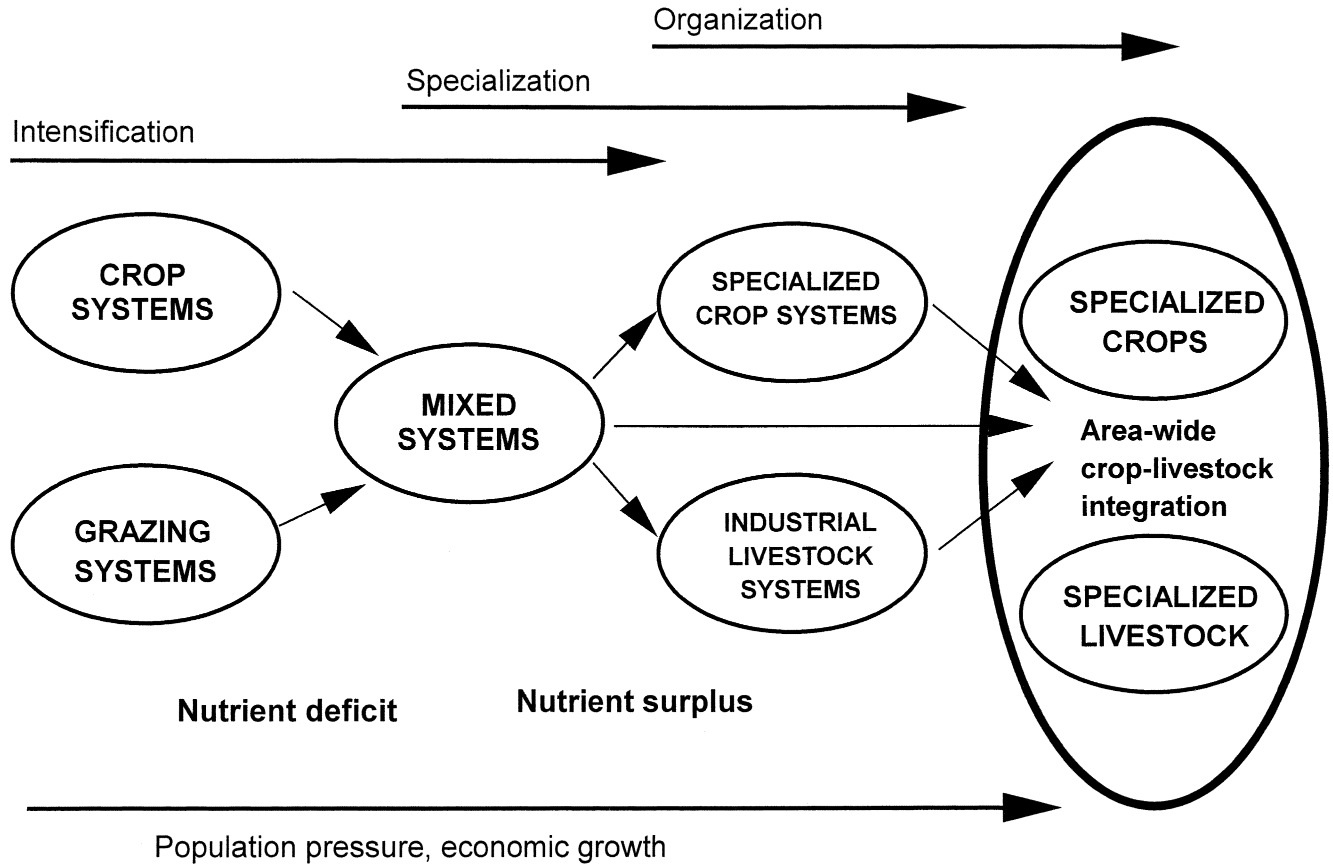

Fig. 2. Pathways of crop–livestock integration (Steinfeld, 1998).

long-term weather changes are transforming livestock systems based on transhumance and communal grazing of rangelands, and cropping systems based on shifting cultivation, to more sedentary, mixed farming enterprises (Winrock International, 1992). The transformation from specialized to integrated crop–livestock systems is a dynamic and evolutionary process. As livestock husbandry becomes more settled, it increasingly incorporates crop production while specialized, extensive cropping systems integrate livestock. In the process, many of the traditional exchange relationships between crop farmers and pastoralists disappear. Although many crop–livestock interactions continue to be mediated by barter and market transactions between separate crop and livestock producers, they increasingly occur within closely integrated mixed farms.

While mixed farming is just one form of crop and livestock production, it occupies an important phase in the evolution of agricultural systems (Fig. 2). Pingali (1993) suggested that intensification of crop and livestock production typically evolves through four stages in the process of agricultural and overall economic development: (i) preintensification phase where crop and livestock production are operationally separate enterprises; (ii) intensification phase where crop and livestock production integrate mostly through animal draft power, feed, and manure linkages; (iii) income diversification phase when investments are made to improve forage supply and quality; and (iv) a return to specialization through commercialization. A key driving force in moving from crop and livestock specialization to integration and back to specialization is the opportunity costs of land, labor, and urban income growth. At low population pressures and when high labor and few external inputs are used for agricultural production, specialized and independent crop and livestock production systems are more attractive than integrated systems because land is relatively abundant. Labor is the major constraint, and its cost is high relative to land. Cropland productivity is maintained through fallowing, which is preferred to land application of manure because it requires less labor. As population pressures rise, the demand for arable land increases. Because fallows occupy too high a proportion of the land, farmers look for alternatives to maintain soil fertility. The utilization of manure and integration of crops and livestock within the same production system offer increased efficiencies and productivity to farmers.

Land tenure in West Africa generally does not impede cropland expansion, except in some key pastoral areas such as along corridors of livestock movement and around water points. As land cultivation increases, grazing lands diminish. This has several consequences for feed availability and quality. Not only is there a reduction in total rangeland areas, but rangeland may also become seasonally inaccessible due to fragmented cropping and/or the expansion of dry-season gardening in low-lying areas. Cropland expansion may shift the nutri-

tional constraint facing livestock from the dry to the wet season and increase the risk of overgrazing rangelands. However, the lack of wet-season feed may be accompanied by an increase in the dry-season feed supply. In northern Nigeria, croplands provide more feed of higher quality, and animals perform better grazing crop residues than livestock grazing natural pastures (van Raay and de Leeuw, 1974). As animal pressures increase, free grazing gives way to the harvesting of crop residues, which are bartered, sold, or fed to the farmers' own livestock. Manure is used to fertilize the fields of the livestock owners, rather than pastoralists providing manure to crop farmers

As the pressure on land elevates and more land is cultivated, many livestock are kept away from the cultivated zone to avoid crop damage. In three locations in western Niger, livestock densities decreased during the cropping season and increased soon after crop harvest and as the dry season progressed (Hiernaux et al., 1997). The percentage of the total livestock population that left the cultivated zone during the wet season was related to cropping density, or the proportion of total land that is cultivated. For example, in a village where 30% of the total land area was cultivated, 18% of the herd went on transhumance; where 36% of the land was cultivated, 21% of the herd left; and where 62% of the total land area was cultivated, 32% of the herd left during the cropping season.

There is evidence to suggest that beyond critical cultivation and livestock densities, competition increases between crops and livestock for scarce resources, particularly labor and land (Sandford, 1989, 1990; van Keulen and Breman, 1990; McIntire et al., 1992). It has been estimated that cattle numbers in the subhumid zone of Nigeria will continue to expand up to cultivation densities (percentage of total land that is cultivated) of 20 to 40% (Bourne et al., 1986). As these cultivation densities are approached, it is expected that extensive crop–livestock production systems will gradually give way to more intensive, integrated mixed farming systems. However, the competition for land and labor between crops and livestock for the production of food and feed continues, even in fully integrated crop–livestock systems.

INCOME LINKAGES BETWEEN CROPS AND LIVESTOCK

In many dryland agroecosystems of West Africa, poor soil fertility and low and erratic rainfall are major limitations to crop production (Breman and de Wit, 1983). For many households, diversification into livestock (Table 1) reduces risk by providing insurance in the case of crop failure. In these systems, livestock are also a source of liquidity and investment capital in the absence of savings and credit institutions. The importance of livestock and nonagricultural activities to total household income is highest in countries (Burkina Faso, Niger, and Senegal) having the lowest rainfall.

Table 1. Contribution of crops, livestock, and nonagricultural sources to household income in four West African countries.†

	Income source		
Country	Crops	Livestock	Nonagricultural
	total household income, %		
The Gambia	78	1	21
Senegal	43	13	44
Burkina Faso	49	13	38
Niger	45	8	47

† Source: von Braun and Pandya-Lorch (1991).

At first glance, livestock's contribution to total income (Table 1) appears lower than one might expect, with seemingly little potential to influence productive investments in the crop subsector. However, income from the sale of livestock can significantly improve crop production by providing the investment capital needed to enhance productivity and by increasing the demand, and hence profitability, of food production. In Niger, this occurs through a variety of direct and indirect mechanisms (Hopkins and Reardon, 1993). At the household level, income from the sale of livestock influences crop production directly by allowing households to invest in inputs such as fertilizer, hired labor, and carts and indirectly by allowing poor households to improve the nutritional status, and thereby productivity of their most important resource, their own labor. At more macro (village or national) levels, as an agricultural tradable, livestock can serve as a source of export revenues and thus a catalyst for economic growth. This growth stimulates the demand for locally produced food staples as well as higher-valued nonstaple products (such as meat and milk) and thus provides an opportunity for farmers to benefit from overall economic growth.

The income derived from livestock can provide the capital needed to initiate remunerative nonagricultural activities, which in turn provide the cash needed to finance crop production activities (Hopkins and Reardon, 1993). For example, a wife may sell several goats to finance a son's travel to the site where he will work during the dry season. Income from the son's dry season employment is then used to finance variable inputs, such as fertilizer and hired labor, as well as fixed inputs such as carts for the transport of agricultural inputs and produce. In low-rainfall zones, income from the sale of livestock is also used to purchase food during the *hungry season*, or few months before harvest when food reserves from the previous harvest diminish. This sale of livestock could be considered a *productive investment* during this labor bottleneck (weeding) period when labor demands are highest and nutritional status lowest.

USE OF ANIMAL POWER IN CROP PRODUCTION AND TRANSPORT

In some West African dryland areas, draft animals, most commonly cattle, but also donkeys, horses, mules, and even camels contribute to crop production through the provision of power to assist farmers in the production, harvesting, processing, and marketing of crops. Many farmers using animal power initially acquire a cart for transport (Dawson and Barwell, 1993) or equipment for primary tillage associated with a cash crop. Carts for transport can significantly reduce labor requirements and workloads in both cropping and household activities (Pearson et al., 1998: Zenebe and Fekade,

1998) and help intensify production. Animal-drawn weeders and planters are sometimes regarded as part of the later stages in the adoption of animal power and are usually owned by only a small proportion of the community (Wanders, 1994).

Impact of Animal Power on Farm Size and Cultivated Area

Farmers owning draft animals tend to have larger farms than those not owning animals. This pattern can be attributed to two factors: (i) animal power requires greater capital investment than manual labor, thereby making it less attractive to farmers on the smaller farms (Reddy, 1988), and (ii) farmers with access to animal power increase the area they cultivate (Francis, 1988; Panin and de Haen, 1989; Sumberg and Gilbert, 1992). The implication is that there is a positive relationship between the use of animal power and cultivated area. However, large farms using animal power also have large households so that there may be no difference in area cultivated per active household member between farms using animal power and farms that do not (Table 2).

When the use of animal power results in the cultivation of less suitable marginal land, then it can encourage soil erosion and land degradation, as well as poor crop yields. Kruit (1994) suggests that this has been the case in southwestern Niger where animal power has been largely used to extend the cropping area to increase total production. Stocking (1988) has highlighted similar problems in other countries using animal power in crop production.

Changes in Manual Work Load with Animal Power

When cultivated areas expand, animal power may not result in an overall reduction in labor inputs, but more to a shift of the work demand from one aspect of crop production to another. In cropping systems that rely on hand tillage, the labor bottleneck is usually in land preparation. Use of animal power removes this bottleneck but can shift the labor bottleneck to weeding. A shift in work demand from land preparation to weeding can place increased work on women in those cultures where women traditionally do the weeding and men are more closely associated with land preparation. Weeding bottlenecks can be overcome partially by the use of animal power to weed between rows. Wanders (1994) determined that labor saving can occur if farmers have access to weeders, ridgers, and planters in addition to ploughs so that they can take full advantage of the animal power that is available to them. Savings in labor used for weeding can be impressive. For example, the labor requirement for weeding maize was reduced by up to 80% when animal-drawn cultivators were used in place of traditional hand hoeing (Kwiligwa et al., 1994). However, yields were also reduced because of poor weeding within the rows. A combination of animal power and hand labor for within-row weeding restored yields and still reduced labor inputs by 40% compared with manual weeding alone.

Impact of Animal Power on Crops Cultivated and Yields

The use of working animals in crop production involves an investment that is often unattractive to farmers (Reddy, 1988). One way to make animal power more attractive is to increase the area under cultivation and the proportion of the land planted to cash crops. Delgado and McIntire (1982) and Panin (1987) suggested that groundnut and other cash crops increase the profitability of draft animal power more than staple food crops, such as millet, maize, and sorghum. However, there has been little evidence that the introduction of animal power has resulted in significant shifts from the production of staple crops to cash crops (Barrett et al., 1982; Panin, 1986; Francis, 1988).

The impact of animal power on crop yield is difficult to assess. Whereas farmers using animal power tend to opt for more extensive production than those using hand-tillage techniques (Francis, 1988), this often results in lower yield per hectare. However, provided the area cultivated is increased, crop output from the farm can increase under animal traction. Also, the adoption of animal power associated with cash crops and fertilizer also benefits the production of staple crops. For example, in the cotton (*Gossypium hirsutum* L.)-growing regions of West Africa, food grain production increased in some areas when animal power was introduced. The production of food crops benefited not just from more timely tillage, but also from the residual fertility when food crops are rotated with the fertilized cotton cash crop (Mahdavi, 1992).

The use of animal power can improve the timeliness of planting and therefore increase yields in areas where growing seasons are short and time of planting is crucial (Shumba, 1984). However, in areas where good weed control is essential, then use of animal power may result in lower yields. This can be due to two factors: (i) Soil inversion using an animal-drawn implement does not result in as good a weed smother as when soil inversion is done by hand, and (ii) an increase in area cultivated means that weeding may be done less frequently and

Table 2. A comparison of cultivated areas and household sizes on farms using manual and animal power.†

	Cultivated area		Household size		Cultivated area	
Country	**Manual**	**Animal power**	**Manual**	**Animal power**	**Manual**	**Animal power**
	ha farm^{-1}		members		ha laborer^{-1}	
Ghana	3.56	5.58	10.75	14.53	1.01	1.05
Zambia	2.75	5.62	4.70	10.10	0.79	1.34
Burkina Faso	4.00	6.40	7.42	11.72	1.17	1.26

† Source: Adapted from Panin (1994).

may be less effective, resulting in lower yield. In a comparison of manual labor and animal power in the cultivation of rice and maize in an inland valley region in central Nigeria, weed infestation was heavier, and weeding took longer on ox-cultivated plots of both rice and maize (Lawrence et al., 1997). This did not significantly affect yields on the weeded plots, but where weeding was not done, yields were almost halved for rice and were almost nonexistent for maize, whether animal power or manual labor had been used for land preparation. In northern Nigeria on different soil types, the use of ox-drawn implements to form and remold ridges for millet and sorghum production required less weeding than those prepared using the traditional hand-hoe techniques (Olukosi and Ogungbile, 1994).

Use of Animals to Transport Crops

Although a cart is 4 to 10 times more expensive than a plough, it can be used for most of the year for a range of activities, many of which can be income generating. Ownership of a cart can have a significant impact on a farmer's ability to utilize crops after harvest. Animal transport can reduce postharvest losses from pests by allowing timely removal of crops from the fields (Anderson and Dennis, 1994). Farmers with a cart seem to make better use of crop residues than farmers not having access to a cart and are better able to market their produce. Several studies have shown that farmers with a cart can get a higher price for their goods since they can sell directly to markets (Scheinman, 1986). Farmers with a cart also find it easier to move manure and fertilizer to the field. Higher use of manure and fertilizer has been recorded on farms owning an animal cart (Scheinman, 1986; Anderson and Dennis, 1994).

NUTRIENT CYCLING IN MIXED FARMING SYSTEMS

Nutrient cycling in agricultural systems that involve only crops is highly affected by the types and amounts of fertilizer used, the sale of crops (hence, nutrients exported off the farm), crop residue management, and tillage. The integration of livestock into cropping systems converts some crop residues into meat and milk (Fig. 3). Additional nutrients may also be introduced in the form of purchased feed concentrates and forages. Part of these feed nutrients are returned to fields as excreta (feces and urine). If soils, crops, fertilizer, and manure are managed intensively, the input/output for nutrients could be in balance or actually in surplus depending upon the quantities of commercial fertilizer used, feed purchased, and how effectively manure is returned to the soil (Stangel, 1995).

Nutrient Balance of Croplands and Rangelands

Based on national data of nutrient inputs and harvests, it is widely believed that West African farmers are mining their soils of nutrients (Breman, 1990; Stoorvogel and Smaling, 1990; van der Pol, 1992; Stoorvogel et al., 1993). Annual nutrient deficits (nutrient inputs minus nutrient harvest, kg ha^{-1}) for N (-39 to -21), P (-6 to -3), and K (-33 to -15) are highest in the more humid areas of West Africa (Henao and Baanante, 1999). Across various production systems in semiarid

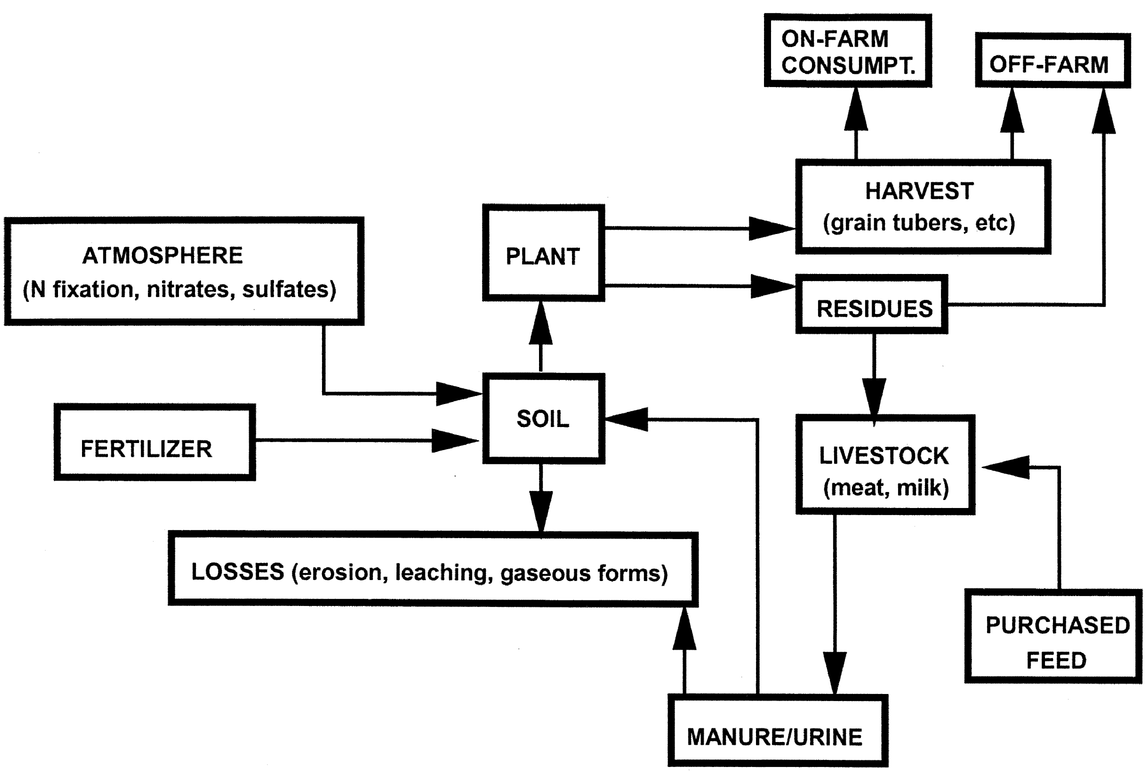

Fig. 3. Pathways of nutrient flow in mixed crop–livestock farming systems (Stangel, 1995).

Mali, N deficits approximately equal the amount of N removed as grain (Table 3). Variable amounts of nutrients are also exported from croplands through the removal of weeds, either by grazing animals, by carrying them to the homestead for feeding, or by selling them (Schlecht et al., 1995). Brouwer and Powell (1995) determined that a cultivated Alfisol (Pssammentic Paleustalfs) in southwestern Niger contains approximately 2500 kg total N ha^{-1} and 2000 kg total P ha^{-1} in the upper 2.0 m of soil. Much of this N and especially P are in recalcitrant forms and below the crop root zone. The low nutrient stock and estimated rates of soil nutrient depletion imply that soil nutrient levels may be declining rapidly.

On a regional scale, even in situations of intense grazing pressure, N exports from rangelands in the form of livestock products appear to remain lower or equivalent to N inputs (Diarra et al., 1995; de Leeuw et al., 1995; Powell et al., 1996). The amount of N removed via grazing appears to be compensated by the N returned through trampling, plant roots, and atmospheric deposition. In the Gourma pastoral region of Mali, livestock consume only 11 to 19% of the annual herbage production of rangelands (Hiernaux et al., 1997). Even long histories of high animal densities in these areas appear to have had no measurable impact on soil N and P levels and plant uptake of N and P (Tolsma et al., 1987; Turner, 1998).

Crop Residues

Crop residues are used as livestock feed, fuel, and construction material and provide income through their sale (Sandford, 1989; McIntire et al., 1992). Residues that remain in fields provide mulch and erosion protection. Farmers use various methods to feed crop residues to their livestock. Arranged in increasing order of labor requirements, these include livestock having open access to whole residues on harvested fields, harvest and removal of stalks with subsequent open access to stubble on harvested fields, harvest and removal of stalks with subsequent restricted access to stubble on harvested fields, transport and storage of residues for feed or sale, and harvest of crop thinnings from fields for selective feeding before the harvest of the main crop residue (McIntire et al., 1992). As more intensive modes of agricultural production are adopted in densely populated areas, all crop residues may be harvested for livestock feed and/or for sale. The privatization and marketing of crop residues lowers the attractiveness of an area for grazing by transhumant herds and, therefore, the availability of manure for cropping.

Table 3. Nitrogen removals, returns, and balances for croplands in mixed crop–livestock systems of Mali.†

	Production systems			
	Millet and sorghum	Upland rice	Flooded rice	Maize and cotton
	N removals, kg ha^{-1}			
Grain				
Range	11–28	17–28	26–30	14–19
Mean	18	20	29	16
Crop residues				
Range	8–14	11–12	19–23	9–16
Mean	11	11	22	
	N returns, kg ha^{-1}			
Crop residues				
Range	3–5	3–4	3–4	4–5
Mean	4	3	4	5
Manure				
Range	0–6	1–3	0–2	0–2
Mean	1	2	1	1
Crop roots				
Range	2–3	2–3	3–4	2–3
Mean	2	2	4	3
	N balance, kg ha^{-1}			
Range	−29 to −12	−19 to −16	−38 to −31	−17 to −11
Mean	−18	−18	−35	−15

† Source: Powell et al. (1996).

Crop residues are vital livestock feeds, especially in the drier parts of West Africa (Sandford, 1990). Feeding crop residues and using manure to fertilize cropland is perhaps a rational strategy. Under current situations, few alternative feeds exist. In many areas of West Africa, cereal crop residues remaining on the soil surface at the onset of planting are usually gathered and burned. Farmers apparently do this for various reasons, including to facilitate manual tillage and cultivation and to reduce insects and plant diseases. Also large amounts of fibrous residue may temporarily immobilize soil N during the initial stages of the next crop's growth. Manure-bound nutrients are more plant available than crop residue–bound nutrients (Somda et al., 1995; Powell et al., 1999).

Feeding crop residues to livestock has many disadvantages. Crop residue removal can exacerbate soil nutrient depletion. Approximately half of the crop residue N consumed would be excreted as urine and susceptible to loss via volatilization. When left in the field, crop residues provide a physical barrier to soil movement, allow soil and organic matter to accumulate, and enhance soil chemical properties and crop yield (Geiger et al., 1992; Bationo and Mokwunye, 1991; Bationo et al., 1995; Buerkert et al., 1996). Benefits resulting from surface residues generally increase with increasing amounts available. However, the retention of even small amounts of surface residues can help conserve soil and water and maintain favorable soil organic matter and nutrient levels (Power et al., 1986; Pichot et al., 1981; Unger, 1978; Unger et al., 1991).

Manure Availability for Crop Production

Manure remains perhaps the most important soil fertility amendment in West African farming systems. Manure availability for cropping is limited by livestock types, numbers, and manure output per animal; the location of livestock during the time when manure is needed; and the efficiency of manure collection (Berger et al., 1987; Landais and Lhoste, 1993; Fernandez-Rivera et al., 1995; Schlecht et al., 1995). Most farmers in the semiarid regions of West African are too poor in livestock assets (and cash income) to manure a significant portion of their cropland (Table 4). To overcome this problem, farmers pool herds and also enter into various crop residue–manure–water exchange contracts with

Table 4. Cropland area and livestock holdings of Djerma farmers and Fulani agropastoralists in western Niger.†

Farm type	Wealth ranking	Number of farms	Cropland area	Livestock holdings Cattle	Sheep	Goats
			ha farm^{-1}	head farm^{-1}		
Djerma crop farmers	Low	213	9.1	1.1	1.0	1.0
	Medium	126	21.4	0.7	1.1	1.4
	High	27	25.2	12.7	5.1	4.1
Fulani agropastoralists	Low	92	8.7	4.5	4.6	11.9
	High	74	12.7	15.4	13.1	22.5

† Source: Hiernaux et al. (1997).

pastoralists (McCown et al., 1979; Toulmin, 1983, 1992; McIntire et al., 1992). Whereas the manure of livestock owned by pastoralists continues to be an important source of crop nutrients in some areas, as cultivated areas and dry-season gardens expand due to demographic pressure, pastoralist access to the cultivated zone, and therefore manure availability, decreases. Also, the growing transaction costs involved in securing manure contracts between farmers and herders provide an increased incentive for farmers to own livestock to secure manure and other livestock goods (Turner, 1992; Toulmin, 1992; Thébaud, 1993; Scoones and Toulmin, 1995). As long as natural pastures remain the major source of livestock feed, livestock-rich farmers will benefit the most from nutrient harvesting from rangelands and transport to cropland via manure (Scoones and Toulmin, 1995).

Affecting manure output is the wide fluctuation in feed availability and quality that characterize most dryland grazing systems. In the Sudano-Sahelian zone of West Africa, livestock gain weight during the latter part of the rainy season and early part of the dry season when sufficient good quality pastures and crop residues are available. Livestock loose weight during the latter dry season and early wet season as grazing resources diminish. As a consequence of these variations in feed availability, manure output varies. In such wet–dry tropical environments, the daily manure output of grazing cattle during the wet season can be twice the manure output during the dry season (Siebert et al., 1978; Omaliko, 1981). Manure N and P content of grazing cattle is up to three times greater during the wet season and crop residue–grazing period than during the dry season (Powell, 1986).

Drought, a common occurrence in West Africa, has had a tremendous impact on the number and type of livestock and therefore manure availability. During the 1972–1974 drought, the cattle herd in northern Mali declined from 4.75 to 2.64 million. Thereafter, it increased to 4.02 million in 1982 followed by a sharp drop to 2.69 million between 1983 and 1985 due to drought (IEMVT, 1989). During the mid-1990's, herd sizes in many parts of northern Mali remained much lower than what was supported in the recent past (Erickson and Traoré, 1995). The availability of manure for crop production, and therefore the positive impact of livestock on crop production, may decline dramatically during the years following drought.

Apart from its negative effect on livestock numbers, drought may also influence the type of livestock kept by farmers. Cattle, sheep, and goats have varying degrees of susceptibility to drought. During drought, small ruminants, particularly goats, have a higher survival rate than cattle (Arnal and Garcia, 1974; Dahl and Hjort, 1976). Also, the rapid reproduction and growth rates of small ruminants allow these flocks to be reconstituted much faster than cattle herds. As a result of drought, total manure availability not only decreases, but the manure from small ruminants is likely more available than that of cattle.

Importance of Rangelands as Nutrient Source for Crop Production

Many farmers purposefully manage livestock to graze and capture nutrients from rangelands and transfer them to cropland in the form of manure. The ability of rangeland to feed livestock and supply manure nutrients for fertilizing cropland depends on the amount of rangeland available within the daily grazing orbit of livestock, the high variability in the productivity of rangelands (Hiernaux, 1995), livestock production goals (Breman and Traoré, 1986), and the management strategies of farmers (Turner, 1995). Hiernaux et al. (1997) studied the rangeland–cropland nutrient-cycling patterns in three villages of western Niger with similar climate and soils but different land use patterns (Table 5). Farmers in these villages annually manure from 3 to 8% of their total cropland area. Areas where livestock were corralled overnight accounted for 0.5 to 1.2% of the total village cropland. The amount of manure deposited on cropland during overnight corralling averaged 12.7 Mg ha^{-1} for cattle and 6.8 Mg ha^{-1} for small ruminants. In these villages, manured fields were the only fields to have positive balance in organic matter and nutrients. The greatest contribution of manure to crop nutrient requirements was found to occur in the village (Banizoumbou) that had the highest rangeland/cropland ratio (2.3). Conversely, the lowest contribution of manure to crop nutrient requirements was found to occur in the village (Ko Dey) that had the lowest rangeland/cropland ratio (0.6). This relationship shows the importance of rangelands as a feed, and therefore manure nutrient source, for crop production (Turner and Hiernaux, 2002).

Crop Response to Manure

Rainfall, temperature, soil type, manure nutrient content, and farmer management affect manure application rates and crop response. In Niger, higher manure application rates, shorter intervals between applications, and

Table 5. Annual balance of organic matter (OM), N, and P flows due to livestock intake and excretions calculated for main land use type in three village lands of western Niger. Offtake by livestock and N losses through urine are calculated for the whole village land.†

	Land use type	Village sites		
		Banizoumbou	Tigo Tegi	Ko Dey
Land use (% of total village lands)	Rangelands	23.8	15.0	13.2
	Fallows	45.9	49.0	25.0
	Crop unmanured	27.0	32.0	53.9
	Crop manured	3.3	4.0	7.9
Balance of OM livestock-mediated flows per land use type (kg ha^{-1} yr^{-1})	Rangelands	−67	−25	−135
	Fallows	−75	−100	−112
	Crop unmanured	−75	−113	−126
	Crop manured	+527	+492	+400
OM offtake (kg ha^{-1} yr^{-1})		−53	−59	−82
Balance of N livestock-mediated flows per land use type (kg ha^{-1} yr^{-1})	Rangelands	−1.6	−0.7	−3.7
	Fallows	−1.9	−2.6	−2.9
	Crop unmanured	−1.4	−1.9	−2.4
	Crop manured	+10.5	+9.0	+7.7
N offtake (kg ha^{-1} yr^{-1})		−1.3	−1.4	−1.9
Balance of P livestock-mediated flows (kg ha^{-1} yr^{-1})	Rangelands	−0.10	−0.04	−0.23
	Fallows	−0.08	−.12	−0.10
	Crop unmanured	−0.08	−.11	−0.13
	Crop manured	+1.56	+1.33	+1.09
P offtake/losses (kg ha^{-1} yr^{-1})		−0.03	−0.03	−0.04

† Source: Hiernaux et al. (1997).

smaller cultivated areas occur in higher rainfall areas where cattle are more important than small ruminants (Powell and Williams, 1993). Farmers tend to apply less manure in drier areas given the risk of *crop burning* under dry conditions.

Across various agroecological zones in SSA, crop response to manure during the year following application ranged from 15 to 86 kg grain Mg^{-1} (McIntire et al., 1992). In semiarid West Africa, the range of crop grain response to manure was 20 to 60 kg Mg^{-1}, and for crop residue, it was 70 to 178 kg Mg^{-1} (Williams et al., 1995). In subhumid Nigeria, 180 kg maize grain Mg^{-1} manure was obtained (Powell, 1986). Also, the combination of manure with fertilizer resulted in higher yields than if manure alone was applied. Across various locations in West Africa, manure applied with fertilizers produced 32 to 90 kg grain Mg^{-1} and 84 to 192 kg stover Mg^{-1} (Williams et al., 1995). Soil acidification associated with repeated applications of fertilizer N is reduced when fertilizer and manure are applied together (de Ridder and van Keulen, 1990).

Approximately one-half of the N excreted by ruminants is in the form of urine. The capture of urine N by corralling livestock directly on fields between cropping periods can have a dramatic positive impact on crop yields for up to 3 yr (Table 6). Enhanced crop yields due to corralling results from the combined effects of urine on increasing soil pH and P availability, as well as the additional N applied in the form of urine (Powell et al., 1998).

Although manure applications improve soil conditions and increase crop yields, it has many intrinsic properties that make it an unbalanced source of crop nutrients. For example, the N/P ratio of ruminant livestock manure is often lower than the N/P requirement of cereal crops (Powell et al., 2001). Therefore, if the intent in manure recycling is to optimize nutrient use, then crop P requirement and manure P content should be tar-

Table 6. Cattle and sheep manure and urine effects on total aboveground biomass yields of pearl millet in western Niger.†

Animal type	Manure applied first year‡	Cropping season following manure application‡					
		First		Second		Third	
		Urine application§					
		Yes	No	Yes	No	Yes	No
		pearl millet yield, Mg ha^{-1}					
Cattle	3.1	5.5	3.6	2.4	2.0	2.6	2.5
	7.1	6.0	4.2	4.6	2.7	4.9	2.8
	10.1	5.9	3.8	4.0	2.9	4.5	2.9
		(0.40)¶	(0.28)	(0.58)	(0.29)	(0.74)	(0.35)
Sheep	1.5	5.0	3.0	2.6	1.7	2.2	2.2
	3.2	5.8	3.7	2.6	1.7	3.4	1.9
	5.0	5.7	4.0	2.7	1.8	3.6	2.4
		(0.24)	(0.36)	(0.23)	(0.22)	(0.29)	(0.26)
Control (n = 4 plots)	0	3.0		0.9		1.1	
		(1.41)		(0.23)		(0.34)	

† Source: Adapted from Powell et al. (1998).
‡ Manure applied in 1990 (first year) only. Yields during second and third cropping season reflect millet response to residual manure from the first year.
§ Manure applied either by corralling animals on plots for one, two, or three nights (urine "yes") or manure hauled from the barn (urine "no").
¶ Values in parentheses are standard errors of the mean.

geted. However, this leaves a shortfall in crop N requirements. Manure applications to meet crop N demands result in P application in excess of crop P demands. Soil fertility management using manure is also less flexible than using fertilizer. Whereas manure is usually applied in a single application in advance of crop planting, fertilizer applications are commonly split. During cropping seasons of low rainfall, fertilizer applications after planting can be withheld. This flexibility is not possible with manure, and applied manure can *burn* the crop and negatively affect crop yield in environments having low and erratic rainfall.

Strategies for Improving Crop and Livestock Production

The greatest opportunity for sustainable increases in agricultural productivity in West Africa lie in the evolution and maturation of mixed farming systems, especially in the wetter portions of the semiarid zone (Winrock International, 1992). Intensification may include the development of cost-effective animal power systems that alleviate labor shortages and improve soil quality and crop yields; feeding systems that overcome large fluctuations in feed supply and quality; manure handling, storage, and land-spreading techniques that conserve and recycle nutrients through crops; and cropping systems that provide both food and feed of high quality. Approaches to improving the productivity of mixed farming systems differ considerably. For example, grazing-based feeding operations make limited use of external inputs (e.g., feed supplements and fertilizer) and rely almost exclusively on pastures and crop residues for animal feed, on manual labor for crop production, and on manure as precious soil fertility amendment. On the other hand, the emerging confinement-based feeding operations, especially in peri-urban areas, attempt to maximize production through a more intensive use of purchased inputs and household labor. Many of these systems import feed and may have an animal traction component. Classification of crop–livestock production systems having similar characteristics and opportunities for intensification and using quantitative techniques such as cluster analysis can be particularly useful in tailoring research to specific systems and system components (Williams, 1994; Monicat et al., 1992).

Animal Power

The greatest positive impact of animal power on crop production has been on well-resourced farms. These farms typically have sufficient labor and feed resources to manage and use animals for crop production in a timely manner. The research and development challenge, particularly in West Africa, is to find ways to support families on smaller farms. The use of the cheaper, lower-maintenance donkeys can make animal power more affordable on small farms. Hiring, loan, and exchange schemes can assist farmers in getting started in animal traction, whether it be animals, implements, or both (Pearson et al., 1998).

Improvements or advancements related to animal power within crop–livestock systems are often concerned with infrastructure development to improve access to implements and carts. In West Africa, where animal power use is relatively recent and largely confined to plowing, there is a need to increase the number and the skills of local artisans in the production and repair of animal-drawn implements and carts.

Any approach to improve mixed crop–livestock systems needs to consider labor implications. Delineation of work between men and women and availability of labor on farms are changing in many parts of West Africa as men work off-farm and children are in school. More women now have access to animal power, and often their requirements are very different to those of the men (von Keyserlingk, 1997; Sylwander and Simalenga, 1997).

Herd Management

In the drier regions of West Africa, pastoralism continues to provide not only food security and income to herders and farmers alike, but also a vital supply of manure nutrients for maintaining cropland productivity. The survival of pastoralism depends on herd mobility to exploit seasonal water and forage supplies. The expansion of cropping and dry-season gardening that encroaches onto traditional pastures and paths of livestock movement not only jeopardizes the livelihood of pastoralists (Traoré and Breman, 1992), but also the supply of manure and, therefore, crop yields. Land tenure and use policies are needed that facilitate herd mobility and farmers' access to the manure of transhumance herds.

Overnight corralling of livestock on fields between cropping periods results not only in much higher yields (Table 6), but also allows more nutrients to be recycled (feces plus urine) than if livestock are kept outside cropping areas and only manure (most urine lost) is available for recycling. In some locations, community-based efforts to improve the security of livestock corralled overnight on cropland and policies and markets that increase farmers' access to manure may allow for more efficient nutrient cycling and higher crop yields.

The evolution from extensive livestock management based on grazing to semi-intensive stall feeding of livestock will require not only high quality feed, but also methods of capturing and recycling the nutrients contained in feed refusals, manure, and urine. Composting in confinement-based feeding systems could reduce nutrient losses by capturing and stockpiling feed refusals, feces, and urine and allow farmers to calculate the nutrients they have to apply. The application of organic amendments to soil such that their decomposition and nutrient release coincide with crop nutrient demands can greatly increase the efficiency of nutrient cycling in low-input farming systems (McGill and Myers, 1987; Swift et al., 1989; Ingram and Swift, 1989). Whereas improved manure handling, storage, and land-spreading techniques can enhance nutrient cycling in these mixed farming systems, the additional labor needed to accom-

plish these tasks needs to be considered when evaluating the feasibility and benefits of such practices.

Feed Resources

A more extensive use of concentrates and crop by-products will be critical to increasing livestock production (Winrock International, 1992; Steinfeld et al., 1997). In the West African drylands however, the widespread feeding of grain involves ethical issues of competition between humans and livestock for food security. Feeding grain is currently limited to brief fattening periods before marketing livestock and slaughter during religious festivals. The feed supply from croplands can be enhanced by incorporating forage legumes into cropping systems, through crop variety improvement and management that enhance crop residue yield and quality while leaving sufficient residues in fields for soil conservation, and through a more widespread and integrated use of fertilizers and other nutrient sources.

Forage Legumes

The integration of herbaceous forage legumes, shrubs, and trees into cereal-based cropping systems can control soil erosion, improve soil water conservation, suppress weed growth, accelerate nutrient cycling, enhance soil productivity, and provide food, fodder, and wood (Nair et al., 1999; Tarawali et al., 2002). In production systems where fallowing is practiced, forage legumes that fix atmospheric N can be more effective than native grasses in restoring soil fertility, thereby reducing fallow period requirements. However, the establishment of forage legumes in cereal-based cropping systems can be challenging. If interplanted too early, forages may decrease grain yield of the companion cereal crop (Waghmare and Singh, 1984; Mohamed-Saleem, 1985; Kouamé et al., 1993). This may be due to the competition between the two crops for water, especially during years of low and erratic rainfall. The greatest benefit of forage legumes occurs when they are rotated with cereal crops. When cereals follow forage legumes, greater grain and crop residue yields are obtained than when followed by natural fallow (Tarawali and Mohamed-Saleem, 1995).

The adoption of forage legume fallows, instead of utilizing the natural regeneration of indigenous plant species, depends on their superior ability to support more livestock and restore soil fertility (Ruthenberg, 1980). Land allocation to forage production is positively related to land tenure security (especially of access rights) and is negatively related to access to communal or other land and to the ability to acquire additional land. Increased labor requirements to produce forages in relation to the effect of forages on livestock output impede forage production in most dryland areas (McIntire et al., 1992). Other problems associated with introducing forage legumes into cereal-based cropping systems include the need for land to devote to forages, high cost of fencing in areas where livestock graze freely, forage management to keep predominance of legume, soil trampling by livestock, and legume diseases. Profitable management techniques are still required if forage legumes are to be widely cultivated in the drylands of West Africa. Legumes have to be easy to cultivate, they need to regenerate readily and not be a hazard to the succeeding crop. The problem in many dryland areas is the lack of legume persistence when grown in association with grasses.

Crop Residues

Farmers raising both crops and livestock in West Africa cultivate crop varieties that assure not only food, but also adequate crop residue production to satisfy on-farm feed, fuel, and construction material requirements. Large differences in cereal morphological and chemical characteristics may offer possibilities for breeding crop genotypes that improve both grain and crop residues that can be used for multiple purposes. However, crop breeding for such diverse use presents particular challenges. Crop variety improvement programs have traditionally focused on enhancing grain production by shifting yield from crop residue to grain. For cereals, this not only reduces crop residue yields, but also often produces residues of poorer feed quality than the unimproved varieties (Reed et al., 1988). Crop breeding strategies need to consider farmer multiple uses of the total crop biomass, not only grain.

Utilization of Wasteland Areas

Some areas unsuitable for crop production are present on many farms and near many villages. These may be next to streams or roads, on rocky outcrops, in low-lying or marshy areas, along property lines, and in irregular-shaped sites within fields. Plants from such areas often are used as livestock feed, but greater production could be obtained through improved management, which could further reduce the demand for crop residues as livestock feed.

Nutrient Replacement

Sustainable increases in biomass productivity are fundamental to providing adequate food and feed for expanding human and livestock populations. An expanded use of fertilizers will be crucial to increasing food and feed supply and quality (Breman, 1990; McIntire and Powell, 1995). However, fertilizers continue to be costly and unavailable to most West African farmers. The necessary increase in fertilizer use may require loans and/or the granting of subsidies to farmers, proper instruction in fertilizer use, the provision of fertilizer-responsive varieties, and policies that give farmers timely access to fertilizer at reasonable costs and attractive prices for their commodities.

Decisions related to crop nutrient replacement using fertilizer need to be based on sound understanding of the farming system. In a review of the effects of fertilizer on crop yields in semiarid West Africa, Williams et al. (1995) concluded that light fertilizer applications with crop residues or manure are superior to heavy fertilizer applications alone. The application of fertilizer alone to poorly buffered soils leads to decreases in soil pH and

aluminum toxicity (Pieri, 1989). Much greater than the issue of soil acidity in terms of pH is the effect of soil acidification on the soil resource itself, particularly the reduction in soil cation exchange capacity (Barak et al., 1998). The addition of small amounts of crop residues in combination with inorganic fertilizers can counteract soil acidification (de Ridder and van Keulen, 1990) and increase soil cation exchange capacity (Bationo et al., 1995; de Ridder and Van Keulen, 1990), populations of N-fixing bacteria, and root length and density, leading to an increase in total P uptake by the crop (Hafner et al., 1993a, 1993b). The partial rather than total removal of crop residues from fields is vital for these benefits to be realized.

Before advocating an increase in herd size for the purpose of increasing manure availability, more information would be needed on current rangeland and cropland carrying capacities and stocking rates. The practices of farmers would also need to be evaluated to estimate how much manure would be required to offset nutrient harvests. The observations that farmers manure their fields every 2 to 3 yr (Powell and Williams, 1993) and that manure has positive residual effects on crop yields (Table 6) indicate only a portion of fields need to receive manure annually. Under current rangeland/cropland ratios, feed availability, and herd size, only 3 to 10% of total cultivated area would be able to receive manure annually (Turner, 1995; Hiernaux et al., 1997).

The efficient recycling of manure nutrients through cropland depends on land type (slope, texture, and nutrient attenuation potential), amounts and method of manure application (surface-applied or incorporated), timing of application (months before or just before planting), and the nutrient demands of the subsequent crops to be grown. Strategies for optimizing manure use must therefore be site specific. For example, runoff is greatest from slopping land and on heavier-textured soils having slow infiltration. Leaching losses can be great on sandy soils having high infiltration rates. Varying manure application rates in correspondence with microtopographical differences in texture and soil chemical characteristics at the field level can enhance nutrient cycling (Brouwer and Powell, 1998).

Integrated Nutrient Management

Approaches to achieving tandem, sustainable improvements in crop and livestock production from mixed farming systems in West African need to seek a holistic understanding of the biophysical and socioeconomic factors affecting nutrient flow at various scales. Models are needed that assess the impact of current and alternative practices on landscape, whole-farm, and within-farm nutrient cycles. For example, most current attempts to improve on-farm nutrient management target either the feed, fertilizer, and/or manure nutrient components, often with little regard of how nutrient flow through one component (e.g., feed–livestock) affects nutrient flow through other system components (e.g., manure quality, soils–crops). Also, criteria for selecting forage legumes and browse for use as windbreaks, in fallows, as intercrops with cereals, etc., need to consider not only their value as food, fuel, and fodder, but also their impact on nutrient cycling through other system components. Separate feed, fertilizer, and manure management strategies may result in suboptimal nutrient use and reduce their profitable use. For example, feed supplements may not only improve the productive and reproductive performance of livestock, but also enhance manure quality, which many improve crop yields.

CONCLUDING REMARKS

In West Africa, animal power can assist farmers in the production, harvesting, processing, and marketing of crops. Substantial gains in crop and livestock production can be achieved through an increased use of diet supplements and fertilizer, the integration forage legumes into cropping systems, and through crop genetic improvement and land management practices that improve crop residue yield and quality for use as livestock feed and in soil conservation. Innovations need to consider not only the biophysical response of crops and livestock to additional nutrient inputs, but also farmer accessibility to these inputs and how these and other inputs may be used to minimize the risk associated with erratic rainfall. Successful agricultural intensification is currently underway in many regions of West Africa, and there may be lessons to be learned in terms of what motivates farmers to invest in technologies and practices that improve crop and livestock production while conserving natural resources. Maintaining a balance between the food and feed supply, nutrient inputs and outputs, and human and livestock populations will be critical to the sustained productivity of rangelands, cropland, and livestock as these systems intensify production.

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