Deutscher Tropentag 2003
Göttingen, October 8-10, 2003

Conference on International Agricultural Research for Development

The Scale Issues in Assessing Matter Fluxes and Balance in/out Agro-Ecosystems

Pierre Hiernaux[a] and Eva Schlecht[b]

[a] Centre for Agriculture in the Tropics and Subtropics; email: hiernaux@uni-hohenheim.de
[b] Institute for Animal Production in the Tropics and Subtropics;
University of Hohenheim 70593 Stuttgart, Germany

Historical context of the assessment of nutrient fluxes and balances

Since the 1970[ies] it appeared that poor soil organic matter content and limited nutrient availability to plants were key in explaining the low agricultural productivity and the limited adoption of improved management strategies by farmers. Similarly, the poor protein content and the low digestibility of the feed available to ruminants in the dry season were identified as the major limiting factors for livestock productivity. The droughts of the 70's and 80's aggravated human pressure on natural resources, accelerating the losses in soil fertility. Assessment of nutrient flows and balances were then attempted to consider these trends at all scales from plot to subcontinent. The balance results have been used to try and support alternative natural resource management strategies and policies (Smaling et al. 1996), especially with regard to fertilizer input (Breman et al. 2001) and import-exports of agricultural products. Although they generally converge towards negative figures, the nutrient balances differed largely in absolute terms. Given this background, the objectives of this paper are: (1) to analyse why the established nutrient balances diverge so much; (2) to evaluate the difficulties of up-scaling and down-scaling nutrient flows; (3) to examine how geographical information systems (GIS) and mathematical models address the scale constraints; (4) to discuss uses of the outputs of nutrient flux and balance calculations and models.

Case studies of organic carbon and nutrient fluxes and balances

The agro-ecosystem components considered in the calculation of nutrient fluxes and balances are climate, farm household, land and soils, primary and secondary production, and input-output markets. Organic matter and nutrient fluxes either remain within the farm system other relate to external pools. Nutrient fluxes and balances are calculated at various spatial scales ranging from individual plants or animals, to plots and herds, farms, villages, districts, countries and continents. The hierarchy of scale does not match for all the processes involved in nutrient flows; farm, village territory and administrative units, for example, do generally not match with catchments and watersheds.

On the time scale, days and years are main biological time units, and most balances are established on a year basis. Days and years are obvious units to consider, but subdivisions such as hours, or seasons within a year, and periods extending over several years may be determinant. While the seasonality of biological and economic processes is obvious, the fact that biological and economical effects also function over longer time is often neglected.

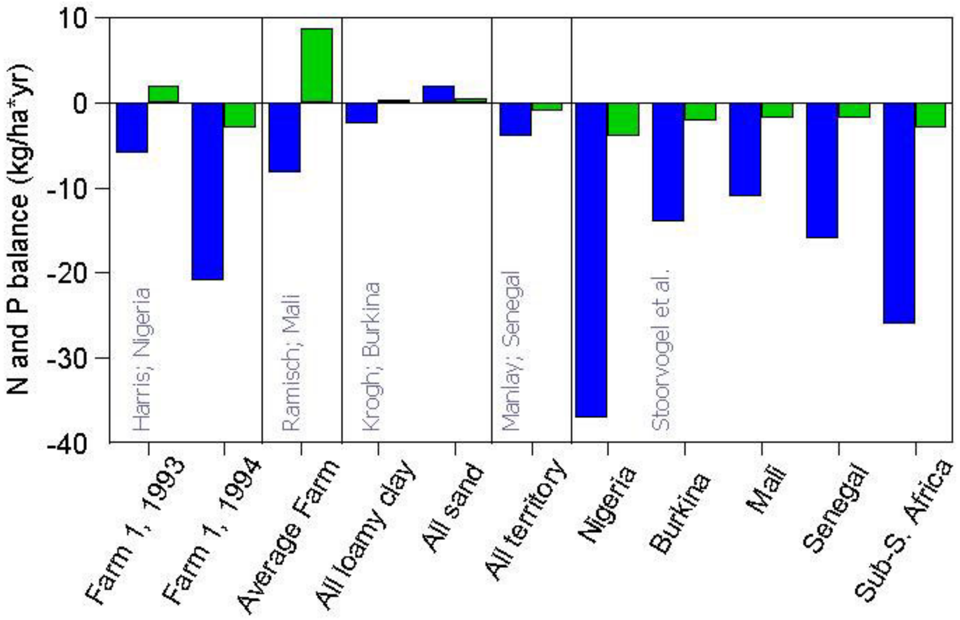

Figure 1: Nitrogen (N, ■) and phosphorus (P, ■) balances established by different authors and ranging from farm to sub-continental scale across Africa. For complete references see text.

Among many assessments of organic matter and nutrient fluxes and balances carried out in Africa, case studies have been selected of assessments conducted at different spatial scales. In Niger, Evequoz and Yadij (1998) established balances for C, N and P at the scale of individual fields. In Nigeria, Harris (1998) assessed N, P, K, Mg and Ca balances at the scale of the farm by considering all individual fields. The extrapolation of balances established at the field scale to the village territory was undertaken by Krogh (1997) in Burkina Faso for N and P, by Ramisch (1999) in Mali for C, N, P and K, and in Senegal by Manlay et al. (2000, 2002a,b) for C, N and P. Extrapolation of balances from the field to the scale of districts, countries and to Sub-Saharan Africa as a whole, respectively, was undertaken by Smaling et al. (1993) and by Stoorvogel and Smaling (1990) for N, P and K. Analysing and comparing the different balances reveals several reasons for divergent outputs (Figure 1). Firstly, the assessments of fluxes are often partial and do not include the same agro-ecosystem components, some being excluded or only included as black boxes. The assessments also cover a more or less large part of the C and nutrient cycles. Secondly, elementary fluxes are either internalised completely (Krogh 1997) or partially (Ramish 1999) or averaged when up-scaling (Stoorvogel and Smaling 1990). The data required to internalise fluxes are not always available, and the results can be misleading because elementary fluxes are confounded. Likewise, averaging fluxes, even after weighing by the source area, is not always valid, especially when the sources are interacting. Thirdly, the computation of annual balances mostly considers seasonal processes, while longer term biological and economical processes are often ignored. Examples are the residual effects of fertiliser treatments and of crop rotations (Ramish 1999), long-term soil organic matter decomposition (Manlay et al. 2000), livestock reproduction cycles and long-term market trends.

The scale dependency of organic carbon and nutrient fluxes and balances

Flux outputs depending on spatial scale

Nutrient flows related to soil erosion by wind are one example for processes where the output depends on the spatial scale. At site scale, there is an input of matter through dust deposition, and a loss through wind erosion. The distance of transportation by the wind is strongly related to particle size, whereby only particles <20µm are lifted off the soil by wind, and, depending on wind strength, topography, soil surface features and vegetation and litter cover, is deposited several or thousand of kilometres away, while coarser particles are only locally moved by saltation or creeping. At any site the balance between particle deposition and erosion will depend on the relative importance of the flows affecting the two particle sizes. Small particles originating from the Sahara are deposited by the Harmattan wind during most of the dry season, while a few storms at the onset of the wet season redistribute particles from eroding local areas. As a result, the balance for fine particles is generally positive in the Sahelian and Soudanian zones although local balances vary with surface roughness, from 30 kg ha^{-1} y^{-1} on millet fields to 700 kg ha^{-1} y^{-1} on a fallow (Rajot 2001). The balance for coarser particles is much more variable, being largely negative in erosion prone patches (low vegetation cover, loose soil surface) and positive wherever soil surface features or vegetation and litter cover limit erosion. In an experiment conducted in Niger, 160 t ha^{-1} where eroded from un-mulched millet fields while 130 t^{-1} ha were deposited on the neighbouring mulched plot in only two storms (Buerkert and Lamers 1999). The total balance is thus very much a matter of spatial scale and time horizon. If at plot scale the balance calculated over a few years could be either positive or negative depending on the local erosion-deposition balance of coarse elements, the fluxes of coarse elements rapidly equilibrate when up-scaling to village territory or watershed scales, so that the overall balance will only depend on the small particle fluxes and, in contrast to assessment extrapolating erosion data measured on croplands (Stoorvogel and Smaling 1990**)**, will result in a positive balance. Rainwater redistribution in the landscape through run-off and the associated soil erosion follow similar rules: the erosion process depends on particle size, and soil erosion/sedimentation balance varies very much and non-linearly with scale (Estèves and Lapetite 2003).

Flux outputs depending on time scale

The nutrient flows related to the cycling of organic matter are an example of processes whose output depends on time scale. Although topsoil content in organic matter (SOM) is generally low in tropical soils, it largely determines soil fertility due to its multiple roles. Indeed, in soils often very sandy in which clay is dominated by kaolinite, SOM content largely determines the soil's cation-exchange capacity (CEC), which has implications on cation buffering, pH and aluminium toxicity. SOM also contributes to the strengthening of soil aggregates, thus increasing soil porosity, which may favour root development (also stimulated by some chemical components of SOM). Under tropical climate, however, the decomposition and mineralization of organic matter is very fast, even in the drier zones. As a result, SOM remains low even when very large amounts of organic matter are recycled like in fallow systems or in experimental mulching and manuring treatments (Bacyé et al. 1998). However, SOM components have contrasted physical, chemical and dynamic properties and can be separated in two main categories based on particle size (Feller 1997). The smaller size SOM particles (<20µm or <50 µm) mineralise much more slowly as demonstrated by the double pool exponential model fit to plant and faeces organic matter decomposition in the soil (Somda et al. 1995). Thus the bulk of SOM mineralization is due to the decomposition of the coarse fraction (Dembélé et al. 1998) that supports soil biological activity. As a result, the mass and chemical composition of the recycled organic material is more determinant than the content in soil organic matter (Manlay 2000). The kinetics of SOM also explain the important residual effects of applied organic matter that have to be accounted for. An example is the residual effect of manure application to millet crop, in which residual effects on grain and stalk yields were observed up to four years after manure application even at modest rates (Hiernaux et al. 1998; Schlecht et al. 2003).

Flux outputs mediated by management

Processes related to livestock mobility and communal resource use exceed the limits of the closed farm and point to the need of integrating social arrangements in ecosystem modelling. Livestock of pastoral and of most crop-livestock systems in sub-Saharan Africa graze range and fallow lands, as well as weeds and crop residues left on the fields irrespective of the farm boundaries. The access rights for grazing are communal and not exclusive, they consist in priorities of access, rely on reciprocity between communities and are negotiable. Yet supplement feeds and the excretions deposited during resting, especially at night, are generally managed within the farm. Nutrient flows through forage uptake and excretion deposit by grazing livestock must be assessed at a wider scale than the farm, although the results can be finally broken up to individual fields and then aggregated per farm. This transfer of scales is facilitated by use of GIS. Yet, assessing forage uptake and excretion of grazing livestock in such communal systems is a challenge. It requires time series analysis of composition and numbers of livestock herds, foraging and excretion behaviour and of daily and seasonal movements that will only be available from detailed monitoring at selected case study sites (Schlecht et al. 2003), or from modelling (Busqué 2002).

Models computing organic carbon and nutrient flows

A range of models have been developed which, among other objectives, aim at assessing, on an annual basis, organic carbon and nutrient flows and derived balances in the agro-ecosystem. Some of these models also attempt to link with geographic information systems in order to express results on a geographic format or more ambitiously to model spatial fluxes.

The static model

The Nutrient Monitoring (Nutmon) toolbox (De Jager et al. 1998; van den Bosch et al. 1998a,b; Gachimbi et al. 2002; Busqué 2002) is not a simulation model but software designed to assess and monitor nutrient fluxes and economic indicators at the farm scale. The toolbox is part of a more general approach of participative agricultural development, in which monitoring of farm ecology and economy are tools to guide on-farm trials and management decisions. Nutmon provides a well-structured framework that enforces systematic recording of variables on primary and secondary production units, on storing and redistribution units, and labour and market flows, all at farm scale and at monthly intervals. The toolbox contains a few simulation routines to assess flows that are difficult to document by interviews or measure and monitor in the field, such as nutrient inputs and outputs by rain, dust, denitrification, volatilisation and soil erosion, whereby the routines are not interactive. Like this, Nutmon calculates nutrient flows and balances both at plot and farm scale and on a yearly basis. When several farms are monitored, their nutrient balances and economic performances can be compared. However, Nutmon does not provide simulation tools that can be used for ex-ante testing of the impacts of a new technology, a management or policy decision. Moreover, the structure of the farm database does not provide easy ways to assess those nutrient fluxes that are due to communal resource management.

The simulation model

The multi-goal linear programming model developed to assess the bio-economic sustainability of farming systems (Hengsdijk and Kruseman 1992; Kruseman 2000) has been adapted to low input farming systems in West Africa (Sissoko 1998; La Rovere 2002). The model encompasses climate, soils, primary and secondary production units, as well as storing and redistribution facilities, labour and monetary flows. These components are interrelated by a web of functions, which contribute to the utility functions that are maximised by the model under criteria of production, feed security, income generation and also soil fertility maintenance. The model thus allows the test of technologies, management decisions and policies under these criteria, alone or combined, for selected farm types and scenarios. However, the simulation of the biological processes of production and nutrient flows remains very coarse. Despite additional iteration facilities that allow assessing trends at medium term (La Rovere 2002), the approach is essentially static. Designed as a farm approach, the model does not provide routines to deal with communal management of resources such as grazing and forestry. Moreover, the relations between farms, and more generally farmers' response to exogenous and endogenous changes are not internalised in this model approach.

The decision rules model

The decision rules model (Struif-Bontkes 1999; Struif-Bontkes and Van Keulen 2003) is composed of a farm and a region sub-model that simulates the management decisions of farmers or regional institutions, respectively. In its application to the farming systems of the cotton belt of sub-humid Mali, the farm sub-model applies to four farm types and consists in a set of equations and parameters representing these farm types. It recognises three subsystems, namely cropping, livestock and soil. The model was run over 45 years, of which years 1980-1996 were used for model calibration. After calibration, the farm model allows to simulate, for each farm type, changes over time in soil fertility (organic C, N, soluble P, soil pH), crop and livestock production, food supply, farm income and employment status. In a second step, the farm model is used to explore the impact of technologies (e.g., introduction of a forage legume). Data inputs to the regional model are the outputs of the farm sub-model run for each farm type. The farm types remain fixed while the number of farms of each type evolves from an initial setup, depending on performance, retirement, succession, partitioning of land and immigration. Occurrences of these events are modelled based on decision rules which are influenced by farmers' age and household demography, crop and livestock performances, herd age-sex structure and growth, and on market prices. Other relations between farms such as labour and land contracts, entrustments, lending and gifts of livestock are not included. As for the farm sub-model, the regional model was calibrated over the 1980-1996 period and run for 45 years. Again, alternative management options, technologies and policies can be tested at regional level in a second step.

In contrast to the previous models, this model simulates the dynamics of the farming systems at the farm and regional scale and allows the test of changes in technology, management and policies. Farm access to communally managed resources is modelled at the regional scale. It is a tool that could help exploring technical (farm) and policy (regional) options in set scenario situations (demography, tenure rules, markets). However, the farm model requires the calibration of a large number of functions against documented farming system dynamics, while the functions used in the regional model are based on chosen decision rules. Among unavoidable simplifications, limiting the dynamics of the farming systems to the change in numbers of pre-set farms types is the major constraint of this model.

Perspectives for the use of calculated and modelled nutrient balances

There is a consensus to consider nutrient balances as indicators of agro-ecosystem's health, which should be used to influence natural resource management policies (van der Pol 1992; Stoorvogel 2003). These indicators are however often biased by the selection of components and fluxes considered and the pathways used in up-scaling (Scoones and Toulmin 1998). The calculation of nutrient balances and the building of models devoted to it have also scientific merits by identifying knowledge gaps, providing trend estimates for complex processes, and exploring ecosystem functions under different scenarios. Simulation modelling can improve the quality of nutrient balances in helping the integration of processes organised at different time scales, while GIS can contribute by transferring processes developed at different spatial scales. Both can also contribute to a better integration of the economic and social variables (Dent et al. 1995). However, the feasibility and pertinence of a universal model in which all biophysical, economic and social processes will be simulated is questionable. The quality of the resulting balances will be constrained by the most poorly quantified process, and their interpretation will thus be problematic. It is thus preferable to restrict the scope of assessments of flows and balances to well defined domains. This approach reduces the risk of confounding factors that influence the processes modelled. However, the resulting fluxes and balances will be of partial nature, which must be taken into account when interpreting the results.

References

BACYÉ B., MOREAU R. AND FELLER C. (1998). Décomposition d'une poudrette de fumier incorporée dans un sol sableux de versant et un sol argilo-limoneux de bas-fond en milieu soudano-sahélien. Etude et Gestion des Sols 5, 83-92.

BREMAN H., GROOT J.J.R. AND VAN KEULEN H. (2001). Resource limitations in Sahelian agriculture. Global Environment Change: Human and Policy Dimensions 11, 59-68.

BUERKERT A. AND LAMERS J.P.A. (1999). Soil erosion and deposition effects on surface characteristics and pearl millet growth in the West African Sahel. Plant and Soil 215, 239-253.

BUSQUÉ J. (2002). Nutrient states and dynamics of low input farming systems in western Niger. ILRI, Niamey, Niger, ILRI. Report of consultancy 19p.

DE JAGER A., NANDWA S.M. AND OKOTH P.F. (1998). Monitoring nutrient flows and economic performance in African farming system (NUTMON) I. Concepts and methodologies. Agriculture, Ecosystems and Environment 71, 37-48.

DEMBÉLÉ F., MASSE D. AND YOSSI H. (1998). Rôle des feux de brousse sur la dynamique des adventices et sur la qualité des sols au cours des premières années de jachère, dans les régions soudaniennes du Mali. In: Floret C. and Pontanier R. (eds) Jachères et Maintien de la Fertilité. I.E.R. Bamako, Mali and Orstom, France. pp. 33-40.

DENT J.B., EDWARDS-JONES G. AND MCGREGOR M.J. (1995). Simulation of ecological, social and economic factors in agricultural systems. Agricultural Systems 49, 337-351.

ESTÈVES M. AND LAPETITE J.M. (2003). A multi-scale approach of runoff generation in a Sahelain gully catchment: a case study in Niger. Catena 50, 255-271.

EVÉQUOZ M. AND YADJI G. (1998). Conservation et gestion des eaux et des sols au Niger. Durabilité du système de production agricole nord-sahélien. Eidgennössische Technische Hochschule ETH, Zurich, Switzerland.

FELLER C. AND BEARE M.H. (1997). Physical control of soil organic matter dynamics in the tropics. Geoderma 79, 69-116.

GACHIMBI L.N., DE JAGER A., VAN KEULEN H., THURANIRA E.G. AND NANDWA S.M. (2002). Participatory diagnosis of soil nutrient depletion in semi-arid areas of Kenya. Series: Managing Africa'a Soils – Issue 26. IIED, London, UK.

HARRIS F.M.A. (1998). Farm-level assessment of nutrient balance in northern Nigeria. Agriculture, Ecosystems and Environment 71, 201-214.

HENGSDIJK H. AND KRUSEMAN G. (1993). Operationalizing the DLV program: an integrated agro-economic and agro-ecological approach to a methodology for analysis of sustainable land use and regional agricultural policy. Report 1, DLV-DLO. Wageningen, The Netherlands.

KROGH L. (1997). Field and village nutrient balances in millet cultivation in northern Burkina Faso: a village case study. Journal of Arid Environments 35, 147-159.

KRUSEMAN G. (2000). Bio-economic modelling for agricultural intensification. PhD thesis, University of Wageningen, The Netherlands.

LA ROVERE R. (2001). Livestock roles and agro-environmental sustainability of Sahelian Niger mixed crop-livestock systems under intensification. PhD thesis, University of Bologna , Italy.

MANLAY R.J. (2000). Organic matter dynamics in mixed-farming systems of the West African savanna: a village case study from south Senegal. PhD Thesis ENGREF, Paris, France.

MANLAY R.J., MASSE D., CHOTTE J.L., FELLER C., KAIRÉ M., FARDOUX J. AND PONTANIER R. (2002a). Carbon, nitrogen and phophorus allocation in agro-ecosystems of a West African savanna. II. The soil component under semi-permanent cultivation. Agriculture, Ecosystems and Environment 88, 233-248.

MANLAY R.J., CHOTTE J.L., MASSE D., LAURENT J.Y. AND FELLER C. (2002b). Carbon, nitrogen and phosphorus allocation in agro-ecosystems of a West African savanna. III. Plant and soil components under continuous cultivation. Agriculture, Ecosystems and Environment 88, 249-269.

RAJOT J.L. (2001). Wind blown sediment mass budget of Sahelian village land units in Niger. Bulletin de la Société Géologique de France 172, 523-531.

RAMISH J. (1999). In the balance? Evaluating soil nutrient budgets for an agro-pastoral village of southern Mali. Series: Managing Africa's Soils – Issue. 9; 28 pp. IIED, London, UK.

SCHLECHT E., HIERNAUX P., ACHARD F. AND TURNER M.D. (2003). Livestock related nutrient budgets within village territories in western Niger. (accepted by Nutrient Cycling in Agro-Ecosystems, Sept. 2003)

SCOONES I. AND TOULMIN C. (1998). Soil nutrient budgets and balances: what use for policy? Agriculture, Ecosystems and Environment, 71: 255-269.

SISSOKO K. (1998). Et demain L'Agriculture? Options techniques et mesures politiques pour un developpement agricole durable en Afrique subsaharienne: cas du Cercle de Koutiala en zone sud du Mali. PhD thesis, University of Wageningen, The Netherlands.

SMALING E.M.A., STOORVOGEL J.J. AND WINDMAIJER P.N. (1993). Calculating soil nutrient balances in Africa at different scales. II. District scale. Fertilizer Research 35, 237-250.

SMALING E.M.A., FRESCO L.O. AND DE JAGER A. (1996). Classifying, monitoring and improving soil nutrient stocks and flows in African agriculture. Ambio 25, 492-496.

SOMDA Z.C., POWELL J.M., FERNÁNDEZ-RIVERA S. AND REED J. (1995). Feed factors affecting nutrient excretion by ruminants and the fate of nutrients when applied to soil. In: Powell J.M., Fernández-Rivera S., Williams T.O., and Renard C. (eds) Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa. ILCA, Addis Ababa, Ethiopia. Vol 2, pp. 227-243.

STOORVOGEL J.J. AND SMALING E.M.A. (1990). Assessment of soil nutrient depletion in Sub-Saharan Africa: 1983-2000. Main report. The Winand Staring Centre, Wageningen, The Netherlands. Vol 1, 113 pp.

STOORVOGEL J.J., SMALING E.M.A. AND JANSSEN B.H. (1993). Calculating soil nutrient balances in Africa at different scales. I. Supra-national scale. Fertilizer Research 35, 227-335.

STOORVOGEL J.J. (2003). Land quality indicators for sustainable land management: nutrient balance. Internet Communication.

STRUIF-BONTKES T.E. (1999). Modelling dynamics of agricultural development: a process approach - the case of Koutiala (Mali). PhD Thesis, University of Wageningen, The Netherlands.

STRUIF-BONTKES T.E. AND VAN KEULEN H. (2003). Modelling the dynamics of agricultural development at farm and regional level. Agricultural Systems 76, 379-396.

VAN DEN BOSCH H., DE JAGER A. AND VLAMING J. (1998a). Monitoring nutrient flows and economic performance in African farming systems (NUTMON) II. Tool development. Agriculture, Ecosystems and Environment 71, 49-62.

VAN DEN BOSCH H., GITARI J.N., OGARO V.N., MAOBE S. AND VLAMING J. (1998b). Monitoring nutrient flows and economic performance in African farming systems (NUTMON) III. Monitoring nutrient flows and balances in three districts in Kenya. Agriculture, Ecosystems and Environment 71, 63-80.

VAN DER POL F. (1992). Soil mining. Amsterdam, The Netherlands, Royal Tropic Institute (KIT). Bulletin 325, 47 pp.