Stratification

There is a well-established body of theory on 'stratified sampling', in both social and biophysical sciences. Essentially it means dividing the 'world' into different zones (strata) on the basis of a priori knowledge, sampling in each of these zones and deriving weighted averages for the 'world'. If n X_i values are the result for n strata, the overall average value X_t is derived from

$$X_t = \sum_{i=1}^{n} f_i X_i \qquad (1.1)$$

where f_i represents the relative weights of the strata. Often the f_i values are taken to be proportional with the area fractions, a_i, of the various strata:

$$X_t = \sum_{i=1}^{n} a_i X_i \qquad (1.2)$$

Taking area fractions can be a practical way to derive 'time averaged' values for a 'land use system', assuming that it is in 'steady state'. For example, the area fractions under various stages of fallow regrowth and cropping should, under this assumption, represent the relative duration of each phase during the cycle.

Sampling within the strata is normally based on 'minimum representative' sample sizes; these are supposed to be internally heterogeneous, but to be replicated within the stratum. For agronomic experiments there are standard ideas of a 'minimum plot size' required, for soil sampling of a minimum number of replications for pooled samples, in plant ecology the concept of 'minimum area' has a long history.

There is still a lot to be improved on in using this approach in land use research, but we also have to face a more serious challenge: for many, if not all, parameters the use of equation (1.2) can lead to the wrong conclusions. Yet, the vast majority of current GIS applications are based on this area-based extrapolation.

Scaling Up

When we take a more critical look at many phenomena, stocks as well as flows, they are not simply proportional to the area they occupy. Equation (1.2) can be modified by introducing a *scaling factor s*:

$$X_t = \sum_{i=1}^{..} a_i^{0.5\,s} X_i \qquad (1.3)$$

The factor 0.5 is introduced here to convert area back to a linear scale; s then represents the appropriate 'dimensionality' of the process (Fig. 1.8). The reasons for s to differ from 2 (and thus for the scaling rule to differ from an area-based one) are manifold, but always appear to involve

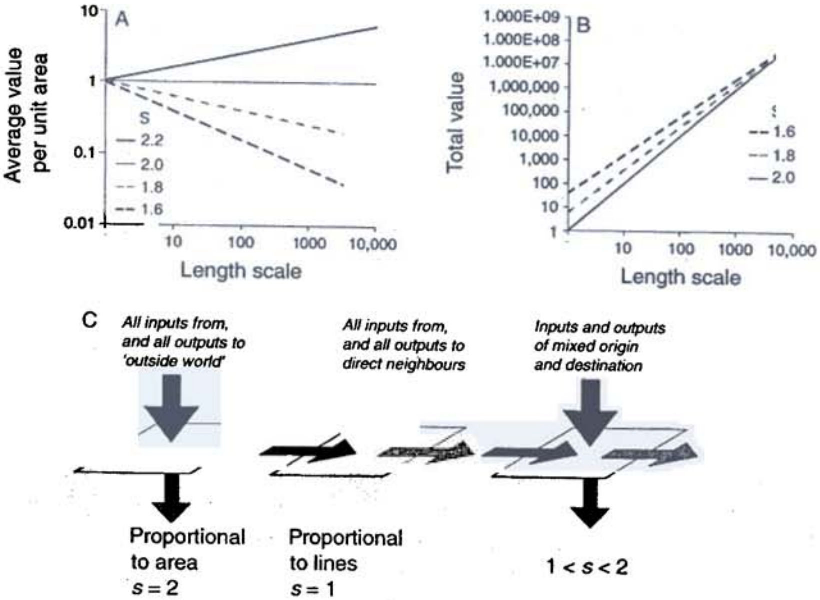

Fig. 1.8. (A), (B) Scaling rules potentially lead to changes in average value per unit area. (C) If all inputs come from, and outputs go to the outside world, an area-based approach with dimensionality of $s = 2$ may apply (left); if all inputs and outputs are laterally transmitted, a linear approach ($s = 1$) is appropriate (middle); if inputs and outputs are of mixed origin and destination, a dimension between 1 and 2 may apply (right).

'interactions'. Spatial interactions are common in 'fluxes' and 'flows', but can also occur in 'stocks', for example in a property such as 'species richness' where only species not yet encountered add to the overall value when scale is increased. Nutrient stocks, however, appear to follow classical ($s = 2$) scaling rules.

In extreme cases we may find that $s = 1$ and lines rather than areas are involved. This may apply, for example, if surface runoff is simply passing through an area with impermeable surface crusts or in 'boundary planting' systems. If the dimensionality is not a whole number (1, 2 or 3) but something in between, we can speak of 'fractal' dimensions. For many phenomena a given fractal dimension may apply across a range of scales, but the scaling rules themselves may change at certain transition points (Lam and De Cola, 1993).

The main reason for the dimensionality to differ from 2, is that there are local *interactions* at a range of scales. If all inputs come from outside the system, and all outputs leave the system, an area-based approach is correct (Fig. 1.8C). If, however, part of the 'inputs' comes from neighbouring areas, and/or some of the outputs go to neighbouring areas, the scaling rule differs from $s = 2$. This makes clear that the 'grain size' of the landscape pattern has an effect on the scaling rule. In fine-grained landscapes, with many boundaries between landscape units, the amount of local interactions will be large and there are many reasons why s differs from 2. In coarse-grained patterns interactions between units will be small. Linking the scaling issue with 'interactions' makes clear that we may have many of the tools needed to tackle the issue.

A simple method exists for generating data with a fractal dimension. If we take a grid of random numbers, some of them negative, others positive, and sample this grid at different scales (1 × 1, 2 × 2, 3 × 3 etc.) with the rule that we record the net value, but take negative values as zero, we will find that the average value per unit area decreases with the scale of sampling. At the 1 × 1 scale all negative values were perceived as zero, while at larger scales they can increasingly offset positive values. This analogy may help us understand the fractal dimension of net sediment loss in erosion studies as sedimentation sites are recorded as sites of zero (and not negative) erosion.

Conventional agronomic experiments are done in fine-grained patterns, in the form of a patchwork of differently treated plots. It is a continuous source of concern that interactions such as lateral resource capture between the plots are not unduly influencing the results, so that these can be scaled up to the coarser-grained patterns of real world farms. We have to pick up the challenge: we are not only dealing with experimental artefacts, but with important principles and results. In agroforestry techniques such as boundary plantings these interactions are about all there is (scaling up here may be based on s values close to 1.0). We may be able to turn a problem into an opportunity if we can quantify how much lateral resource capture contributes to the productivity of small-scale plots (van Noordwijk and Ong, 1996).

SCALING IN TIME: RESIDUAL EFFECTS AND POLICY IMPLICATIONS

The classical question of fertilizer use of Fig. 1.1 does incorporate a time dimension. As not all the nutrients in the fertilizer recently applied have become available and used during the cropping season 'residual fertility' effects were noted early on. A simple way out of this issue is to define this as part of the 'inherent soil fertility' for the next crop; unfortunately many existing measurement methods for inherent soil fertility do not perform well where partly undissolved fertilizer is present.

Residual effects depend on the mobility, biological and chemical transformation of the nutrient under given soil and climatic conditions. N and P represent the two extremes: the mobility of N in mineral form is so high that residual amounts of mineral N at the end of a cropping season run a risk of leaching out of the profile before the next growing season, especially where a relatively wet period (such as the winter in temperate regions) intervenes.

Residual N effects on the N supply to the next crop thus tend to be small, and there is reason for concern about negative environmental effects after the crop harvest. In contrast, the sorption (adsorption and desorption) equilibria for inorganic P_i in most soils mean that plant roots, even when effective mycorrhizal partners are present, capture only a fraction of what is 'available' in the soil in a physico-chemical sense. Due to the low effective mobility of P, leaching rates will be small. Thus, a substantial part of this 'available' pool of P will remain until the next crop, and the total agronomic value of P fertilization cannot be evaluated after the first cropping season. The low mobility of P also makes P depletion a gradual process, so both the costs of nutrient depletion and the benefits of fertilization tend to be underestimated on the basis of one-season experiments. For other nutrients such as potassium (K) and for N in organic pools a situation intermediate between these two poles can be expected: positive residual effects on a next crop may be expected, but losses to other environmental components cannot be ignored. If P is supplied in such large quantities that the effective marginal sorption capacity becomes small, it may behave like a nutrient such as K.

Calculations of (negative) nutrient budgets of agroecosystems can easily lead to a suggestion that (substantial) fertilizer inputs will be needed to redress past neglect of soil fertility. For P, inputs of inorganic fertilizer of moderate solubility may indeed replenish the capital stock. For N, however, the capital is in organic form and adding inorganic N fertilizer does not directly help to replenish the capital. Maintaining N capital depends on sufficient on-site production of organic residues and/or (labour intensive) inputs from outside the plot. P fertilizer, rather than inorganic N fertilizer, may be needed to stimulate the production of legumes supplying N-rich organic inputs.

In a strictly financial evaluation of profitability of investment in fertilizer use, there is no problem in accounting for future benefits (as net present value), as long as they are sufficiently predictable. Yet, it seems likely that the more immediate benefits farmers perceive on using N fertilizers ('consumables'), rather than P ('capital stock') may lead to a bias in their decisions. As unbalanced fertilizer use may increase the depletion of the soil's capital of other nutrients, the short-term decisions of farmers may contrast with the long-term benefits of sustainable soil management.

The argument that farmers are thus likely to mismanage their soil resources, because of their limited perspective on scaling time, is often taken as a starting point for arguments on the need for government policy interventions. In the early 1970s the UN Food and Agriculture Organization (FAO) and other international agencies recommended government subsidies on inorganic fertilizer as a way to stimulate food production. In these subsidy schemes, however, no distinction was made between N and P fertilizers. Abandoning such subsidy schemes as part of deregulation and structural adjustment programmes has revealed that reliance on subsidies has made farmers dependent and vulnerable. Yet, the problem of past soil fertility depletion remains and may be a major bottleneck for current agricultural development. A new initiative on soil fertility replenishment (Sanchez *et al.*, 1997) rightly focuses on P and organic N as the capital stocks to be replenished. It thus clearly differs from past fertilizer subsidy programmes.

There are obvious arguments for government investment in the 'public good' of understanding general principles of soil management, linked to information on local soils, crops and climate, and in developing efficiency increasing techniques. Arguments for direct government intervention in the supply of inputs, however, depend on how yield response to nutrient additions is scaled in time via residual effects.

Under some circumstances cumulative yield response to total nutrient inputs may have an S-shaped curve. Figure 1.9 shows positive interactions between growth factors only in a certain range upon alleviation of initial toxicities. Only then can other inputs be more fully utilized (De Wit, 1994). In order to get an S-shaped curve of plant growth versus total external nutrient inputs, positive interactions have to go beyond the normal build-up

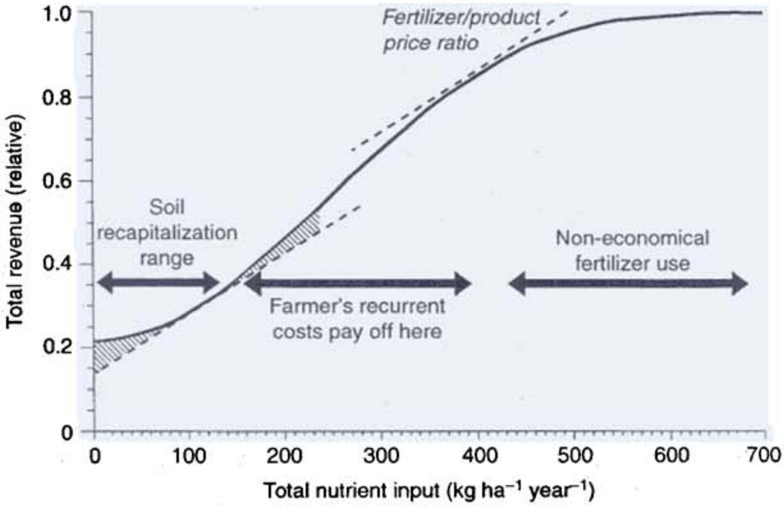

Fig. 1.9. Hypothetical cumulative yield response curve to nutrient addition and domain for government intervention in 'soil fertility replenishment': if the response is S-shaped there are two points where marginal returns equal marginal costs; if one starts from zero, input use is at first uneconomical and in fact only at the point where the two shaded areas are equal in size is input use starting to pay off; a reasonable target for outside help may be to bring the soil up to the first point where marginal returns are non-negative; if the practically relevant part of the curve is not S-shaped the arguments for outside 'soil replenishment' investment will be less convincing.

of residual effects and the expected stimulation of N-fixation by legumes if moderate amounts of P are supplied to the soil.

If the overall response is S-shaped indeed, it may be opportune for governments to help farmers approaching the first point of inflection of the curve (or more specifically, up to the point where marginal returns start to exceed marginal costs). Getting there will improve returns to maintenance fertilization and may start a financially sustainable fertilizer use (up to the second point of the curve where marginal costs equal marginal benefits). 'Economies of scale' in fertilizer use might make future fertilizer use more affordable, once a market has been created, but the empirical evidence that this will happen is not strong. Empirical evidence for S-shaped response curves on farmers' fields is not particularly strong either, and here lies a real challenge for research to address soil fertility from a policy perspective. Perhaps many fields currently used for agriculture have not been depleted to the point that farmers experience an S-shaped response curve to soil nutrient replenishment.

In the absence of S-shaped response curves, if diminishing marginal returns characterize the whole response curve, the debate on soil fertility replenishment is remarkably similar to past fertilizer subsidy schemes and may do little to establish financially as well as ecologically sustainable agricultural systems.

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