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Fertilizer addiction: Implications for Sustainable Agriculture

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To meet increased demand for food spurred by a larger and richer population, FAO projects that global agricultural production in 2050 will be 60 percent higher than in 2005/07. Most of this increase in production over the next 40 years is expected to derive from improved yields (FAO 2012).

This brief presents a model-based examination of short and long-term trade-offs between two alternate agricultural paradigms: industrial agriculture dependent on agrochemicals, fuel-based mechanization and irrigation operations, etc.; and sustainable, low external input agriculture centered on preservation of soil organic matter (Pedercini, Zullich and Dianati 2014a, 2014b). The associated policy implications for long-term sustainability in agricultural yields, and food security, are huge.

Industrial agriculture practices are used as a cost-effective form of insurance against low yields, without regard to their inherent effect on the ecosystems below the soil's surface. This has led to a net loss of soil organic matter observed in numerous long-term studies of chemical-based cropping systems. Soil organic matter (SOM) consists of plant residues and animal manure at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by soil organisms. SOM improves water-holding capacity and aeration, enhances absorption and release of nutrients, and makes soil less susceptible to leaching and erosion.

Numerous studies have concluded that routine NPK fertilization depletes SOM in the long-run (Kotschi 2013). Loss of SOM decreases soil productivity and the agronomic efficiency of fertilizer N, calling for increasingly intensive practices and larger amounts of fertilizer (Mulvaney et al. 2009). This dynamic is the reason some have portrayed excessive fertilizer use as equivalent to an addiction.

Conceptual model of fertilizer addiction

The essence of fertilizer addiction is captured in the causal loop diagram in Figure 1. Balancing feedback loop B1 captures the introduction of industrial agriculture practices as a (short-term) solution to low yields, intending to directly increase soil nutrients and bring yield closer to a given target. Reinforcing feedback loop R1 describes the mechanism where intensified use of industrial practices damages SOM, reducing mineralization and available soil nutrients. This leads to lower than otherwise yield, intensifying the need for industrial practices.

The implication of the loss of SOM on yield is not immediately evident, because rapid decomposition of organic matter releases large amounts of nutrients that boost yield in the short run. The reduction of SOM undermines natural mineralization only after some years. Feedback loop R2 exacerbates this vicious dynamic by undermining nitrogen use efficiency, implying the need for larger amounts of fertilizer to maintain high yields.

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The reinforcing loops R1 and R2 are eventually stabilized by two distinct mechanisms, not shown in the CLD for simplicity. In the case of R1, the loss of SOM gradually decreases as the more unstable SOM is depleted. In the case of R2, as nitrogen efficiency decreases, a point is reached where further increasing nitrogen input does not make economic sense.

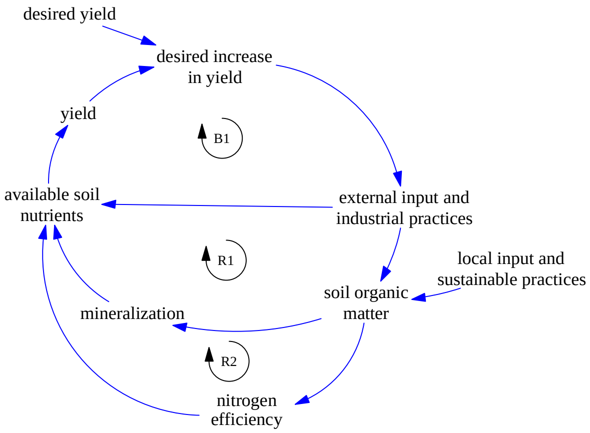

Figure 1 - Causal Loop Diagram of fertilizer addiction (Pedercini, Zullich and Dianati, 2014b).

Formal Model

To simulate the above-described dynamics we have built a stock-and-flow model (Pedercini, Zullich and Dianati, 2014a, 2014b). The model structure reflects how the stocks of soil carbon (our proxy for SOM) and mineral nitrogen interact and evolve, and how industrial agriculture practices moderate this interaction.

The model is parameterized to represent soil characteristics at a location in Kisii District, Kenya. Initial conditions reflect soil conditions of natural grasslands. The expansion of industrial agriculture in Kenya is a highly relevant issue. The formal model, however applies equally well to other agroecological zones.

Industrial vs. sustainable practices

To assess industrial vs. sustainable practices three scenarios are presented:

Maize-NIL: intensive practices, including detrimental practices such as tillage, mono-cropping, burning crops residues, etc., without external inputs (including fertilizers); Maize-N: industrial practice, as above, but including extensive use of fertilizers; and Maize-S: sustainable cultivation, crop rotation, integrated fertilizer and pest management, cover crops, etc.

Mineral nitrogen (Figure 2) shows overshoot patterns for all three scenarios. Under intensive practice mineral nitrogen initially rises while SOM (simulated SOM not shown here) quickly decomposes, causing rapid nitrogen mineralization. Following the decline in SOM, and drastic decline in SOM decay due to increasing chemical stability of remaining organic matter, mineral nitrogen availability falls rapidly.

Under industrial agriculture, mineral nitrogen initially rises rapidly as decomposition of SOM accelerates. This initial tendency is further strengthened by usage of N-fertilizer seeking higher yields. This trend is reversed once the loss of the less stable SOM reduces mineralization, and ability of the soil to retain N-fertilizer decreases. Attempting to counteract this decline, the farmer applies increasingly larger amounts of fertilizer, up to a point where it no longer makes economic sense to increase fertilizer usage. The continuous use of industrial practices kills even more organic matter, bringing fertilizer efficiency lower, further exacerbating the problem, in a classic example of policy resistance.

Under sustainable practices, mineral nitrogen follows a much smoother trajectory. The initial rise in this case is less steep because sustainable practices are less demanding on SOM, with decomposition and mineralization happening at slower rates, and also due to absence of mineral fertilization application. Consequently, the ensuing fall is much less precipitous as a result of better conserved soil organic matter. However, without the introduction of any mineral fertilizer or N-fixating crops, nitrogen in the Maize-S scenario tends to be lower than in the Maize-N scenario, although by a decreasing margin.

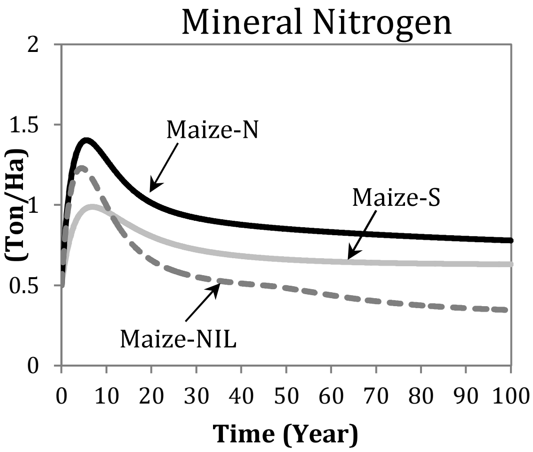

Figure 2 - Mineral Nitrogen in Soil: Industrial without Fertilizer (Maize-NIL), Industrial with Fertilizer (Maize-N), Sustainable Practices (Maize-S) (Pedercini, Zullich and Dianati 2014a).

Fertilizer scarcity shock scenarios

To mimic the effect of a fertilizer scarcity shock we assume a gradual five-year reduction of fertilizer use to zero, starting at year 30. We compare the impact of the shock on four types of agriculture practices: sustainable practices (Maize-S-Shock); industrial practices (Maize-N-Shock); industrial practices followed by post-shock adaptation (Maize-N-Shock-Adaptation); and industrial practices with pre-emptive adaptation starting at year 20 (Maize-N-Shock-PreAdaptation).

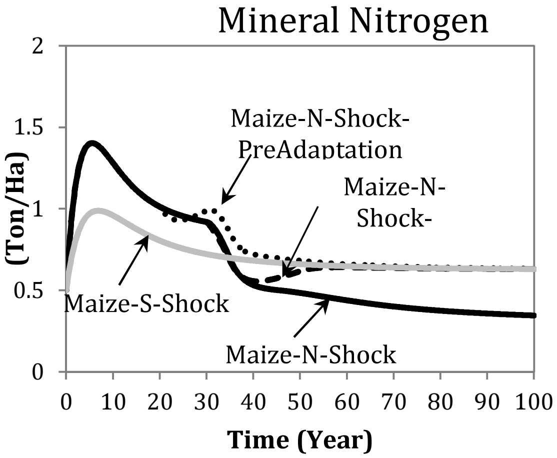

Figure 3 - Mineral nitrogen in soil under fertilizer scarcity shock (Pedercini, Zullich and Dianati 2014a).

In Figure 3, following the fertilizer scarcity shock, mineral nitrogen falls by > 40 % in the Maize-N-Shock scenario. The shock does not affect mineral nitrogen in the Maize-S-Shock scenario, where mineral N is provided by SOM decomposition only. In the Maize-N-Shock scenario, nitrogen availability is permanently damaged and declines continuously.

Such trend can be avoided through adaptation measures (Maize-N-Shock-Adaptation), i.e., conversion to sustainable practices. Assuming an immediate shift to sustainable practices, it takes about 25 years for SOM and mineral nitrogen levels to return to those of sustainable practices, in line with empirical research findings (Derpsch 1997).

Transitioning to sustainable practices is time and resource demanding. The observed trends suggest that about two decades of good yields can be lost in the transition. We also analyze a scenario in which a likely future scarcity in synthetic fertilizer is anticipated and the same adaptation measures start earlier to avoid unaffordable costs and loss of crop production (Maize-N-Shock-PreAdaptation).

In the Maize-N-Shock-PreAdaptation scenario soil mineral nitrogen falls slightly below the business-as-usual scenario, an example of a worse-before-better outcome, while SOM is restored. This is because policies to preserve SOM imply an initial reduction of SOM decomposition and nitrogen mineralization. After approximately six years, the pre-adaptation scenario overtakes business-as-usual in terms of soil N content while the two non-proactive scenarios suffer significant decline in soil N. With pre-adaptation measures soil N does not fall below the originally sustainable scenario, converging with it around 20 years after the shock.

Issues for further consideration

- Policies for long-term agricultural sustainability and food security must address preservation and restoration of SOM.
- Agricultural systems that nurture SOM are more resilient than industrial agriculture to shocks such as fertilizer price hikes.
- Large time lags are involved when transitioning from industrial to sustainable agriculture. Transitioning pre-emptively to anticipated shocks is much less costly than after the fact.
- Simulation models that consider feedback loops and stock-flow structure can help us understand the dynamics of coupled human-natural systems and design more effective policies for sustainability.

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