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Desertification and Development: some broader contexts

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Abstract.

The dominant direct physical processes responsible for desertification are water erosion, wind erosion and salinization. Other threats that degrade the soil include loss of biodiversity, loss of soil organic matter, fire, changing water resources, soil compaction, soil sealing and contamination. Soil management inevitably combines human and physical effects. Climate, which is the most important driver of the physical systems, is now being rapidly modified by human action, and at a scale which is much coarser than any local remedial action.

In a model of near-subsistence systems, productivity is limited by climate and available labour, with some options for additional inputs through improved seed, fertilizer or tillage equipment. Optimum solutions in a particular environment depend on both climate and access to markets. Agricultural surpluses, if any, allow investment in infrastructure – some of it directly supporting agriculture through irrigation and market systems, some less directly useful through, for example, warfare or pyramid building.

Today some traditional drivers of desertification, based on subsistence agriculture and grazing, may have become less relevant, as land, particularly in the global South, is developed for intensive irrigated farming, and populations move into mega-cities. The dominant drivers may become soil sealing around cities and transfers of urban and irrigation water. In semi-arid areas this will lead to competition for the best land – for urban expansion and agricultural land with irrigation potential. Desertification then becomes an issue increasingly focussed on abandoned marginal land, maintaining biodiversity, managing regional water resources and controlling erosion in the face of global climate change.

Key Words: desertification, subsistence agriculture, human potential.

Introduction

Desertification is defined by the United Nations Convention to Combat Desertification (UNCCD; Mainguet, 1999; Martello, 2004) as 'land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities'. The dominant direct physical processes responsible are water erosion, wind erosion and salinization, but a number other threats that degrade the soil have also been identified (EU, 1999). These include loss of biodiversity, loss of soil organic matter, fire, changing water resources, soil compaction, soil sealing and contamination (Gregory et al, 2015). Management of both the soil and the broader environment are strongly influenced by human activity, so that it is almost impossible to disentangle human and physical effects. Even climate, which is the most important driver of the physical systems, is now being modified by human action, and at a scale which is much coarser than any local remedial action.

Desertification may be compartmentalised and analysed in terms of the three inter-dependent components included in the UNCCD definition, soil, water and people. The soil component refers to the land that is potentially degraded. In semi arid areas water is the key to the survival or degradation of the land; and human actors determine the balance between degradation and recoveryof the land as they attempt to support themselves. The definition of desertification is related primarily to degradation of the soil, by water and wind erosion, by loss of organic matter and by salinisation, and is relevant for both cultivation and grazing. These forms of degradation can be partially or completely offset by management practices, such as fallow rotation in shifting cultivation, by various forms of terracing or bund construction and through the application of manure or fertilizer (Morgan et al, 1994; Rose, 1994; Panagos et al, 2016) . Water is also critical to desertification and its mitigation or prevention. The retention of scarce water is critical to crop production in semi-arid environments, either through irrigation or water harvesting (Critchley & Gowing, 2012) that control its spatial and temporal allocation for effective cultivation, and for the annual recovery of pasture and natural watering holes However, intense rains on poor soils can also increase soil erosion and lead to unwanted flooding. At a broader scale, water retention in headwater areas may increase water scarcity downstream

Desertification and the potential for recovery can be seen as due to the interlocking of human and physical responses Central to this, at a local scale, is the tension between sustainability, productivity and degradation. On the physical side, overuse of the land leads to degradation and abandonment. If degradation has not become irreversible, then the land slowly recovers, in a process of natural re-wilding, and may once again support sustainable, and perhaps more intensive, agriculture, risking a return to overuse and degradation. On the human side, improved public health has increased population pressure on the land, leading to over-exploitation of the land and forcing migration toward the cities and overseas. Money transfers from migrants then becomes essential components of an economy that may then sustain rural livelihoods.

The management of threatened lands has two components that cannot easily be separated. First it can be seen as a contribution towards maintenance of non-human ecosystems that are threatened by global climate change. Second it can be considered as ultimately, for the benefit of people, providing food and income for subsistence, and maintaining traditional ways of life. Some population is needed to till the land, and obtain fertilizer or other additional support needed, but any additional population needs to be fed, and is a drain on reseources unless productive in other ways. Any food surplus can generate needed additional income by selling it directly, or through income earned (Nicholls, 1963; Onakuse, 2012). In many cases, additional income is also provided through remittances from out-migrants to the city or overseas. Where climatic conditions are marginal, the role of welfare may also be critical to continuing survival.

Combatting desertification is seen as one component in a broader view of managing our environment for the benefit of both the ecosystem and people in it. By doing do, global soil and food resources are maintained. Soil is a threatened and, on a human time scale, irreplaceable resource. 'Tolerable' rates of erosion may balance replacement of the 'A' horizon, but not its organic content, and, only very exceptionally, balance geological rates of weathering (Verheijen at al, 2009). By maintaining a healthy ecosystem that returns moisture to the atmosphere through transpiration, atmospheric moisture is re-cycled, allowing weather systems to convey moist air masses farther into continental interiors.

Not only can erosion be slowed by efficient agriculture that conserves the soil, but good practice fosters biodiversity and improves food security (Baiphethi & Jacobs, 2009). Effectively combatting desertification also helps to sustain rural life, slowing urban growth and maintaining national and cultural identities. One important component is to make best use of scarce water, constraining intensive irrigation and helping to minimise trans-national conflict. Effective action against desertification is unlikely to be effective unless there is clarity about the primary objectives so that soil conservation, for example, on its own, will provide only local and short-lived mitigation.

Some current literature (Puigdefabregas, 1998; Hellden, 2008) treats the balance between environmental resources and people as a predator-prey relationship. This analysis however ignores the potential for additional people to generate additional cash or other resources that support communities and is able to improve the quality of agricultural production through, for example. improved seed, fertiliser, machinery or wells. Surpluses may be redistributed within a single household, or at community or higher level. Where re-distribution is at the level of the state, this provides a mechanism for political control, as occurred in early Mesopotamian societies (Frangepane, 2018). Focussing here on more individual enterprise, the use of surpluses may represent transition from true subsistence farming to a more cash-based society (Alexandri et al, 2015). The challenge is to maintain both the environment and the cultural links between the farmer and the land in an economically viable way.

Estimating productivity of rain-fed agriculture

In near-subsistence systems, productivity is limited by climate and available labour, with some options for additional inputs through improved seed, fertilizer or tillage equipment that may be considered as alternative uses of labour, to earn the costs incurred. In a given physical environment, critical farmer decisions include the choice of cereal crop to grow, the level of fertiliser application and the balance between alternative uses for labour (to till the land or earn money that will buy fertiliser or equipment) Optimum solutions, maximising the number of families supported, lead to hunter-gatherer, subsistence or intensive farming, according to climate, its reliability and access to markets. Here we present a simple model that maps labour surplus as a function of available labour and fertilizer inputs in the context of near-subsistence cereal farming. Potential cereal production is estimated here from annual (wet season) rainfall and fertilizer input using a modified Michaelis-Menten (1913) equation, based on data presented by Harmsen (2000) for crop yields in Syria. Although the equation for potential yield that is used here, and set out below, is quantitative in form, it is used primarily to exemplify the following observed qualitative behaviours.

1. Response to annual rainfall is very limited below about 100 mm, rising more steeply thereafter, and reaching an upper limit of around 10 tonnes/ Ha above annual values of 1000 mm (Doorenbos, J. E., and Kassam, A. H., 1979).
2. The addition of nitrogen fertilizer further reduces yields at low annual rainfall, but strongly and progressively increases yields at higher rainfalls (Cantero-Martinez et al, 2003).
3. It is recognised that soils contain a low background level of available nitrogen that is supplemented by fertilizer additions.

These principles have been combined in this equation for potential yield.

$$\left(\frac{Y_0}{Y_P}\right)^{nY} = \left(\frac{N_0}{N+N_B}\right)^{nN} + \left\{\frac{R_0}{R\left[1-exp\left(-\frac{R}{5(N+N_B)}\right)\right]}\right\}^{nR} \qquad (1)$$

where Y_P = potential grain yield in T/Ha (1 T/year is assumed sufficient to support 5 people),

R = annual rainfall in mm,

N = Nitrogen fertilizer application rate (kg/Ha) and

Y_0, R_0, N_0, N_B, nY, nN, nR are constants, assigned these values:

Y_0 = 10 T/Ha: maximum upper yield

N_0 = 100 kg/Ha: maximum useful nitrogen application rate

N_B = 5 kg/Ha: background soil nitrogen level

R_0 = 1000 mm/yr: maximum effective rainfall for yield increase

nY =1: nN =1: exponents of linear yield response to fertilisation

nR =2: exponent provides threshold response at low rainfalls

The form of this expression gives a response that is dominated by the scarcer resource (water or nitrogen). Figure 1shows the response to rainfall and fertilizer inputs. In (a) it can be seen that for the expression in equation (1), production always increases with rainfall for a given fertilizer input, but (b) shows how higher fertiliser inputs raise the threshold rainfall required to obtain acceptable yields while offering the potential for greater yields in more humid environments. Increased fertilizer input has a negative impact on yields under arid climates, but an increasingly beneficial effect in wetter areas. These relationships have been developed to provide a quantitative illustration of what are essentially qualitative relationships. They have been generated with wheat in mind. The underlying physiological responses are common to other grain crops although each differs in detail, and, perhaps as importantly, in its suitability in areas of more saline soils or greater inter-annual variability of rainfall.

[Insert figure 1 near here]

Potential yield is finally modified by labour available to cultivate the crop. It is assumed that an adequate labour force L is required to achieve maximum yields, and final yield Y_F is here related to the potential yield Y_P by

$$Y_F=Y_P(1-\exp(L/L_0)\qquad (2)$$

where L_0 =200 /km2.

These expressions have been used to estimate the labour surplus, if any, where a crop is grown in an environment defined by its annual (wet season) rainfall, with a known fertilizer input and supporting a known population density. The potential labour surplus S, providing resources to develop non-agricultural business or infrastructure, is then calculated as

$$S = P - L - F \qquad (3)$$

where P is the resident population (per km^2),

L is the labour force needed to produce enough grain to feed the population

F is the labour force needed to earn enough to pay for the fertilizer applied.

To calculate the labour needed L, we solve the equation

$$P/5=Y_P(1-\exp(-L/L_0)]. \qquad (4)$$

In this expression, the left hand side represents the yield needed to support the population and the right hand side is the actual production, where a labour force of L is engaged in cultivation.

Rearranging equation (4),

$$L=-L_0 \ln[1-P/(5\ Y_P)] \qquad (5)$$

with solutions valid where $L<=P$.

Exploration of this model illustrates how, in less arid climates, there is scope for considerable investment in fertilizer and technical innovation, supporting large agricultural or labour surpluses, whereas in semi-arid climates there is little opportunity for improvement and minimal surplus. Figure 2 shows that, in low rainfall areas, there may be only very restricted possibilities to create labour surpluses, and these are achieved with low fertilizer inputs. In contrast, wetter areas benefit from increased fertilization and are able to generate large labour surpluses, in many cases more than 50% of the total population. Figure 3 shows the strength of this dependence on adequate rainfall to generate a viable production base. The diagram is drawn for a modest fertilizer input (14 kg/Ha), and shows a weak dependence on this value, with the threshold raised as additional fertilizer is applied.

[Insert figure 2 near here]

Estimating productivity of pastoralism.

Herding cattle or sheep as a primary food source has advantages in arid conditions where grain yields are no longer sufficient to justify tillage. Perhaps 50% of the world's livestock is supported in this way (Puigdefabregas, 1998). If sufficient grazing areas and watering locations are available, then sufficient fodder is always available if there is unrestricted nomadic or seasonal herd movement, but overgrazing can reduce the carrying capacity of the land, and adequate grazing must be available within range of water (Accatino et al, 2016) . To support a pastoral economy, there must be sufficient rainfall to support enough animals to feed the population. If that condition is satisfied then the number of herders required is a more or less constant proportion of the population, generating a labour surplus for other activities. In this way the surplus, if any, can be put in com parable terms to those for cereal cultivation above.

The first step in analysing the optimal management is to select the appropriate intensity of grazing. Figure 1c shows a modelled example of the relationship between grazing pressure, expressed as percentage of biomass grazed and carrying capacity, based on applying the PESERA model (Kirkby at al, 2008) with climate data based on Cyprus.. Similar relationships are found in observed data (eg. Miao at al, 2015). Under any given climatic conditions, increased grazing leads to reductions in biomass that soon outweigh the nutritional gains, giving a clear optimum for sustainable grazing pressure and carrying capacity, at a level which both allows pasture to be maintained and recover and brings benefits in limiting runoff and erosion.

With increasing rainfall, the optimum carrying capacity increases, more or less linearly. At a rainfall of 200 mm, it is assumed that optimal grazing will support a sheep population of about 6 per Ha and a human population of 20 per km^2. Where population density is lower than this, approximately half the population is required to support herding, leaving the other half as a surplus labour pool. Combining the models for pastoral and arable subsistence, the available labour surplus for both activities is shown in figure 3. The choice of dominant agricultural activity is determined by the greater calculated labour surplus. It can be seen that pastoralism is only the more viable alternative in the most arid conditions and where population density is too low to farm the land. It should be borne in mind that weather and other conditions change from year to year, but that changes in farming style generally take place only slowly.

[Insert figure 3 near here]

Interactions between physical and social systems

Agricultural surpluses have, since the beginnings of civilisation, allowed investment in infrastructure – some of it directly supporting agriculture through irrigation and market systems, some less directly useful through, for example, warfare or pyramid building. Exploitation of human or material resources has also provided surpluses that support industrial development in ways that may no longer be sustainable in the face of opportunities for mass migration. Today some traditional drivers of desertification may no longer be relevant, as land, particularly in the global South, is grabbed for intensive irrigated farming, and populations move into mega-cities. As labour surpluses become more important, there is also a drift away from subsistence to a more cash dominated economy. The dominant drivers may soon become soil sealing around cities and transfers of urban and irrigation water. In semi-arid areas this will lead to competition for the best land – for urban expansion and farmland with irrigation potential. Control of desertification is then increasingly focussed on the management of abandoned marginal land to maintain biodiversity for conservation and recreation. Abandoned land then also becomes critical for managing regional water resources and for controlling erosion which will become more severe as increasingly variable climates lead to greater frequency of fires and more intense storms.

Climate change and global heating are expected to increase aridity and make rainfall less effective in many areas, increasing abandonment as farmland becomes less productive and threatening nomadic herding. Coastal inundation and migration from marginal regions toward cities can only add to the potential risks. These trends are already apparent due to population growth and technological changes but are exacerbated and interact with desertification processes.

At progressively coarser scales, socio-economic factors become increasingly important. The model described above shows that one of the key drivers of desertification is population pressure, where the land can no longer support the farming population depending on it (Geist &Lambin, 2004). Although desertification and desertion are quite distinct concepts, there is no doubt that desertification leads to desertion and abandonment of the most marginal land. Where land is irreversibly degraded by erosion, with gullying of steep slopes, natural regeneration and recovery may be impossible, but, in most cases, the natural vegetation regenerates on a decadal time scale, and there has been an observed greening of much abandoned upland. By making full use of available rainfall, this greening may, however, reduce water availability to the water courses, transmitting the risk of desertification to areas downstream (Garcia-Ruiz et al, 2011).

Desertion of the land, together with the perception of greater prosperity, drives migration, initially to cities and, indirectly, to other regions and countries (Requier-Desjardins , 2008). With an increasing risk of widespread desertification and increasing levels of information, these migration pressures have, in the past, and will, increasingly in the future, lead to potential conflict for scarce resources. Water, and land where it can be used, may be the critical resource. The equitable partition of river flows between headwater steepland source areas and downstream irrigable plains will become ever more contentious as marginal areas become increasingly degraded and abandoned.

Turning to the positive, the potential population surpluses shown in the model above provide the basis for development. Figure 4 illustrates how these surpluses can, under favourable conditions, fuel regional or national investment in infrastructure and enterprise that can benefit agriculture and help to mitigate desertification. However, this potential may not be fully realised if government or other power structures siphon off too much of the wealth generated instead of investing it in developing infrastructure.

[Insert figure 4 near here]

Surplus labour can, most directly, be applied to enhance agricultural production, through investment in improved seeds, adequate fertilizer and appropriate mechanisation. Such investments can enhance the population surplus that can provide earnings to allow cultivation of additional and/or more marginal land and to increase the prosperity of agricultural communities. More broadly, earnings increase GDP and provide governments with a tax base for improving rural infrastructure through, for example, roads, education, welfare, housing, energy and internet provision. Such improvements further improve production, providing access to markets and business opportunities. Under ideal circumstances, rarely realised in full, there is scope for a virtuous cycle with a positive feedback between agriculture, wealth creation and provision of infrastructure.

The potential for positive development may be constrained by both internal and external factors. Perhaps the key internal factor is population growth, with growing numbers that outstrip the ability of cities to accommodate them. Little resource is then available to support rural livelihoods, and farming communities have little incentive to remain on the land. Development is also squeezed by external factors. Some of these are built into the geography of each area, with differing access to non-renewable mineral and energy resources, and constraints of access to external markets dependent on transport systems and access to ports .

Discussion

It is a truism to say that there are complicated two-way links between desertification and development. Agricultural surplus is needed to support infra-structure, which can, in turn, further support agriculture, and this positive feedback can only take off if the required population are there, and the climate is sufficiently reliable to maintain accumulated surpluses from year to year.

Ideally there is then a benign positive feedback, in which labour surpluses support the improvement of health, education and communications, and these improvements provide access to markets and encourage enterprise, but there is a risk that they will also undermine traditional ways of life, encouraging a drift away from subsistence farming, and towards closer engagement with urban economies. If this trend becomes established, then rural livelihood can only persist though explicit guardianship of the natural environment. This is already happening in the context of wild life safaris in Africa, and can be seen in many rural areas of more developed countries, either through subsidies that support partial re-wilding or through the availability of alternative tourist-focused employment.

It is much easier to drive this virtuous circle in regions with other natural advantages, for example with a coastal location or with mineral wealth, and where the climate supports higher and less variable yields. Even in favorable situations this positive feedback may be cut in various ways. In the context of this paper, the most relevant are those that affect labour supply. Social or armed conflicts may destroy production and absorb person power, reducing both yields and the possibilities of enhancing infrastructure. Inflexible dependence on technologies that are no longer appropriate has, in some cases, stunted new developments, as for example through persistent use of irrigation without guarding against secondary salinization. In many cases external exploitation of mineral or localized crop resources has not properly benefitted the local economy.

The maintenance of positive feedbacks that support and maintain local environments and rural economies is therefore constantly under threat, but there are measures that can help to mitigate desertification. Physical measures are most widely discussed and trialed, focusing on controlling runoff and damaging erosion at the field and catchment scale. However, development of local infrastructures can also be very effective by improving access to water, healthcare and education, and providing better access to markets. The provision of cheap and renewable energy can increase productivity and release labour. Energy can also enhance electronic communication, widening access to markets, healthcare and social interaction. However well managed, regions and countries are liable to external shocks, often incompletely foreseen and demanding increasingly global remedies. Examples, such as the 2020-2021 pandemic and ongoing global heating are all too apparent. Many of these have a disproportionate impact on less developed countries that are severely threatened by desertification, and add to the already daunting prospects for many marginal areas. In the face of many difficulties, the over-arching question is whether the physical demands of combatting desertification can be separated from the human problems of maintaining rural populations and rural livelihoods, and whether sensitive management of semi-arid lands can be supported in the face of increasing urbanization and accelerating moves from a mixed subsistence basis to a fully cash-based society.

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Figure Captions

1: (a) and (b) Production functions from equations (1) and (2), respectively showing dependence on annual rainfall and nitrogen fertiliser application rate. Production increases with precipitation, but high fertiliser input hinders growth under the most arid conditions. Only for the highest rainfalls is additional fertiliser uniformly beneficial. (a) shows dependence on rainfall; (b) shows dependence on fertiliser application rate.
(c) Example of relationship modelled by the PESERA model (Kirkby et al, 2008), between percentage of biomass grazed and sheep carrying capacity. In the model, biomass grows and decays in response to the annual cycle of actual evapotranspiration, with losses due to the proportion grazed that reduce cover and re-growth. The amount of biomass grazed then determines the carrying capacity. At low grazing intensity there is a proportional increase in carrying capacity. More intensive grazing strips the surface, preventing re-growth, and gives a clear optimum. Curves are for 300 – 600 mm annual rainfall, based on seasonal pattern for Cyprus.

2: Modelled optimum farming stategies at different rainfall levels. Colours indicate the labour surplus attainable for the various conditions. Grey areas are those for which no surplus is obtained, and which are therefore not viable.
At a low annual rainfall (left hand diagram) only a very limited range of population and fertliser is viable. The central point in the green area and the path-line leading from it shows the positions of the optimum configuration for different annual rainfalls. At higher rainfall (right hand diagram), a wide range of both population and fertiliser is viable, fostering higher population surpluses, and providing greater resilience in the face of inter-annual variations.

3: Arable farming model (from Figure 2) overlain with model for pastoralism, showing labour surplus for the preferred system as conditions are varied. (Arable shown for 14 kg/Ha nitrogen fertilizer addition). Areas in grey do not generate a viable labour surplus from either activity.

4: Conceptual relationships between desertification and development at regional to national scales.