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The Expansion of Modern Agriculture and Global Biodiversity Decline: An Integrated Assessment☆

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ABSTRACT

The world is banking on a major increase in food production, if the dietary needs and food preferences of an increasing, and increasingly rich, population are to be met. This requires the further expansion of modern agriculture, but modern agriculture rests on a small number of highly productive crops and its expansion has led to a significant loss of global biodiversity. Ecologists have shown that biodiversity loss results in lower plant productivity, while agricultural economists have linked biodiversity loss on farms with increasing variability of crop yields, and sometimes lower mean yields. In this paper we consider the macro-economic consequences of the continued expansion of particular forms of intensive, modern agriculture, with a focus on how the loss of biodiversity affects food production. We employ a quantitative, structurally estimated model of the global economy, which jointly determines economic growth, population and food demand, agricultural innovations and land conversion. We show that even small effects of agricultural expansion on productivity via biodiversity loss might be sufficient to warrant a moratorium on further land conversion.

1. Introduction

The world population is projected to grow by a further 50% this century, reaching an estimated 11.2 billion by 2100 (United Nations, 2015, medium scenario). The same demographic projections put a five per cent chance on a world population of as much as 13.3 billion in 2100. Concomitantly, the world is projected to become significantly richer. According to the Intergovernmental Panel on Climate Change, which has collected together over a hundred projections of global GDP this century, real global mean GDP per capita will increase by 350% between now and 2100 (Clarke et al., 2014).[1] Together these imply an expansion of the modern agricultural system in order to meet growing dietary needs and food preferences (Alexandratos and Bruinsma, 2012; von Lampe et al., 2014; Lanz et al., 2017a). Not only do more mouths require more food, there is also a strong positive (if concave) relationship between income per capita and various measures of food consumption (Tilman et al., 2011).

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[1] Median estimate, assuming no significant costs of climate change or greenhouse gas emissions abatement.

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But expanding the modern agricultural system will have important implications for ecological systems and creates a number of challenges for global management of the commons. Our objective in this paper is to study what this expansion might imply for global food supply, taking into account the feedbacks between agricultural intensification, extensification, biodiversity loss and agricultural productivity.

An increase in agricultural output can be achieved in various ways and the great increases seen in the second half of the twentieth century came mainly from intensification and corresponding increases in yields (FAOSTAT; Klein Goldewijk et al., 2011). Nonetheless the clear consensus from global land-use models is that some of the additional future production will come from expanding the agricultural land area. According to the Agricultural Model Intercomparison and Improvement Project or AgMIP, the area of world cropland in 2050 will be between 10 and 25% larger than today, under a reference scenario in which world food production rises by 43 to 99% (von Lampe et al., 2014; Schmitz et al., 2014).

The expansion of modern agriculture through a combination of intensification and extensification has managed to sustain the world population explosion that began with the industrial revolution and accelerated in the early to mid twentieth century (United Nations, 2015). For example, the prevalence of undernourishment has declined globally (Fogel, 1997; World Bank, 2016), while the real prices of agricultural commodities fell quite significantly between 1950 and 2000 (Alston and Pardey, 2014).[2] However, the expansion of modern agriculture has had other, less desirable consequences.

Both agricultural intensification – of the prevailing, non-ecological or unsustainable variety (cf. Bommarco et al., 2013; Godfray and Garnett, 2014) – and extensification have been primary causes of a historically unprecedented loss of global biodiversity. According to the Millennium Ecosystem Assessment (2005), the current global rate of species extinction is up to 1000 times higher than the background rate that has been estimated from the fossil record. A broader index of global biodiversity has been in decline since 1970 (the first year for which data are available) and there is no statistical indication that the rate of decline is slowing (Butchart et al., 2010). Local species richness is estimated to have declined by over 10% in the last 200 years, globally on average (Newbold et al., 2015).

In terms of agricultural biodiversity, Khoury et al. (2014) have documented how global crop production has become less diverse in the last 50 years, in the sense that it has become more dominated by a small number of crops. Using data from the Food and Agriculture Organization of the United Nations (FAO), they show that, while national food supplies have come to rely on a more diverse set of crops on average, the opposite is true of the global food supply. Although this might seem paradoxical at first, it is in fact because the same crops have been driving both greater diversity in most countries (particularly developing countries) and greater similarity globally: wheat, rice, soybeans and oil crops such as palm oil and sunflowers. These are precisely the crops we would expect to become more prevalent as diets change with rising incomes (Poleman and Thomas, 1995). In addition to inter-specific diversity of crops, nearly all countries reporting to the FAO's global stocktake of crop genetic diversity documented the erosion of genetic diversity, with the most commonly identified causes being respectively the replacement of local varieties as part of the modernization of production systems, and land clearing (FAO, 1996, 2010).

Following a proliferation of research in the last 25 years, there is now a consensus that biodiversity at different levels increases the plant productivity of natural ecosystems, as well as reducing the variability of plant productivity (Cardinale et al., 2012). Plant productivity decreases more than proportionally as biodiversity is lost. Once more than 20% of species are lost, the effects may rival other drivers of global environmental change such as planetary warming, ozone and acidification (Cardinale et al., 2012; Hooper et al., 2012). While the negative relationship between biodiversity loss and plant productivity is reliably found in natural ecosystems such as grasslands, it is clearly possible for intensively managed monocultures to be highly productive. Nonetheless a recurrent finding from empirical studies by economists is that genetic and species diversity on farms reduces the variability of crop yields and sometimes increases the mean yield (see notably Di Falco, 2012; Tilman et al., 2005). This has been found not only in low-intensity, biologically diverse farming systems such as Ethiopia (Di Falco and Chavas, 2009; Di Falco et al., 2010) and Pakistan (Smale et al., 1998), but also in high-intensity, low-biodiversity farming systems such as the East of England (Omer et al., 2007).

There are several reasons why more biologically diverse farming systems would display lower yield variability, and sometimes higher mean yields. These include symbiotic interactions and resource-use complementarities between species, as well as statistical averaging between species that respond differently to exogenous shocks such as extreme weather, pests and pathogens (Tilman, 1999). This is a portfolio effect (Baumgärtner, 2007) that is also provided within crop species by genetic diversity. In the ecological literature, there is a particular emphasis on how biologically diverse farming systems can be less vulnerable to pests and pathogens thanks to these kinds of mechanism. Pests and pathogens have a very significant impact on global crop yields, with direct losses estimated to be in the range of 20 to 40% (Oerke, 2006; Savary et al., 2012). A famous example is the potato famine of 1845-8 that contributed to 1.5 million deaths in Ireland. Furthermore, expanding the agricultural land area reduces the extent of natural reserve lands, so that the pool of genetic material that can potentially be used as an input to agricultural R&D activities decreases (Simpson et al., 1996; Rausser and Small, 2000).

In this work we explore the implications of global biodiversity loss, caused by the expansion of modern agriculture, for agricultural production itself. At the extensive margin, the conversion of natural lands into modern agriculture is undertaken with the intention of increasing the production of food, but at the same time the evidence we have just presented suggests that it imposes a risk on agricultural productivity, through the loss of biodiversity on natural and agricultural land.[3] The creation of this risk to global agricultural productivity results from individual decisions. Profit-maximizing farmers clear land and plant it with small numbers of high-yielding crop varieties, leading to the loss of biodiversity at the local and global scales. In this process, farmers only partially take into account their marginal impact on biodiversity, and in turn on agricultural productivity (Bowman and Zilberman, 2013; Heal et al., 2004; Weitzman, 2000). Decisions at the individual level about land conversion and crop selection thus cause an externality with respect to aggregate production.

To study the socially optimal expansion of agricultural land in this setting, we employ a quantitative two-sector endogenous growth model of the global economy. This model was first presented in a companion paper (Lanz et al., 2017a) and provides an integrated framework to study the future evolution of global population, economic growth and food production.[4] In the present paper, we extend the model to include a biodiversity externality by means of a global-level hazard or damage function, which links cropland conversion

[2] Since 2000 they have been on a slightly increasing trend.

[3] From the evidence presented by Khoury et al. (2014), for instance, we might assume that agriculture at the extensive margin displays lower-than-average crop and genetic diversity.

[4] More specifically, in Lanz et al. (2017a) we set out our framework for integrated modeling of global population, economic growth and food production, and used the model to make 'baseline' projections. See also Lanz et al. (2017b) where we study the impact of exogeneous, stochastic shocks to agricultural TFP. However, those papers do not include any specific consideration of the effects of biodiversity loss.