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Bruno Lanz, Simon Dietz and Tim Swanson

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The expansion of modern agriculture and global biodiversity decline: An integrated assessment*

Bruno Lanz [†]

Simon Dietz [‡]

Tim Swanson [§]

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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.

Keywords: Agricultural productivity; biodiversity; endogenous growth; food security; land conversion; population

JEL Classifications: N10; N50; O31; O44; Q15; Q16; Q57.

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[†]Corresponding author. University of Neuchâtel, Department of Economics and Business, Switzerland; ETH Zurich, Chair for Integrative Risk Management and Economics, Switzerland; Massachusetts Institute of Technology, Joint Program on the Science and Policy of Global Change, USA. Mail: A.-L. Breguet 2, CH-2000 Neuchâtel, Switzerland; Tel: +41 32 718 14 55; email: bruno.lanz@unine.ch.

[‡]London School of Economics and Political Science, Grantham Research Institute on Climate Change and the Environment, and Department of Geography and Environment, UK.

[§]Graduate Institute of International and Development Studies, Department of Economics and Centre for International Environmental Studies, Switzerland.

1 Introduction

The world population is projected to grow by a further 50 per cent 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 per cent 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; Lampe et al., 2014; Lanz et al., 2016). 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). 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 per cent larger than today, under a reference scenario in which world food production rises by 43 to 99 per cent (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

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

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 an 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

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

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 agricultural economists is that genetic and species diversity on farms reduces the variability of crop yields and sometimes increases the mean yield (see Di Falco, 2012, for a review of these studies). This has been found not only in low-intensity, biologically diverse farming systems such as Ethiopia (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 per cent (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 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

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.

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. We represent the biodiversity externality by means of a global-level hazard function, which links cropland conversion with depreciation of agricultural productivity. This is in the spirit of damage functions in integrated assessment models of climate change (e.g. Nordhaus, 1992; Nordhaus and Boyer, 2000), which, despite legitimate concerns about their predictive capabilities, have proved fundamental to our understanding of that problem. Our growth model has a number of other features, which enable us to derive insights about the interactions between global economic growth and the impact of declining biodiversity on food production. In order to characterize agriculture's role in producing food and sustaining population, the model distinguishes agriculture from other economic activities. Demand for food in the model is proportional to the size of the population and it increases with per-capita income. The world population is endogenously determined by households' preferences for fertility (Barro and Becker, 1989), as well as the opportunity cost of raising children, which is itself linked with technical progress in the economy (Galor and Weil, 2000). Technical progress in agriculture and the rest of the economy is therefore key and it is modeled as Schumpeterian innovation (Aghion and Howitt, 1992), whereby total factor productivity (TFP) growth requires labor as an input to R&D activities. The model is structurally estimated to fit 1960-2010 data on world GDP, population, TFP growth and cropland area, providing an empirical framework to study the socially optimal allocation of land to meet the growing demand for food in the future.

In the absence of the biodiversity externality, we project that world population increases by about 40 per cent by 2050, world GDP doubles and cropland area increases by about 7 per cent. In 2100 the world population reaches about 12.4 billion. In the presence of the externality, the global-level hazard function links cropland conversion with depreciation of agricultural TFP. This means agricultural innovation is a contest between man-made R&D on the one hand and natural depreciation from biodiversity loss on the other hand (Goeschl and Swanson, 2003). We first consider the socially optimal response from a global perspective. Our model suggests that a social planner would respond by immediately preventing the further expansion of cropland, as well as

allocating more labor to agricultural production and agricultural R&D, with negligible effects on fertility and population. Given that the planner can select the least-cost management strategy to tackle the biodiversity externality, and that land is assumed to be relatively easily substituted in agricultural production (the elasticity of substitution between land and other factors is 0.6, which is taken from Wilde, 2013), we find that the welfare cost is small.

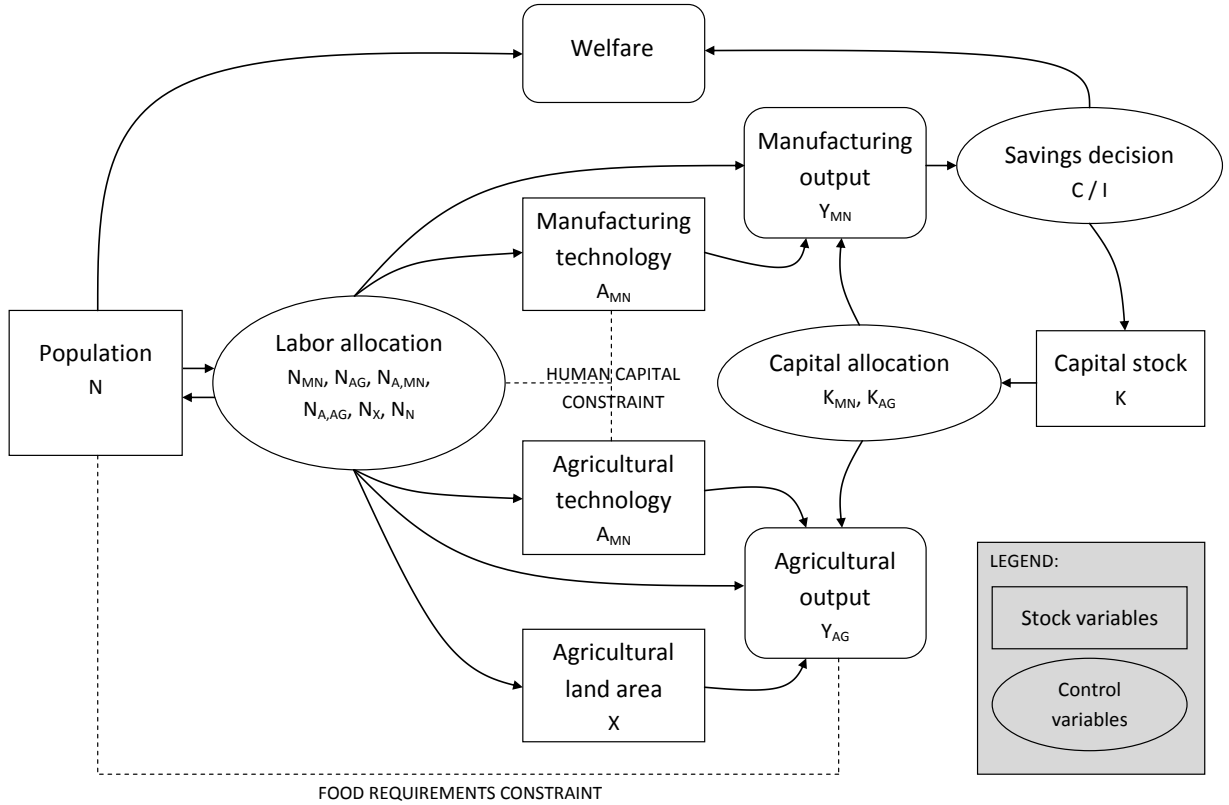
We then consider situations in which managing the externality might impose greater social costs. First, we solve the model under the assumption that fertility and land-conversion choices cannot feasibly be controlled by a global social planner. Instead, these choices are made in a decentralized manner by atomistic farming households, who do not take into account the biodiversity externality. In this scenario, the planner increases the share of labor in agricultural production and agricultural R&D, in order to counter TFP depreciation, but the biodiversity externality still generates a substantial welfare cost, suggesting a global policy to limit cropland expansion might have significant value. Second, we consider lower substitutability of land in agricultural production (the elasticity of substitution between land and other factors is lowered to 0.2) and how this affects the optimal response of the global social planner. In this scenario, the reduction of cropland is significantly lower, and, despite allocating more labor to agricultural production and agricultural R&D, the welfare cost is again larger.

The remainder of the paper is structured as follows. Section 2 describes the model and its estimation on historical data, while Section 3 focuses on the specification and parametrization of the biodiversity hazard function. The following three sections report our results. Section 4 analyzes the socially optimal use of cropland in the presence of the biodiversity externality, compared with a baseline scenario without the externality. Section 5 then considers the scenario in which land-conversion and fertility decisions are decentralized to households. Section 6 analyzes the effect of lower substitutability of land. Section 7 concludes.

2 The model

This section summarizes the key components of the model and estimation procedure. A comprehensive discussion of the structure of the model, selection and estimation of the parameters, the ensuing projections from the model, as well as sensitivity analysis, is reported in Lanz et al.

Figure 1: Schematic representation of the model



(2016).⁴ A schematic representation of that model is provided in Figure 1. This paper deploys the model described therein, but adds the hazard function that captures the external cost of land conversion to agricultural productivity.

2.1 The economy

2.1.1 Production and capital accumulation

The model comprises two sectors: a manufacturing sector that produces the traditional consumption good in one-sector models, and an agricultural sector that produces food to sustain contemporaneous population. In manufacturing, aggregate output is represented by a standard Cobb-Douglas production function:

$$Y_{t,mn} = A_{t,mn} K_{t,mn}^{\vartheta} N_{t,mn}^{1-\vartheta}, \quad (1)$$

⁴ The GAMS code of the model is available from Bruno Lanz's website.

where $Y_{t,mn}$ is real manufacturing output at time t , $A_{t,mn}$ is an index of productivity in manufacturing, $K_{t,mn}$ is capital allocated to manufacturing, and $N_{t,mn}$ is the manufacturing workforce. We assume that technology is Hicks-neutral, so that the Cobb-Douglas functional form is consistent with long-term empirical evidence (Antràs, 2004). We use a standard value of 0.3 for the share of capital (see, for example, Gollin, 2002).

Agricultural production requires land services X_t as an input and, following Kawagoe et al. (1986) and Ashraf et al. (2008), we employ a nested constant-elasticity-of-substitution (CES) function to represent substitution possibilities between land and a capital-labor composite:⁵

$$Y_{t,ag} = A_{t,ag} \left[(1 - \theta_X) \left(K_{t,ag}^{\theta_K} N_{t,ag}^{1-\theta_K} \right)^{\frac{\sigma-1}{\sigma}} + \theta_X X_t^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}, \quad (2)$$

where σ is the elasticity of substitution between the capital-labor composite and agricultural land. We set $\sigma = 0.6$ based on long-run empirical evidence reported in Wilde (2013).⁶ We come back to the importance of this parameter for our results in Section 6 below. We further set $\theta_X = 0.25$ and $\theta_K = 0.3$, consistent with data reported in Hertel et al. (2012).

2.1.2 Innovations and technological progress

As in the Schumpeterian model of Aghion and Howitt (1992), sectoral TFP evolves according to

$$A_{t+1,j} = A_{t,j} \cdot (1 + \rho_{t,j} S), \quad j \in \{mn, ag\}, \quad (3)$$

where S is the maximum growth rate of TFP each period and $\rho_{t,j} \in [0, 1]$ is the arrival *rate* of innovations each period. Actual sectoral TFP growth is then the share of the maximum feasible TFP growth (we set $S = 0.05$ based on Fuglie, 2012) and depends on the number of innovations arriving within each time period.⁷ The rate at which innovations arrive in each sector is a function

⁵ A Cobb-Douglas function is often used for agriculture, notably in Mundlak (2000) and Hansen and Prescott (2002). However, this implies that, in the limit, land is not an essential input to agriculture, with drawbacks that have been extensively discussed in relation to the scarcity of non-renewable resources (see Dasgupta and Heal, 1979, for a seminal contribution).

⁶ The estimate by Wilde (2013) is based on 550 years of data from pre-industrial England, thus reflecting long-term substitution possibilities, and is estimated in a way that is consistent with our CES functional form (2). However, external validity may be an issue, in particular when applying results for pre-industrial England to developing countries with rapidly growing population. In the discussion of the results below, we also consider the case of $\sigma = 0.2$.

⁷ In the original work of Aghion and Howitt (1992), time is continuous and the arrival of innovations is modeled as a Poisson process. Our representation is qualitatively equivalent, but somewhat simpler, as $\rho_{t,j}$ implicitly uses the law of large number to smooth out the random nature of innovations over discrete time periods.

of labor allocated to sectoral R&D:

$$\rho_{t,j} = \lambda_j \left(\frac{N_{t,A_j}}{N_t} \right)^{\mu_j}, \quad j \in \{mn, ag\},$$

where N_{t,A_j} is labor employed in R&D in sector j , $\lambda_j > 0$ is a productivity parameter and $\mu_j \in (0, 1)$ is an elasticity. This formulation implies that TFP growth increases with the share of labor allocated to the R&D sector, rather than the absolute amount (Chu et al., 2013). The latter implication, known as the ‘scale effect’, is not supported by data (Jones, 1995).⁸ Furthermore, our representation of R&D implies decreasing returns to labor in R&D through the parameter μ_j , which captures the duplication of ideas among researchers (Jones and Williams, 2000).

The parameter λ_j is normalized to unity to ensure that TFP growth is bounded between 0 and S , and the parameters μ_{mn} and μ_{ag} are estimated as described below.

2.1.3 Labor and population dynamics

In each period, the change in world population is given by the difference between fertility n_t and the rate at which population exits the labor force δ_N :

$$N_{t+1} = N_t(1 - \delta_N) + n_t N_t, \quad N_0 \text{ given.} \quad (4)$$

Since population equals the total labor force in our model, δ_N is the inverse of the expected working lifetime, which we set to 45 years (hence the ‘working mortality rate’ is $\delta_N = 0.022$).

Fertility derives from the allocation of labor to child-rearing activities, so that child-rearing competes with other labor-market activities:

$$n_t N_t = \bar{\chi}_t \cdot N_{t,N},$$

where $N_{t,N}$ is labor allocated to child-rearing activities and $\bar{\chi}_t$ is an inverse measure of the time cost of producing effective labor units. We postulate an increasing relationship between the time

⁸ Scaling the labor force in R&D by N_t is also in line with micro-foundations of more recent representations of technological change. In the models of Dinopoulos and Thompson (1998), Peretto (1998) and Young (1998), R&D activities simultaneously develop new products and improve existing ones, and the number of products grows with population, thereby diluting R&D inputs and avoiding the population scale effect. Another strategy to address the scale effect involves postulating a negative relationship between labor productivity in R&D and the existing level of technology, giving rise to “semi-endogenous” growth models (Jones, 1995, 2001). In this setup, however, long-run growth is only driven by population growth, which is also at odds with the data (Ha and Howitt, 2007).

cost of child-rearing and the level of technology:

$$\bar{\chi}_t = \chi N_{t,N}^{\zeta-1} / A_t^\omega,$$

where $\chi > 0$ is a productivity parameter, $\zeta \in (0, 1)$ is an elasticity representing scarce factors required in child-rearing, A_t is an index of technology and $\omega > 0$ measures how the cost of children increases with the level of technology. This formulation implies that, as the stock of knowledge in the economy grows, additions to the stock of effective labor units become increasingly costly. In other words there is a complementarity between technology and skills (Goldin and Katz, 1998), which implies that a demographic transition will occur as education requirements increase over time (Galor and Weil, 2000). The ‘quality’ of children required to keep up with technology will be favored over the quantity. Furthermore, ζ captures the fact that the cost of child-rearing over a period of time increases more than proportionally with the number of children (see Barro and Sala-i Martin, 2004, p.412 and Bretschger, 2013). The parameters determining the cost of fertility and how it evolves over time (χ , ζ and ω) are estimated from the data, as described below.

Population dynamics are further constrained by food availability, as measured by agricultural output.⁹ Specifically, in each period agricultural production is consumed entirely to sustain contemporaneous population:

$$Y_t^{ag} = N_t \bar{f}_t,$$

where \bar{f}_t is per-capita food demand, i.e. the quantity of food required to maintain an individual in a given society. We further specify per-capita demand for food as a concave function of per-capita income:

$$\bar{f} = \xi \cdot \left(\frac{Y_{t,mn}}{N_t} \right)^\kappa,$$

where ξ is a scale parameter and $\kappa > 0$ is the income elasticity of food consumption. Food demand thus captures both physiological requirements (e.g. minimum per-capita caloric intake) and the way that preferences imbibe a positive relationship between income and the consumption

⁹ Food consumption does not contribute directly to social welfare. As discussed below, however, the level of population enters the social welfare criterion (together with the utility of per-capita consumption of the manufacturing good). Therefore food availability will affect social welfare through the impact of the subsistence requirement on population. For a similar treatment, see Strulik and Weisdorf (2008), Vollrath (2011) and Sharp et al. (2012).

of calories. We set the income elasticity of food demand $\kappa = 0.25$, which is consistent with evidence across countries and over time reported in Subramanian and Deaton (1996), Beatty and LaFrance (2005), and Logan (2009). The parameter measuring food consumption for unitary income (ξ) is calibrated such that the demand for food in 1960 represents about 15% of world GDP, which corresponds to the GDP share of agriculture reported in Echevarria (1997). This implies $\xi = 0.4$.

2.1.4 Land

As a primary factor, the land input to agriculture has to be converted from a total stock of available land \bar{X} by applying labor. Over time the stock of land used in agriculture develops according to

$$X_{t+1} = X_t(1 - \delta_X) + \psi \cdot N_{t,X}^\varepsilon, \quad X_0 \text{ given}, \quad X_t \leq \bar{X}, \quad (5)$$

where $N_{t,X}$ is labor allocated to land-clearing activities, $\psi > 0$ measures labor productivity in land-clearing activities, $\varepsilon \in (0, 1)$ is an elasticity, and the depreciation rate δ_X measures how fast converted land reverts back to natural land. We assume the period of regeneration of natural land is 50 years, so that $\delta_X = 0.02$. The parameters ψ and ε are estimated from the data as described below.

2.1.5 Preferences and savings

The utility function of a representative household is defined over own consumption of the manufactured good c_t , fertility n_t and the utility its children will experience in the future $U_{i,t+1}$. More specifically, we represent household preferences with the recursive formulation of Barro and Becker (1989):

$$U_t = \frac{c_t^{1-\gamma} - 1}{1-\gamma} + \beta n_t^{1-\eta} U_{i,t+1},$$

where γ is the elasticity of marginal utility of consumption of the manufactured good or in other words the inverse of the intertemporal elasticity of substitution, β is the discount factor and η is an elasticity determining how the utility of parents changes with n_t . The objective function is given by the utility function of the dynastic head and obtained by successive substitution of the

recursive utility function (see Lanz et al., 2016, for the detailed derivation):

$$U_0 = \sum_{t=0}^{\infty} \beta^t N_t^{1-\eta} \frac{(C_t/N_t)^{1-\gamma} - 1}{1-\gamma}, \quad (6)$$

where $C_t = c_t N_t$ is aggregate consumption at t .

The parametrization of the objective function is as follows. First, the elasticity of intertemporal substitution is set to 0.5 in line with estimates by Guvenen (2006). In the model, this corresponds to $\gamma = 2$. Second, we set $\eta = 0.001$ so that altruism towards the welfare of children remains almost constant as the number of children increases, while at the same time ensuring concavity of the objective function. This implies the objective function is very close to being Classical Utilitarian. Third, we set the discount factor to 0.99, which corresponds to a pure rate of time preference of 1 per cent per year.

Aggregate consumption derives from manufacturing output, which can alternatively be invested into a stock of capital:

$$Y_{t,mn} = C_t + I_t, \quad (7)$$

where C_t and I_t are aggregate consumption and investment respectively. The accumulation of capital is then given by:

$$K_{t+1} = K_t(1 - \delta_K) + I_t, \quad K_0 \text{ given}, \quad (8)$$

where δ_K is the per-period depreciation rate. Because we solve for the social planner solution of the problem (see below), savings cum investment decisions mirror those of a one-sector economy (see Ngai and Pissarides, 2007, for a similar treatment of savings in a multi-sector growth model).

2.2 Estimation of the model

We consider the planner's problem of selecting the allocation of labor and capital as well as the saving rate to maximize the utility of a representative dynastic household.¹⁰ Specifically, a repre-

¹⁰ The fact that we solve the model as a social planner problem simplifies the notation and allows us to exploit efficient solvers for constrained non-linear optimization. However, it abstracts from externalities that would arise in a decentralized equilibrium. As discussed below, however, market imperfections prevailing over the estimation period will be reflected in the parameters that we estimate from observed trajectories.

sentative household chooses paths for $N_{t,j}$, $K_{t,j}$, and C_t by maximizing (6) subject to technological constraints (1), (2), (3), (4), (5), (7), (8) and resource allocation constraints for capital and labor:

$$K_t = K_{t,mn} + K_{t,ag}, \quad N_t = N_{t,mn} + N_{t,ag} + N_{t,A_{mn}} + N_{t,A_{ag}} + N_{t,N} + N_{t,X}.$$

The numerical model is solved as a constrained non-linear optimization problem and thus mimics the welfare maximization program by directly searching for a local optimum of the objective function (the discounted sum of utility) subject to the requirement of maintaining feasibility as defined by the constraints of the problem.¹¹

As mentioned above, parameters determining the cost of fertility (χ, ζ, ω), labor productivity in R&D ($\mu^{mn,ag}$) and labor productivity in land conversion (ψ, ε) are estimated by fitting the model to 1960-2010 trajectories for world GDP (Maddison, 1995; Bolt and van Zanden, 2013), population (United Nations, 1999, 2013), crop land area (Goldewijk, 2001; Alexandratos and Bruinsma, 2012) and sectoral TFP (Martin and Mitra, 2001; Fuglie, 2012). The estimation procedure includes three main steps, and is discussed in more detail in Appendix A. First, we impose specific parameter values for a number of quantities that are standard in the literature (see discussion above). Second, we calibrate values for the state variables to initialize the model in 1960. Third, we define a minimum distance criterion for GDP ($Y_{t,mn} + Y_{t,ag}$), population (N_t), crop land (X_t), and TFP ($A_{t,mn, ag}$) as a way to select the vector of parameters that best fits the observed trajectories. Using simulation methods to select the vector of parameters that minimizes our criterion, we find that the model closely fits the targeted data (see goodness-of-fit measures in Appendix A).

3 Specification of the biodiversity externality

As described above, innovation in agriculture is driven by allocating labor to R&D activities, while land acts as an input to agricultural production. We now introduce the critical second role of land allocation, which is to modulate biodiversity loss and in turn the depreciation of agricultural TFP. The rate of depreciation of agricultural TFP is endogenous and depends on the size of the agricultural system in terms of global cropland area.

¹¹ The numerical problem is formulated in GAMS and solved with KNITRO (Byrd et al., 1999, 2006), a specialized software for constrained non-linear programs.

Agricultural R&D proceeds in a similar fashion to R&D in the manufacturing sector,

$$\tilde{A}_{t+1,ag} = \tilde{A}_{t,ag} \cdot (1 + \rho_{t,ag}S - \phi_t S), \quad (9)$$

except that in this case ϕ_t measures the rate at which man-made R&D depreciates. This depends on the amount of cultivatable land allocated to crop production:

$$\phi_t = \lambda_D (X_t)^{\mu_D}, \quad (10)$$

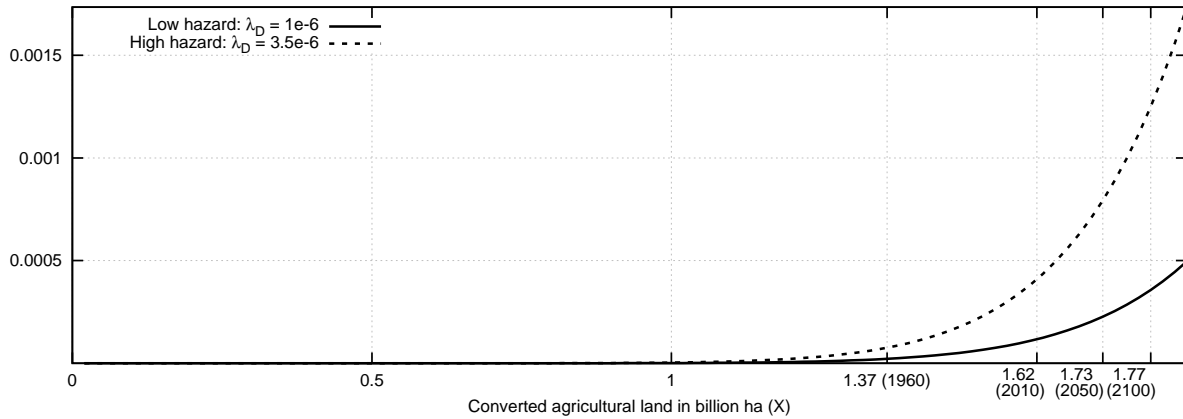
where $\lambda_D \geq 0$ and $\mu_D > 1$, which is consistent with the relationship between biodiversity and plant productivity in natural ecosystems (Hooper et al., 2012). The expected growth rate of agricultural TFP is then the net result of the flow of innovations out of man-made R&D (or moves up the TFP ladder) and the arrival of biological hazards associated with the scale of agriculture (moves down the technological ladder), in the spirit of Goeschl and Swanson (2003).

While the ecological processes underpinning Equation (10) are well documented (see the Introduction), there exists as yet no empirical evidence that can directly guide the parametrization of an agricultural biodiversity hazard function at the global level. Separately identifying man-made innovation and natural depreciation of agricultural TFP is challenging in empirical data.¹² The large body of ecological experiments is strongly suggestive of a negative relationship between species diversity and plant productivity that holds globally (Cardinale et al., 2012; Hooper et al., 2012), but many of these experiments have been conducted outside cropping systems. The empirical evidence from agricultural economics (Di Falco, 2012) is directly relevant, but it is simply more sparse at this point. We therefore select the parameters determining the scale of the externality, λ_D and μ_D in (10), in order to simply illustrate the processes at play and how these impact the macro-economy.

We run with two specifications, low and high, as shown in Figure 2. In the low hazard function, $\lambda_D = 1.6e - 6$ and $\mu_D = 10$. In the high hazard function, $\lambda_D = 3.5e - 6$ and again $\mu_D = 10$. Both functions imply that the TFP depreciation rate is almost insignificant for the area of cropland up to and including 2010. Under the low hazard function, the impact on TFP depreciation of additional land conversion beyond the 2010 area remains small, but under the high hazard function it rises

¹² However, because the model is fitted to the last 50 years of data on agricultural TFP growth, estimates of labor productivity in agricultural R&D will reflect the occurrence of biological hazards in the past.

Figure 2: Land conversion and expected rate of agricultural TFP depreciation



more sharply. Along our baseline scenario (see below), the global area of cropland reaches around 1.8 billion hectares in 2100 and the high hazard function associates this with a TFP depreciation rate of around 0.1 per cent. This compares with TFP *growth* from man-made innovation of around one per cent in 2010, declining over time to 0.5 per cent. Therefore TFP depreciation is relatively small, even under the high hazard function. In view of the fact that biodiversity loss has an impact on crop yield variability, it is appropriate to interpret the hazard function as a certainty equivalent, similar to the treatment of climate damages in Nordhaus' work with the DICE integrated assessment model (Nordhaus and Boyer, 2000).

4 Results: optimal management of the biodiversity externality

In this section we consider the socially optimal response under the two hazard schedules, as well as in a baseline scenario where the biodiversity externality is absent. What is shown is the outcome of a representative household cum social planner controlling all the variables of the problem in order to maximize welfare. In the presence of the biodiversity externality, this implies the social planner can internalize the negative impact of land conversion on agricultural TFP by conserving natural land and reducing fertility, among other things. In the presence of the externality, it is indeed appropriate to interpret the representative agent as a social planner rather

than a household.¹³ To begin with, we are particularly interested in how the social planner would optimally manage the externality. That is why we do not impose the externality on an economy that is constrained in how it can respond. We return to this issue in the next section.

In the following, we first report aggregate impacts for population, land, technology, and agricultural output. We then turn to the implied reallocation of labor across sectors in response to the externality. Finally, we quantify the welfare cost of the optimal policy in terms of consumption of the manufactured good and food.

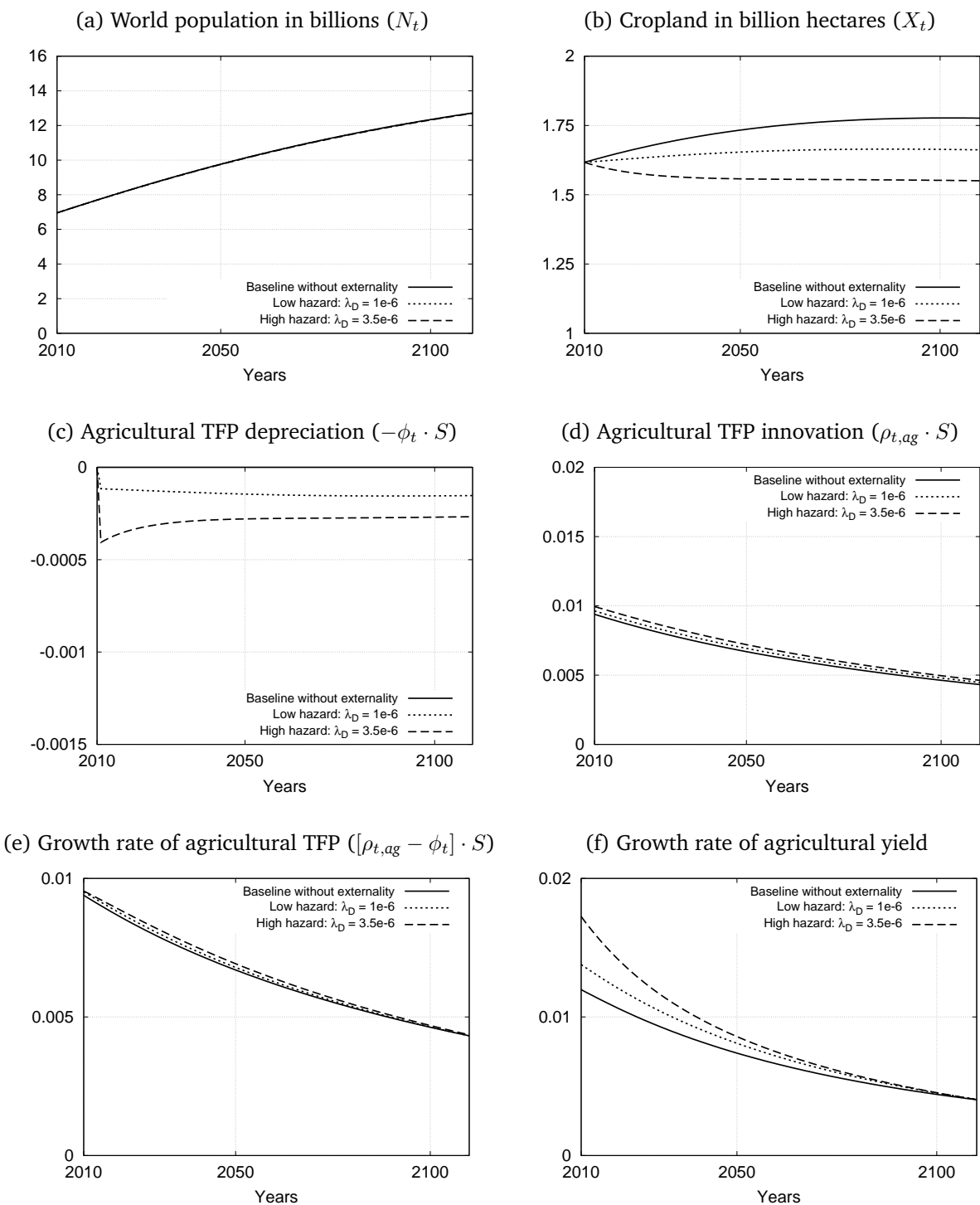
4.1 Aggregate impacts

Figure 3 displays trajectories for world population (panel a) and global cropland (panel b). The baseline scenario delivers a world population of 9.8 billion in 2050 and 12.4 bn. in 2100. This is towards the upper end of the 20-80% confidence interval of the latest UN projections (United Nations, 2015). The area of cropland reaches 1.73 billion hectares in 2050 and stabilizes at 1.78 bn. ha. towards the end of the century, which is in the middle of the range of AgMIP model projections under a broadly comparable baseline scenario (Schmitz et al., 2014). Therefore we find that a steady state in land conversion is consistent with sustained growth in agricultural output, even though we are only mildly optimistic about future technological progress: agricultural TFP growth in 2010 is around one per cent per year and it declines thereafter (see Figure 3, panel e). An important feature of these projections is that the growth rates of the variables decline towards a balanced growth path, where population, land and capital reach a steady state. Thus our results conform with the widespread expectation that the long-standing processes of global population growth and cropland conversion are in decline. This reflects a shift from a quantity-based economy with rapid population growth and associated land conversion, towards a quality-based economy with investments in technology and education, and lower fertility.

Turning to the impact of the biodiversity externality on agricultural TFP, it is plain to see that population is almost unaffected (panel a); under the high hazard function it is just 0.025 bn. lower in 2100. So the optimal response of the planner only involves a small reduction in fertility. By contrast – and even though the rate of cropland conversion is in decline in the baseline scenario –

¹³ In the presence of externalities, the social planner's solution will generally differ from the decentralized allocation. The Schumpeterian model of growth that we use incorporates positive externalities to R&D activities. However, by estimating the model on the past 50 years of data, we rationalize observed outcomes 'as if' they resulted from the decisions of a social planner, so the concepts of a representative household and a social planner are equivalent in the baseline scenario. They are not equivalent when the new land-use externality is introduced, however.

Figure 3: Projections for population, land conversion and agricultural technology, 2010 – 2100



the externality has a large impact on socially optimal land conversion (panel b). Under the high hazard function, cropland immediately declines and reaches a steady state at around 4% below the 2010 level. This corresponds to a reduction of cropland of 60 million ha. relative to 2010, as opposed to an increase of around 150 mn. ha. under the baseline scenario. The planner puts an immediate halt to further land conversion and moreover leaves a portion of global cropland that is in use in 2010 to be reclaimed by nature, in order to mitigate the negative impact of the scale of the cropping system on productivity via biodiversity loss. Under the low hazard function, cropland stays close to its 2010 value throughout the century, increasing very slightly in the first few decades.

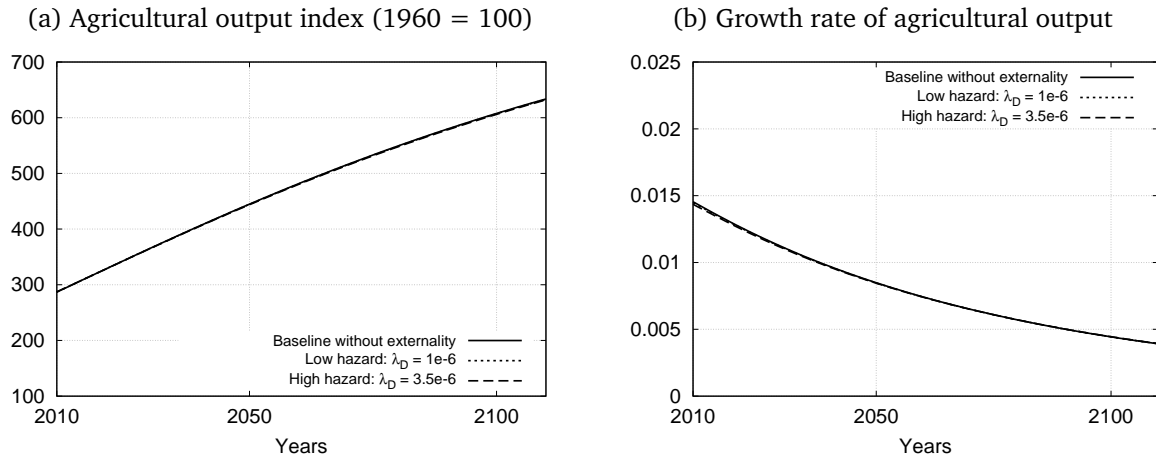
The impact of land conversion on agricultural TFP growth is illustrated in panels (c) and (d). Under the high hazard function, TFP depreciation peaks immediately at about 0.04 per cent, but then the decline in cropland area brings depreciation back down towards a steady-state rate of about 0.027 per cent. Under the low hazard function, the long-term rate of TFP depreciation is roughly half of that, at 0.015 per cent. In response to natural TFP depreciation, the planner increases the level of man-made agricultural R&D, the result of which is shown in panel (d). Consequently overall growth in agricultural TFP is actually higher in the presence of the externality than it is in the baseline scenario (panel e), compensating for the smaller area of land used in agriculture.

In panel (f) of Figure 3, we report the growth rate of agricultural yields, i.e. the rate of change of agricultural output per unit of land area. This is an important measure of the resources allocated to agriculture for a given area of cropland. Under the baseline scenario, agricultural yield growth starts at around 1.2 per cent per year in 2010 and declines towards 0.5 per cent per year in 2100. In the presence of the externality, yield growth is initially higher, but then converges to the baseline growth rate by 2100. This suggests an important reallocation of factors to increase agricultural yields early on, but a convergence of the three paths in the long run.

Figure 4 shows an index of agricultural output (panel a) and its associated growth rate (panel b).¹⁴ It demonstrates that agricultural output is virtually the same in all three scenarios, despite differences in the composition of inputs (recall that population is almost identical in all three scenarios too). Our model suggests an increase of agricultural output of 67 per cent between

¹⁴ The base year of the index is 1960, suggesting that agricultural output increases by a factor of 2.8 over the estimation period. While this figure is not directly targeted by the estimation, it is very close to the factor of 2.7 reported to apply over the same period in Alexandratos and Bruinsma (2012).

Figure 4: Agricultural output and associated growth rate, 2010 – 2100



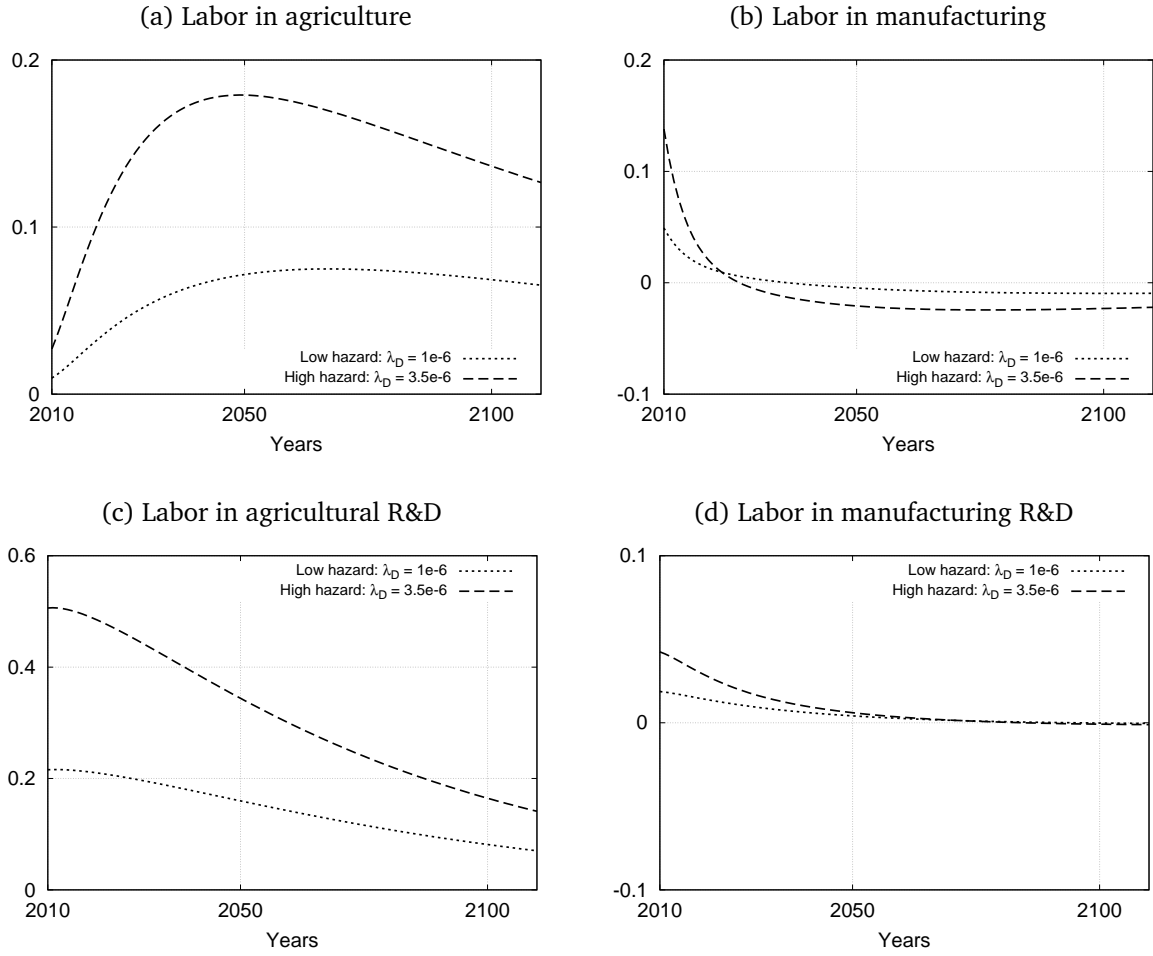
2010 and 2050, in line with other projections (Alexandratos and Bruinsma, 2012; Robinson et al., 2014), and a doubling of agricultural output by 2100.

4.2 Changes in sectoral labor allocation

Figure 5 reports on how the allocation of labor differs across scenarios. This is a potentially important lever for the planner. The baseline scenario without the externality is used as the benchmark and we report percentage point differences in labor *shares* allocated to different activities under the low and high hazard schedules. In the presence of the biodiversity externality, we have already seen that the social planner significantly reduces cropland area relative to the baseline. Panels (a) and (c) show that food supply is maintained by increasing the shares of labor devoted to agricultural production and agricultural R&D respectively. This substitutes for the reduced land input and deals with residual natural TFP depreciation due to the scale of the cropping system. In 2010, the share of labor allocated to agricultural R&D is about 0.5 percentage point higher under the high hazard function than it is in the baseline, which roughly corresponds to a 10 per cent increase in the workforce allocated to agricultural R&D.¹⁵

¹⁵ While the proportion of labor employed in agricultural R&D (around five per cent) may appear high, it should be noted that it includes any labor time dedicated to improving factor productivity. This includes many informal activities taking place in developing economies in particular, such as seed selection or improving irrigation practices.

Figure 5: Sectoral labor shares relative to *Baseline* (in percentage points)

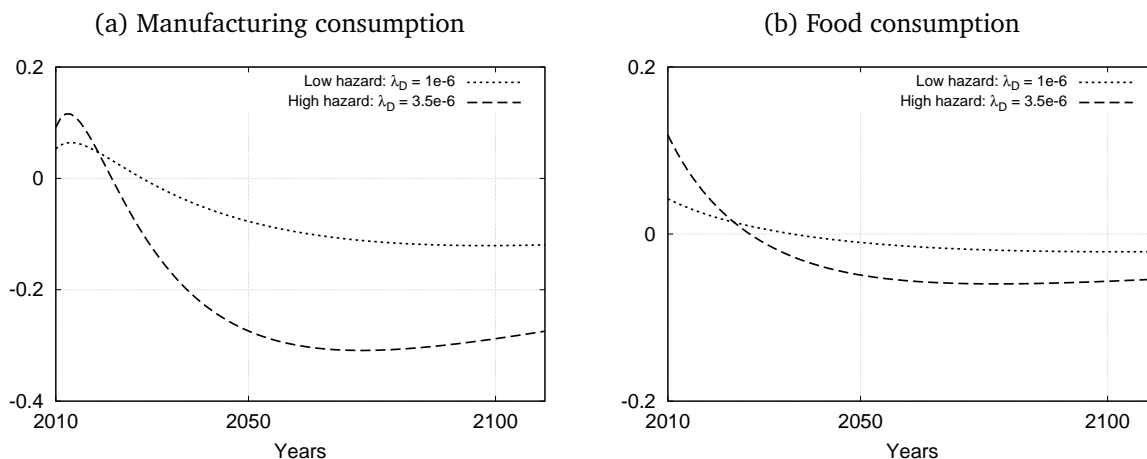


Panel (b) shows that the share of labor allocated to manufacturing is initially higher in the presence of the externality, as labor that would have been employed in land conversion is reallocated, but it quickly converges to a share very close to the baseline. The share of labor allocated to manufacturing R&D is very similar in all three scenarios.

4.3 Per-capita consumption and social welfare

Figure 6 shows the implications of the externality for consumption per capita of the two goods. We report the paths taken by consumption per capita of the manufactured good (panel a) and food (panel b) under the two hazard schedules, as a percentage of the baseline run. In the presence of the biodiversity externality, which is after all a supply-side shock to the agricultural sector, consumption of both goods is lower. Given our representation of preferences in Eq. (6), consumption per capita of the manufactured good is in fact a measure of equivalent variation (as

Figure 6: Per capita consumption relative to *Baseline* (in %)



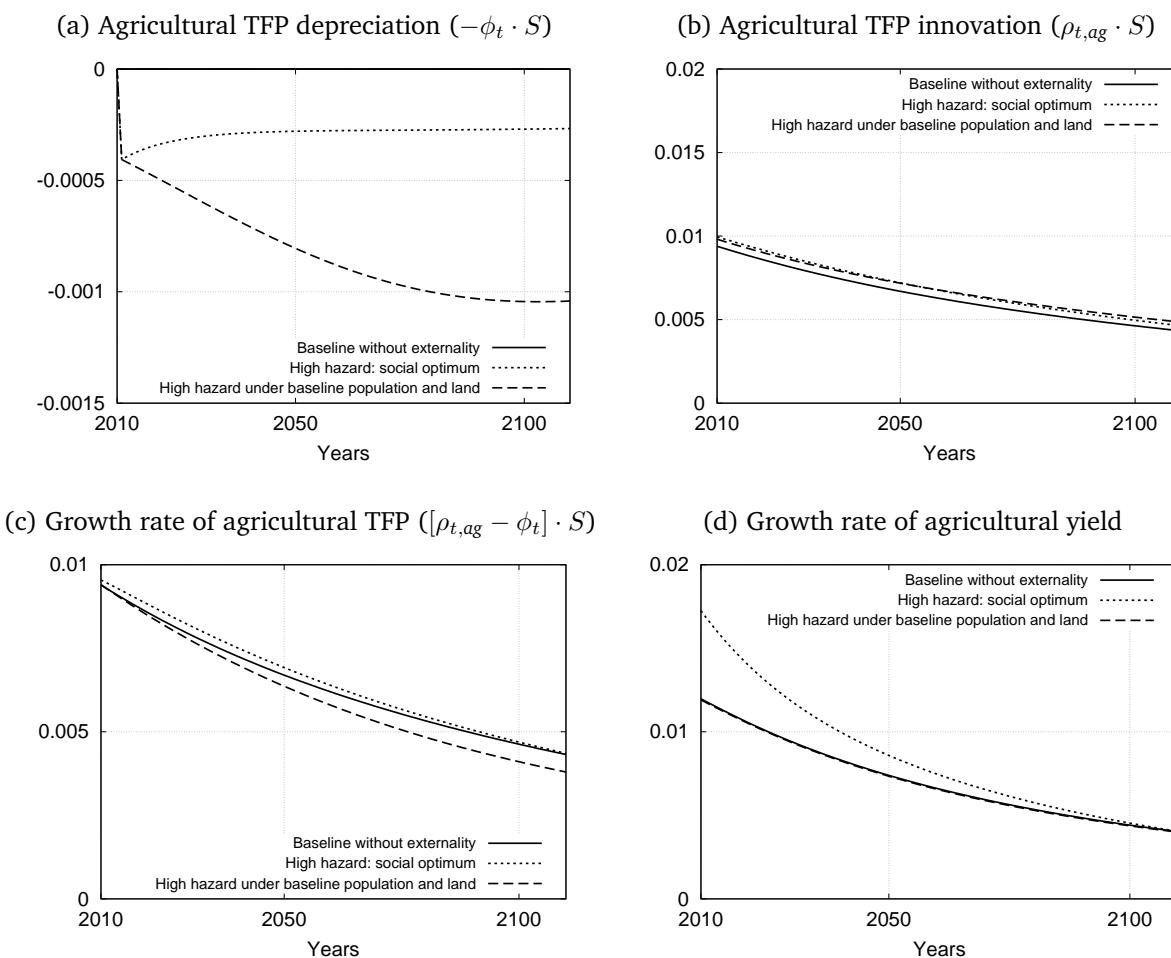
a percentage of baseline consumption). Thus the welfare cost of the externality under the high hazard schedule, optimally managed, rises to about 0.3 per cent in the second half of this century. Under the low hazard schedule this welfare cost is closer to 0.1 per cent. Because consumption of the manufactured good and of food are complementary in our model (which comes from the positive relationship between household income and food preferences), food consumption follows a similar trajectory and is quickly lower in the presence of the externality, though the difference is very small, in line with the empirical evidence on income elasticity of food demand.

5 Results: Fixed population and land

The previous section focused on how a global social planner would optimally manage the biodiversity externality. On the assumption that agriculture continues to employ ecologically damaging practices, our results broadly suggested a moratorium on further expansion of cropland (even under the low hazard schedule, cropland barely expands after 2010), as well as changes in the allocation of labor to different uses, in particular a shift towards agricultural production and agricultural R&D. However, in reality the mechanisms promoting centralized choice of land conversion and fertility are at best weak and at worst non-existent, especially at the global level. Therefore it is of interest to analyze a scenario, in which the biodiversity externality is present, but individual farms/households do not internalize it in their fertility and land-conversion decisions.

In this section, we hence evaluate a scenario in which the high hazard schedule applies, but the trajectories for population and cropland area are constrained to follow the baseline scenario

Figure 7: Projections for population, land conversion and agricultural technology, 2010 – 2100



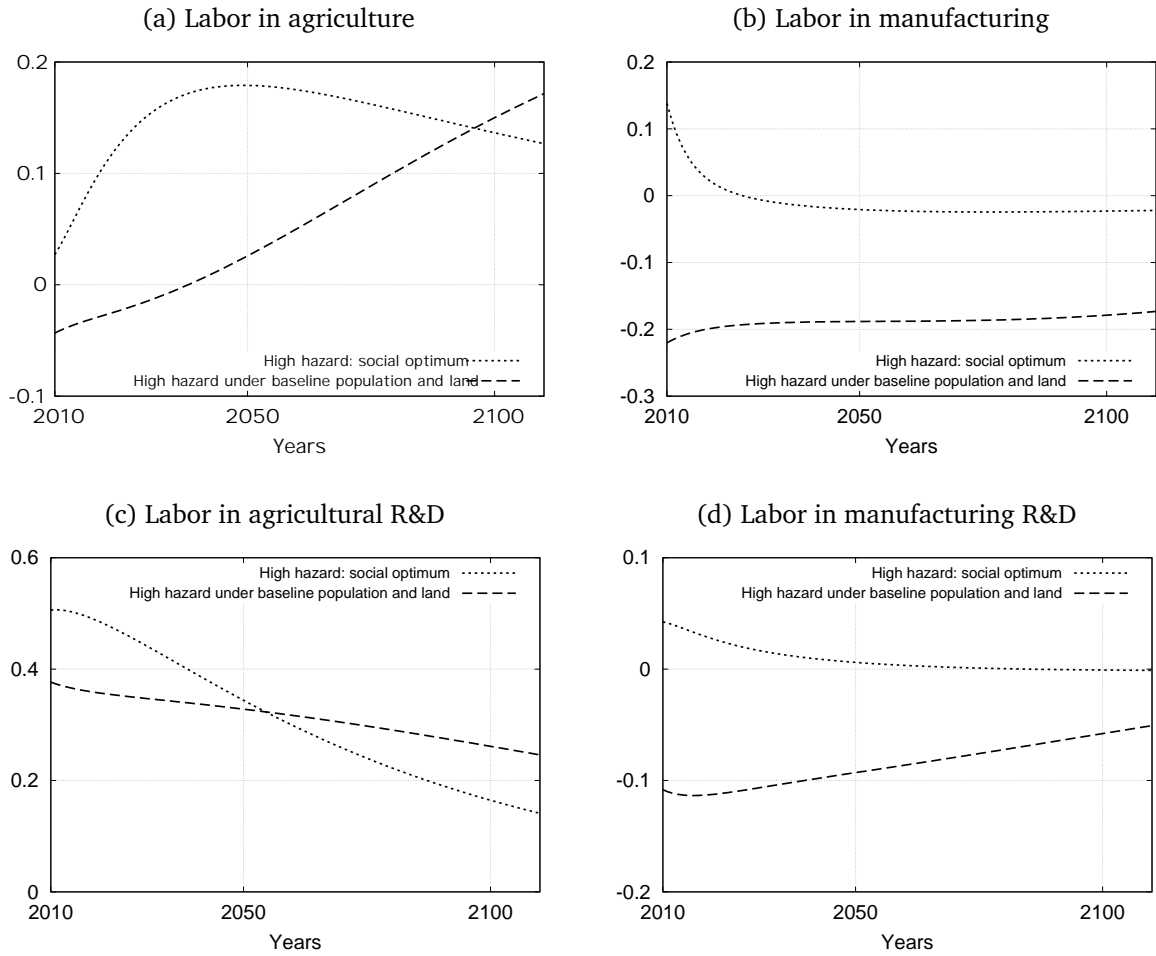
without the externality (from above). We still posit a social planner in this scenario, but the planner’s response to the externality is curtailed and may only involve changing the share of labor allocated to different uses, the share of capital allocated to the two sectors, as well as the overall consumption/savings margin. For comparison, we include both the baseline without the externality and the social optimum in the presence of the high hazard schedule, as explored in the previous section.

In the following, we again focus on three different model outcomes: (i) aggregate impacts; (ii) reallocation of labor across sectors; and (iii) welfare costs.

5.1 Aggregate impacts

Figure 7 displays trajectories for agricultural TFP (panels a-c) and yield growth (d); population and land are omitted since these trajectories are fixed to their baseline levels. Panel (a) shows

Figure 8: Sectoral labor shares relative to *Baseline* (in percentage points)

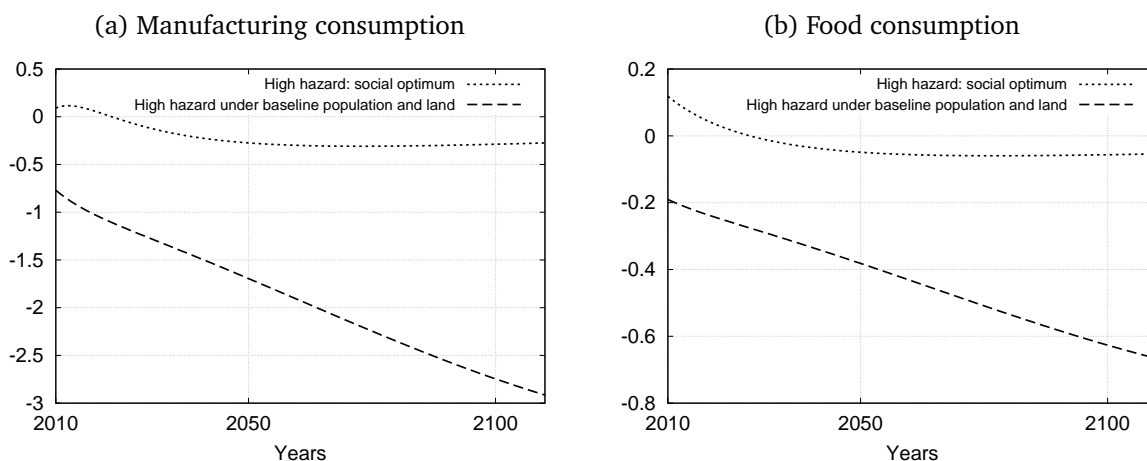


that decentralized fertility and land conversion choices lead to a much larger rate of agricultural TFP depreciation, which increases to about 0.1 per cent by the end of the century, around four times higher than under the socially optimal response to the externality. This carries through to the overall growth rate of agricultural TFP (panel c); rather than being higher than the baseline to compensate for the reduced land input, under the scenario of decentralized fertility and land-conversion decisions it is lower and, as a consequence, yields track the baseline (panel d).

5.2 Changes in sectoral labor allocation

Figure 8 reports on labor shares in the two planning scenarios, relative once again to the baseline without the externality. Panel (a) shows that the trajectory of the share of labor employed in agricultural production is quite different to the unconstrained social optimum. Because land conversion continues along its baseline trajectory, there is not the immediate need to boost labor

Figure 9: Per capita consumption relative to *Baseline* (in %)



in agricultural production that exists under the unconstrained social optimum. However, because continued land conversion puts more and more downward pressure on agricultural productivity, the share of labor in agriculture steadily increases and it overtakes the unconstrained social optimum by the end of the century. For the same reason, the share of labor allocated to agricultural R&D is initially lower under decentralized fertility and land-conversion choices than it is at the unconstrained social optimum, but the former overtakes the latter just after 2050 and by the end of the century it is markedly higher. Importantly, the constrained optimal solution implies that labor is diverted away from manufacturing production (panel b) and manufacturing R&D (d), which will induce large welfare costs, as we shall now see.

5.3 Per capita consumption and social welfare

Figure 9 (panel a) provides estimates of these welfare costs, in the form of the path of consumption per capita of the manufactured good. Compared with the unconstrained social optimum, consumption per capita is much lower, starting at 0.8 per cent below the baseline and falling approximately linearly to 2.9 per cent below the baseline by the end of the century. So, while changing the share of labor devoted to different uses is able to match food supply and demand and sustain a world population of more than 12 bn. by 2100, this comes at a substantial cost in terms of living standards (as proxied by consumption per capita of the manufactured good). The complementarity between living standards and food consumption explains why per-capita food consumption also falls approximately linearly over the course of the century (panel b). By 2100 it is more than 0.6 per cent less than in the baseline.

6 Results: land substitutability

The results of Section 4 demonstrated that the optimal global management of the biodiversity externality involves a very different future for agricultural land-use management. The social planner immediately protects remaining natural land reserves as a buffer against agricultural TFP depreciation. One key assumption underlying this result is the substitutability of land in agricultural production. Our simulations so far have assumed $\sigma = 0.6$, which is based on empirical evidence reported in Wilde (2013). There is, however, considerable uncertainty about the value of this parameter, particularly when considering the global aggregate. Here we consider an alternative scenario in which $\sigma = 0.2$, meaning it is more difficult to substitute land with capital and labor. To get a consistent baseline, it is necessary to re-estimate the parameters of the model. We therefore run both the baseline scenario without the externality, and the social optimum under the high hazard schedule, when $\sigma = 0.2$, and we do the same when $\sigma = 0.6$. We start with aggregate results, then move to labor shares and finally welfare.

6.1 Aggregate impacts

Figure 10 reports trajectories for population (panel a) and cropland (panel b). As we would expect, when there is less scope to substitute capital and labor for land in agricultural production, baseline cropland expansion is higher. In 2050 it reaches 1.77 bn. ha., on its way to a steady state of around 1.82 bn. ha. towards the end of the century. However, the population trajectory is almost identical.

Under low substitutability, the social planner responds to the biodiversity externality by slowing cropland expansion, but not as fast or as far as when $\sigma = 0.6$. Instead of the area of global cropland falling immediately, it increases fractionally over several decades. Because land is more integral to food production when $\sigma = 0.2$, panel (c) shows that the social planner must tolerate a relatively high level of natural depreciation of agricultural TFP, reaching about 0.05 per cent later in the century. The planner compensates for this by allocating more resources to agricultural R&D, the results of which can be seen in panel (d).

As a consequence of low substitutability of land, the planner drives up the rate of agricultural TFP innovation with or without the externality. In the presence of the externality, the rate of agricultural TFP innovation is around 1.2 per cent initially, which is about a fifth higher than when $\sigma = 0.6$. Panel (e) shows that this in turn results in higher net agricultural TFP growth, while

Figure 10: Projections for population, land conversion and agricultural technology, 2010 – 2100

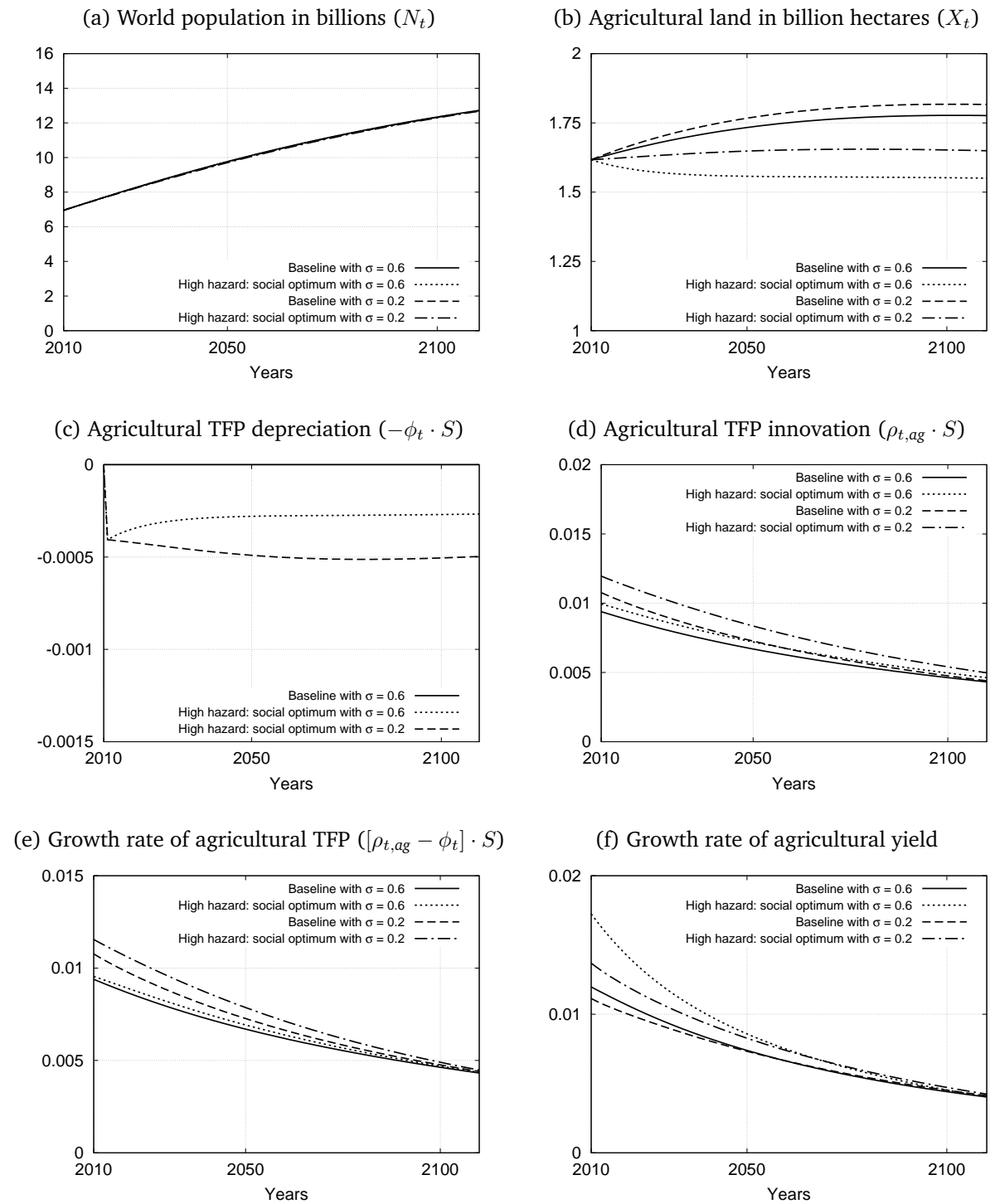
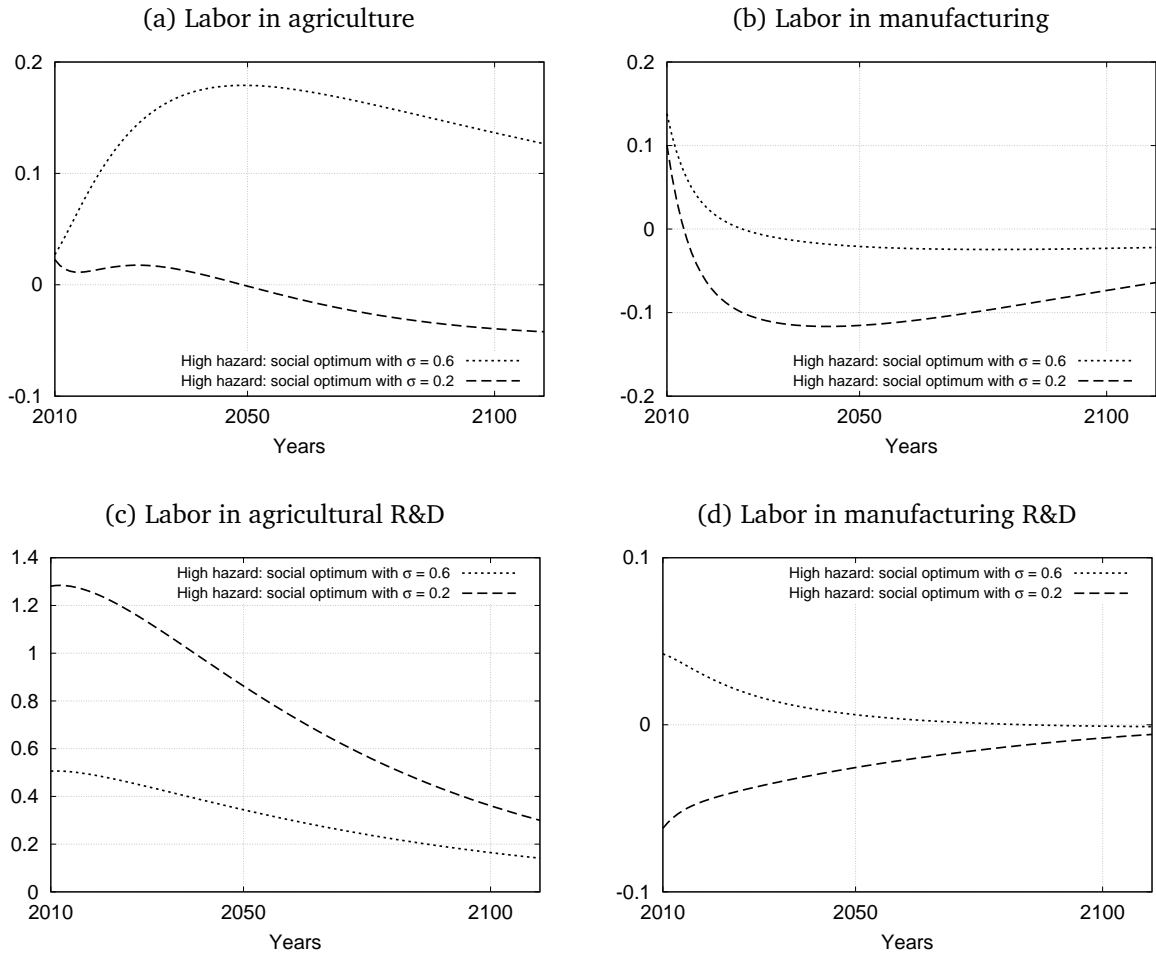


Figure 11: Sectoral labor shares relative to *Baseline* (in percentage points)

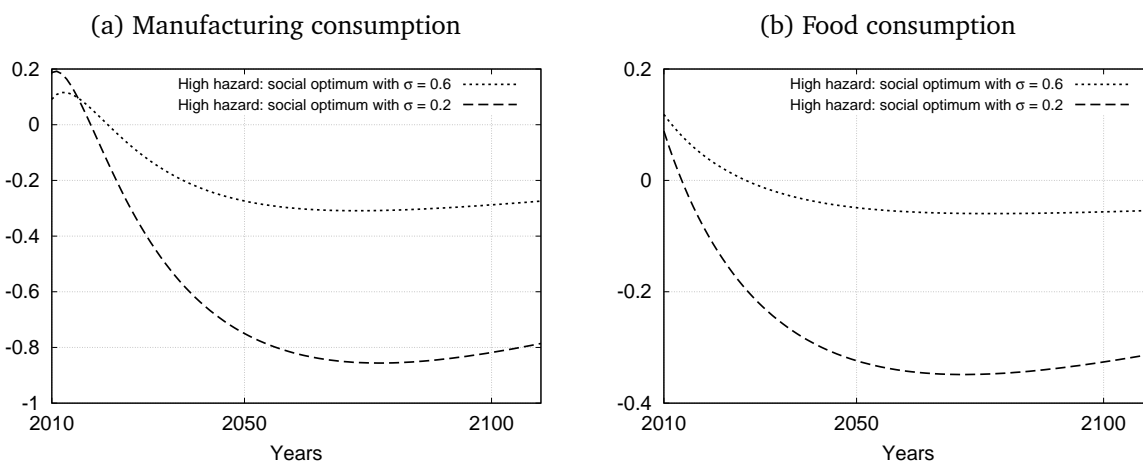


panel (f) shows that, with relatively more cropland in use, yields are lower when substitutability is lower. Finally, once again agricultural output is virtually the same in all the scenarios (and hence is not reported).

6.2 Changes in sectoral labor allocation

Figure 11 compares the allocation of labor with and without the externality, for the two different elasticities of substitution of land with capital-labor. That is, we plot the difference between the social optimum under the high hazard and the baseline for $\sigma = 0.2$ and we do the same for $\sigma = 0.6$. Given that the baselines are not far apart from each other, we can also compare the two social optima to a first approximation. We can see that, in the presence of an externality, lower substitutability of land leads to a reduction of the share of labor in agricultural production (panel a), manufacturing (b) and manufacturing R&D (d). Instead, to manage the biodiversity

Figure 12: Per capita consumption relative to *Baseline* (in %)



externality under conditions of lower substitutability of land, the planner allocates much more labor to agricultural R&D (panel c), initially more than twice as much as when $\sigma = 0.6$. In fact, $\sigma = 0.2$ implies a higher complementarity between primary factors in agricultural production. Hence as land becomes more costly to use (because of the externality), the planner uses less of all the inputs, and instead focuses on increasing agricultural TFP. Note also that, in addition, because cropland area is larger with $\sigma = 0.2$, more labor is allocated to land conversion.

6.3 Per capita consumption and social welfare

Figure 12 shows that lower substitutability of land leads to a considerably higher reduction of per capita consumption, and hence higher welfare cost of the biodiversity externality. Consumption per capita of the manufactured good reaches a minimum of about 0.8 per cent lower than the baseline in the second half of the century. Food consumption also declines, although to a lesser extent, being around 0.3 per cent lower than in the baseline (no externality) situation.

7 Concluding comments

One might summarize the premise of this paper as an argument in three parts. The first part of the argument is that the expansion of modern, intensive agriculture causes biodiversity loss, unless it is practised in a sustainable way that is still rare in reality. This first part of the argument seems incontrovertible. The second part is that biodiversity loss reduces agricultural productivity. This part of the argument does not perhaps have the same status, but it is backed by the balance of

a growing body of empirical evidence from ecology and agricultural/ecological economics. Furthermore it is easy to reconcile the empirical evidence with theory. The third part of the argument is that reductions in agricultural productivity that are due to the expansion of modern, intensive agriculture are partly externalized by the farmers that cause them. This follows logically from the types of ecological mechanism at play, for example how pests and pathogens operate across landscapes comprising many farms. Together these suggest the expansion of modern, intensive agriculture not only increases agricultural production through the cultivation of more land, it also has a negative effect on agricultural productivity. They also suggest growth in agricultural productivity can be conceptualized as a contest between man-made innovations and biological hazards (Goeschl and Swanson, 2003).

We explore the implications of this contest using a quantitative macro-economic model, which owes its intellectual debts to the micro-economic theory of fertility choice (e.g. Barro and Becker, 1989), especially the trade-off between the ‘quality’ and quantity of children emphasized by unified growth theory (e.g. Galor and Weil, 2000), and endogenous growth theory (e.g. Aghion and Howitt, 1992). To the best of our knowledge this is the first such modeling exercise. Our model is novel in how it integrates these different components, as well as treating agricultural/natural land as a stock and incorporating the biodiversity externality.

Running the model without the biodiversity externality, we project large increases in world population and agricultural output, which is based on continued expansion of the area of cropland, albeit growth in the scale of the economy and food system gradually slows down. In the presence of the externality, population and agricultural output are virtually unaffected, but the policy that maximizes social welfare from the global point of view is one that entirely – or almost entirely, depending on the parametrization of the hazard function – curtails further conversion of land into cropping. Together with diverting labor towards agricultural production and agricultural R&D, this policy is able to limit the welfare cost of the biodiversity externality to a low level. Of course, this result and in particular the role of land-use management does depend on our ‘business-as-usual’ assumption about the damage inflicted by farming practices on biodiversity. In recent years attention has focused on how agricultural practices might be made more sustainable (Bommarco et al., 2013; Godfray and Garnett, 2014; Tilman et al., 2011). This would provide an alternative response option that we do not explore in this paper. The choice has been neatly summarized as being between ‘land sparing’ and ‘land sharing’ (Phalan et al., 2011). Land sparing has been the

traditional focus of policies and measures to protect natural land, while land sharing is often the aim of agri-environment schemes, including payments for ecosystem services.

In any case the feasibility of globally managed population growth and cropland expansion can be questioned, to put it mildly. Therefore we also run the model assuming baseline, decentralized choices on fertility and agricultural land conversion. Without these tools in the box, we find that, while our social planner still attempts to mitigate the externality by diverting labor towards agricultural production and R&D, the welfare cost of the externality is much higher. Therefore there could be much value in being able to manage land use at the global scale. Lastly we evaluate the important assumption about the substitutability of land in agriculture. If land is less substitutable, then the social planner is less able to manage the externality by limiting cropland expansion and again a larger welfare cost ensues.

Although our model is structurally estimated on 50 years of data, the lack of evidence that can directly inform the parametrization of the biodiversity hazard function is a notable problem. For this reason we specify two functions, both of which should be regarded as illustrative. In view of the weight of relevant evidence, obtaining better estimates of this function is a research priority.

Appendix A Structural estimation procedure and model fit

As detailed in Lanz et al. (2016), the seven parameters $\{\mu^{mn,ag}, \chi, \zeta, \omega, \psi, \varepsilon\}$ are estimated using simulation-based structural methods. The moments we target are taken from observed trajectories over the period 1960 to 2010 of world GDP (Maddison, 1995; Bolt and van Zanden, 2013), world population (United Nations, 1999, 2013), crop land area (Goldewijk, 2001; Alexandratos and Bruinsma, 2012) and sectoral TFP (Martin and Mitra, 2001; Fuglie, 2012).¹⁶ In the model these correspond respectively to $Y_{t,mn} + Y_{t,ag}$, N_t , X_t , $A_{t,mn}$ and $A_{t,ag}$. We target one data point for each 5-year interval, yielding 11 data points for the targeted quantity (55 points in total), and use these to formulate a minimum distance estimator.

Specifically, the parameters minimize the value of the following expression:

$$\sum_k \left[\sum_{\tau} (Z_{k,\tau}^* - Z_{k,\tau})^2 / \sum_{\tau} Z_{k,\tau} \right], \quad (\text{A1})$$

where $Z_{k,\tau}$ denotes the observed quantity k at time τ and $Z_{k,\tau}^*$ is the corresponding value simulated from the model. For each parameter to be estimated from the data, we start by specifying bounds of a uniform distribution. For elasticity parameters, these bounds are 0.1 and 0.9 and for the labor productivity parameters we use 0.03 and 0.3. We then solve the model for 10,000 randomly drawn vectors of parameters and evaluate the error between the simulated trajectories and those observed. By gradually refining the bounds of the distribution, this procedure converges to the vector of parameters that minimizes goodness-of-fit objective. This procedure converges and the vector of estimates reported in Table A1.¹⁷

¹⁶ Data on TFP is derived from TFP growth estimates and are thus subject to some uncertainty. Nevertheless, a robust finding of the literature is that the growth rate of TFP economy-wide and in agriculture is on average around 1.5-2% per year. To remain conservative about the pace of future technological progress, we assume it declines from 1.5 per cent between 1960 and 1980 to 1.2 per cent from 1980 to 2000, and then stays at 1 per cent over the last decade.

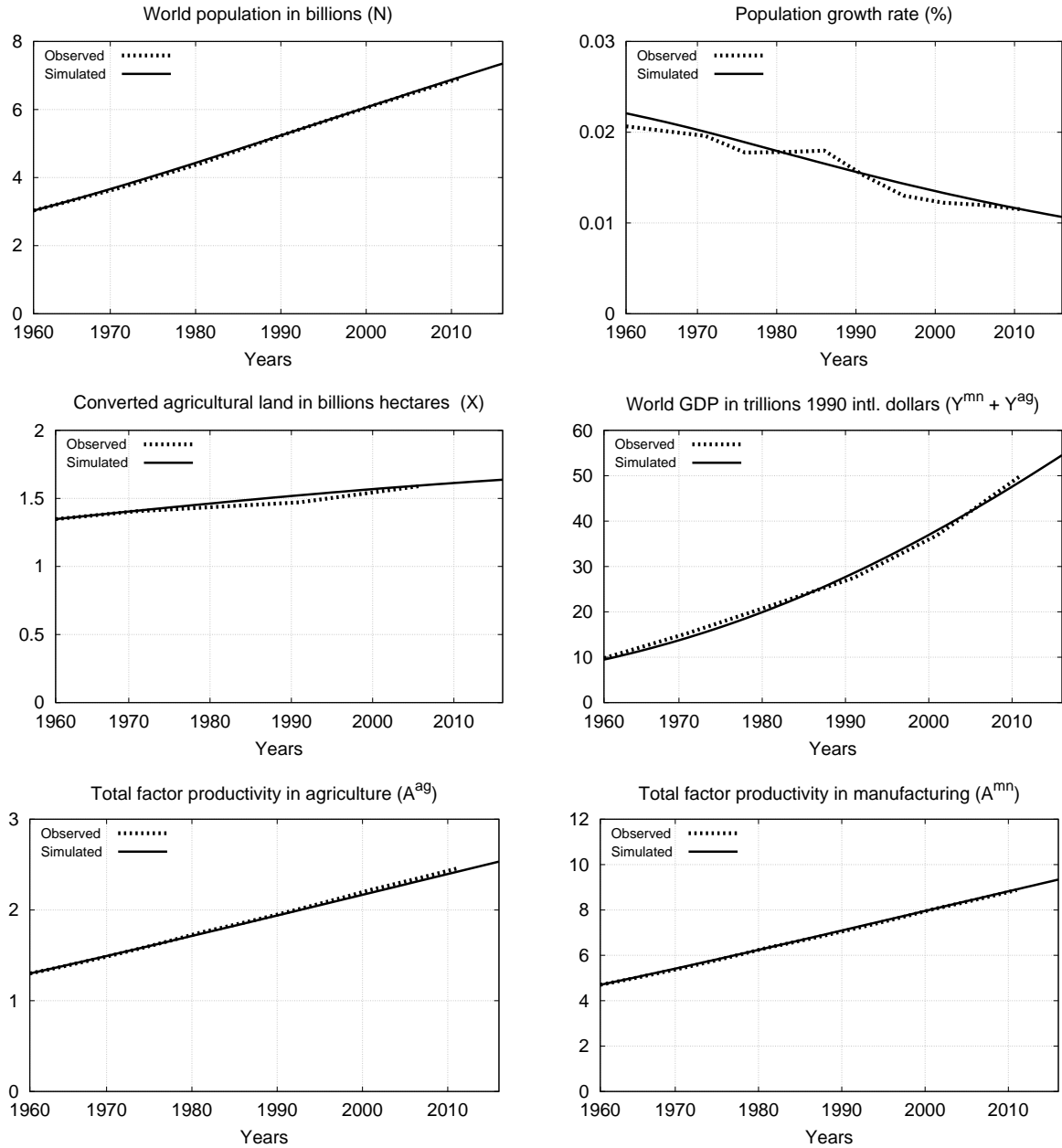
¹⁷ As for other simulation-based estimation procedures involving highly non-linear models, the uniqueness of the solution cannot be formally proved (see Gourieroux and Monfort, 1996). Our experience with the model suggests however that the solution is unique, with no significantly different vector of parameters providing a comparable goodness-of-fit objective. In other words, estimates reported in Table A1 provide a global solution to the estimation objective. This is due to the fact that we target a large number of data points for several variables, and that changing one parameter will impact trajectories across all variables in the model, which makes the selection criteria for parameters very demanding.

Table A1: Estimation results: Parameters

Parameter	Description	Estimates
μ_{mn}	Elasticity of labor in manufacturing R&D	0.581
μ_{ag}	Elasticity of labor in agricultural R&D	0.537
χ	Labor productivity parameter in child-rearing	0.153
ζ	Elasticity of labor in child-rearing	0.427
ω	Elasticity of labor productivity in child-rearing w.r.t. technology	0.089
ψ	Labor productivity in land conversion	0.079
ε	Elasticity of labor in land-conversion	0.251

The resulting fit of the model is reported in Figure A1, which compares trajectories that were observed over the period from 1960 to 2010 with the trajectories simulated from the model. As the charts show, the estimated model provides a very good fit of recent history, and the relative squared error (A1) across all variables is 3.52 per cent. The size of the error is mainly driven by the error on output (3.3 per cent), followed by land (0.1 per cent) and population (0.03 per cent). Figure A1 also reports the growth rate of population, which is not directly targeted by the estimation procedure, showing that the simulated trajectory closely fits the observed dynamics of population growth.

Figure A1: Estimation of the model 1960 – 2010 (source: Lanz et al., 2016).



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