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Interactions between agricultural economics and environmental and resource economics in European research: Insights from the theory of non-renewable resources

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Abstract – Agricultural Economics and Environmental and Resource Economics are two fields which cross-fertilized each other. These interactions are expected to grow in the near future, as the sustainability of agriculture is challenged by the depletion of natural resources. In this article, we focus on three topics in natural resource economics: the resource curse, the sustainable development, and the green paradox. Insights from these topics are then used to discuss the future challenges to be addressed in agricultural economics.

The literature on the resource curse examines the links between resource rent and economic development, and emphasizes that resource richness may jeopardize economic growth. The recent boom in agricultural commodity prices may lock developing countries in a poverty trap if the rent from agricultural products exports is not properly reinvested.

The economics literature on sustainable development emphasizes that defining sustainability is a difficult task, and that there is not a unanimous sustainability criterion to be applied to agriculture. Here again, the question of capital depreciation and investment for future generations is central and calls for the valuation of the capital assets agriculture relies on.

The literature on the green paradox questions the effectiveness of well-intended environmental policies and their possible counter-productive effects. Improperly defined policies, such as biofuel subsidies and mandate, or land use constraints aiming at preserving biodiversity, may result in more rapid resource degradation.

Keywords: agricultural economics, environmental and resource economics, exhaustible resources, growth and sustainable development, green paradox, environmental policies

JEL Classification : Q0

Introduction

Since 1984, the *Review of Agricultural and Environmental Studies* (RAEStud), previously published as the *Cahiers d'Économie et de Sociologie Rurales*, has been following the evolution of both Agricultural Economics and Environmental and Resource Economics.¹ Over the last thirty years these two fields have cross-fertilized each other. Of the 350 economics papers published by *RAEStud*, around 50 can be associated with the field of Environmental and Resource Economics. More than 20 papers are economic valuations of environmental assets related to the agriculture or environmental services provided by agriculture and forests (including landscape and recreational use of rural areas). Slightly fewer than 20 papers examine public policies regulating agricultural pollution or impacts on natural resources (mainly water). The remaining (around 10 papers) study the sectors exploiting renewable resources (forestry, fisheries).

Interactions between the fields of Agricultural Economics and Environmental and Resource Economics are expected to grow in the near future: indeed, the challenges agriculture is now facing are partly related to environmental and resource depletion issues, and the environmental sustainability of the agricultural production system is questioned. Agriculture is asked to produce more food and fuel while respecting the environment and ecosystems (Phalan *et al.*, 2011). Agri-Environmental Schemes (AES) are designed to influence practices and protect the environment. Agriculture is likely to have a growing impact on the environment, while being increasingly dependent on the good health and functioning of ecosystems because of the important role of ecosystem services in agricultural production.

There are many well-established links between environmental economics and agricultural economics (Kling *et al.*, 2010). These include pollution issues (and in particular non-point source pollutions, among other environmental externalities) and efforts to control them by means of public policies, and issues related to the valuation of environmental assets, which can be used to promote the preservation of the environment or natural habitats and biodiversity.

As regards resource economics, links between agricultural economics and renewable natural resources are also numerous (Lichtenberg *et al.*, 2010). In addition to all the interdisciplinary work between economists and life sciences scholars, which have led to tremendous improvements in the representation of agricultural production processes in economic models and the understanding of the effect of inputs such as fertilizers and pesticides, the main links between

¹ The journal has published over 450 articles in economics and sociology, mainly in French, with the first publications in English in 1994. In this article we will not refer to sociology, but focus on Agricultural Economics and Environmental and Resource Economics.

resource economics and agricultural economics concern the optimal use or management of natural resources, such as forest, water and fish stocks.

Links with non-renewable resources economics are less obvious. However, given the current challenges facing agriculture, such as food security (Godfray *et al.*, 2010), global climate and ecological changes, and land scarcity and the exhaustion of arable land (Lambin and Meyfroidt, 2011), defining sustainable agriculture is a scientific question that may have many echoes in non-renewable resources economics.

In this article, we seek to establish whether any insights can be made from non-renewable resource economics literature to improve our understanding of agricultural economics issues. The purpose is different from that of recent surveys adopting a historical perspective on the interactions between the fields of Agricultural Economics and Environmental and Resource Economics (Kling *et al.*, 2010; Lichtenberg *et al.*, 2010; Gerlagh and Sterner, 2013). Firstly, we focus only on the past thirty years, relating the development of these two fields to the existence period and contribution of the journal *RAEStud*. Therefore, rather than adopting a broad, long-term perspective, we consider a few topics in the recent past and the guidance they may provide for future research in Agricultural Economics. Secondly, instead of examining Agricultural Economics' contributions to Environmental and Resource Economics, we adopt the opposite perspective and consider how Environmental and Resource Economics research may influence the evolution of research in Agricultural Economics. Lastly, we adopt a European perspective, focusing on European research teams' contributions to the topics discussed.

Non-renewable resource studies have been shaped by two major rules: Hotelling's and Hartwick's rules, initially formulated in 1931 and 1977 respectively. The former specifies the efficiency condition for the allocation of a non-renewable resource over time. The latter specifies an investment condition to support some kind of intergenerational equity and sustainability. These two rules have recently experienced renewed interest in resource economics studies, in line with two topical trends: climate change policies (through the well-known green paradox) and sustainable development (through the question of genuine savings and the investment of resource rents).

Three research questions that have received particular scrutiny by European environmental and resource economists may be of particular relevance to agricultural economists. The first emphasises that economic booms based on natural resources, including agricultural production, may jeopardise long-term growth prospects. The findings in related literature are at the core of the debate on the resource curse (Brunnschweiler and Bulte, 2008a,b). The second research question is related to the debate between weak and strong sustainability (Neumayer, 2013), which gives us a broader view of the difficulty of defining sustainable development, in particular for the agricultural sector. The third topic relates to the so-called green paradox

and questions the effectiveness of well-intended environmental policies and their possibly counter-productive effects (Sinn, 2012). These three research questions are addressed in turn in the following sections.

Overall, we hope that this short article offers an original perspective by providing insights from the economics of non-renewable resources to shed light on some increasingly important agricultural economics issues. Can agricultural sectors be an engine for economic growth in developing countries now that the prices of agricultural commodities have risen? What is sustainable agriculture? How can we define efficient public policies to mitigate the negative environmental effects of agriculture?

Natural resources and development

Usually, exploiting natural resources has noticeable impacts on the economic development and the rate of growth of resource-rich countries. One of the most debated issues in related literature is whether the abundance of natural resources is a curse or a blessing as underlined by Van der Ploeg (2011) in his survey (see also Torvik, 2009), and European economists have largely contributed to this debate.

There are many reasons why some resource-rich countries (e.g., Norway or Botswana) are far more successful than others (e.g., Nigeria or Venezuela) in generating sustained and balanced growth. Studies have explored not only the long term consequences of specialisation induced by a resource boom in an open economy but also the severity of negative impacts when the quality of institutions is low and corruption is prevalent. They have also shown how parliamentary political systems seem more capable of using resources to fuel growth than presidential systems and nondemocratic political regimes. Lastly, not only do huge resource rents typically increase the probability of inefficient rent grabbing and armed conflicts, but they also lead governments to develop unsustainable policies through, for example, excessive borrowing (Mansoorian, 1991), investments in bad projects or setting up an unsustainable and too generous welfare state, as though resource revenues would last forever. Also, as noted by Van der Ploeg (2011), there is some evidence that labour-intensive resources such as coffee or bananas are less prone to civil conflict than capital-intensive resources.

In this section, we focus on several particular issues: first on the resource-driven impacts on growth through a change in the production structure (the Dutch disease), then on the consequences of resource prices volatility and finally on some of the taxation/savings issues (related to Hartwick's rule).²

² The interested reader could find more on the political economics of resource rents in the survey by Torvik (2009).

The Dutch disease or resource curse

The so-called “Dutch disease” describes the fact that a resource boom in an economy typically tends to make other trading sectors (*e.g.*, manufacturing) less competitive to the advantage of non-trading sectors, because exporting the resource induces the real exchange rate appreciation or equivalently, the appreciation of the relative price of non-traded goods (Corden and Neary, 1982).

This resource-driven expansion of non-trading sectors and decline of trading sectors causes a shift of labour and capital towards the non-trading sectors in the long term. This, in turn, may cause a decrease in learning by doing in the trading sectors and hence their productivity relative to the non-trading sectors declines over time as shown by Torvik (2001). Overall, the growth rate of the entire economy is likely to be permanently reduced following the resource boom. Harding and Venables (2010) recently found empirical evidence of the Dutch disease using data from 135 countries for the period 1975-2007. Clearly, future empirical research may confirm this fact, but it is important that empirical studies also take into account the volatility of resources prices, which we shall now examine briefly.

Resource price volatility

Recently, Aghion *et al.* (2009) suggested that long-term productivity growth can be harmed by real exchange rate volatility because firms are more likely to suffer from liquidity constraints and consequently they tend to innovate less (see also Aghion *et al.*, 2010). This phenomenon is also more significant when the country’s financial system is poorly developed. Van der Ploeg and Poelhekke (2009) argue that this is precisely what often occurs with resource revenues that are typically highly volatile because of the volatility of primary commodity prices. Because there are also other theoretical reasons for why volatility may boost growth (see *e.g.* Aghion and Saint Paul, 1998), the issue needs to be settled empirically. Using cross-country data, Van der Ploeg and Poelhekke (2009) show that the resource curse is primarily a problem of volatility. The volatility of world natural resource prices generates a large volatility of output *per capita* growth in resource-dependent countries and this has a robust negative impact on long-term growth itself. Empirical evidence exists for oil exporters and also exporters of coffee, food, and copper. Moreover, ethnic tensions and civil wars fuelled by resource revenues also increase volatility. Lastly, because a windfall of resource revenues may encourage governments to take bad investment decisions, this also increases volatility as revenue drops inevitably follow at some time. A key remedy is to develop a robust financial system able to cope with the large resource revenues’ volatility, along with openness and physical access to world trade. Indeed, after controlling for volatility, Van der Ploeg and Poelhekke (2009) found a positive direct effect of natural resource dependence on growth. This is an important result in that it indicates that, although it is difficult to lower

resource prices' volatility, it should be feasible to cope with volatility through appropriate policies creating sound financial and political institutions. Some other findings suggest that well-functioning capital markets could help in reducing the effects that shocks in resource share have on volatility. Overall, more research is needed to determine precisely which institutions and reforms are necessary to transform the curse into a blessing.

Resource rent, investment and Hartwick's rule

The final topic in this section refers to the debate concerning Hartwick's rule in resource-rich countries. From a normative point view, it is recommended that countries invest their resource rents into reproducible assets such as human or physical assets (see next section for a more detailed discussion of Hartwick's rule). However, it is typically observed that resource-rich countries do not strictly follow this rule and even can have negative genuine saving rates, meaning that the value of net depletion of natural resources exceeds the sum of public and private savings (net of investment depreciation) and spending in education. Van der Ploeg (2011) suggests that it might be optimal to save less than the resource rents and hence to borrow if the country can expect better prices for the resource in the future or if progress in exploration and extraction techniques can be anticipated. Also, inefficient rent grabbing as well as bad and over-sized investments can contribute to negative genuine saving rates, as does the fear of loss of control over resources that may encourage overinvestment in extraction. Having said this, it is also interesting to investigate how to use resource rents optimally: in developed countries, resource revenues are often put into a sovereign wealth fund but in developing countries it might be more interesting to pay off debt and to lower interest rates in order to boost domestic capital accumulation. Of course, because investment opportunities may be low due to capital scarcity (Dutch disease), it is also interesting to invest resource rents temporarily abroad on financial markets until there are sufficient opportunities to invest domestically (Van der Ploeg and Venables, 2012). From this perspective, whether resource reserves are privately or publicly owned could be of importance for the growth rate and should be confirmed by more research.

Insights for agricultural economists

Small countries exporting agricultural products can be affected by the Dutch disease (Matsuyama, 1992). The recent boom in agricultural commodity prices may trigger the kind of mechanism described above and lock these countries in a poverty trap. This may be particularly true for countries whose growth is based on cash crops (coffee, cocoa, cotton, and, more recently, crops grown for biofuel production). As the price of these resources is highly fluctuating on international markets, these countries may be faced with

short- to medium-term problems in addition to long-term effects on growth. In particular, the boom of cash crops may reduce staple crops' production and enhance local food security problems. Trade-openness and the reliance on international markets for food are then central. Such dependence may jeopardise these countries' sustainable development. The question of recycling the agricultural rent is also crucial. If the rent from agricultural products exports is captured by private interests and not reinvested in reproducible capital (manufactured or human), an agricultural boom will not trigger a development process. Moreover, unsecured property rights on land or rent seeking can trigger land degradation. Short-term cash flows may even jeopardise long-term investment in other crops or sectors, and economic growth may experience a downturn down when agricultural prices fall again.

The sustainable development issue

European economists have played a significant role in the public debate on sustainable development ever since the topic first emerged. It would be impossible to draw up an exhaustive summary in this article, so we have chosen to highlight what seems essential to us, namely the attempt to clarify what is understood by sustainability.

Economists have two main interpretations of this concept, weak sustainability and strong sustainability. The first falls within the neoclassical framework and is an abstract reflection that uses modelling, while the second is characterised by a far more heterogeneous theoretical corpus. For a more detailed vision of these two interpretations, readers are referred to Neumayer (2013). In this article, we focus mainly on weak sustainability, since strong sustainability is not (yet) sufficiently unified for us to summarise it (see, however, Martinet and Doyen (2007), Baumgärtner and Quaas (2009) and Neumayer (2013) for an initial approach).

Characterising sustainable development

According to Solow (1993), sustainability requires that "something be conserved for the very long run". This was initially interpreted as the requirement that a given indicator remains constant (or non-decreasing) along an optimal development path. The indicator is most commonly consumption, utility or an aggregate of the capital stocks (man-made, pollution, human capital...), based on the hypothesis of perfect substitutability between different types of capital. In this line of research, the majority of contributions characterised the optimal path of a representative agent growth model (exogenous and then endogenous growth), integrating various environmental constraints such as the existence of exhaustible resources or pollution. One of the most significant results of this approach is the famous Hartwick's rule (1977) that became the basis for numerous studies by European economists. A

second line of research enjoyed a revival with the publication of an article by Chichilnisky (1996), who addressed sustainable development from an axiomatic perspective, deriving from it a social welfare function that must be maximised to obtain this kind of development. The article met with relatively little success in the United States, and it was not until it was popularised by Heal (1998) that it gave rise to a number of studies, mainly by European economists. These are the two topics that we now address.

Hartwick's rule

As Asheim *et al.* (2003) pointed out, Hartwick's rule is often interpreted as a prescriptive rule, which stipulates that if the total value of net investment under competitive pricing is kept constant and equal to zero, the economy can sustain a constant consumption over time. It was generalised by Dixit *et al.* (1980), who defined a rule of efficiency whereby the net present value of investment under competitive pricing should be kept constant (but not necessarily equal to zero as in the simple Hartwick's rule). If this generalised rule is followed, utility (solely dependent on consumption) will be constant at all times. The second of these results has often been interpreted as a description of sustainability, with Hartwick's rule then being considered a sufficient condition for it. This immediately raises the question of its converse. If consumption along the equilibrium path is constant, is Hartwick's investment rule followed? In other words, is it also a necessary condition of sustainability?

The main contributions from European economists on this topic are described in the books of Asheim (2007) and Martinet (2012). To the above questions, they generally conclude that the answer is no, as Asheim (2013) succinctly explains: "While it is a robust result that Hartwick's rule characterizes efficient and egalitarian paths, it has proven to be an elusive goal to be able to indicate sustainability by the value of net investments as a genuine savings indicator. The value of net investments may be positive even though no positive level of consumption can be sustained. Moreover, even when a positive consumption level is sustainable, neither the scarcity values along the path that the economy actually implements nor the scarcity values along an hypothetical efficient and egalitarian path will produce exact indicators of sustainability. Finally, current markets may not correctly forecast the real scarcity of different capital and resource stocks, in which case the implemented path is not even efficient. From this, it follows that Hartwick's result (and its converse) essentially constitutes a valuable characterization of an efficient and egalitarian path rather than establishing the basis for a useful prescriptive rule for sustainability."

In addition to these theoretical results, Hartwick's rule also poses formidable practical problems, which Martinet (2012) discusses. The first is the hypothesis of a competitive economy with optimal prices from which the rule is derived, a hypothesis that is not verified in practice. For many

environmental assets, markets and therefore prices are inexistent, not to mention other externalities or situations of imperfect information. Lastly and above all, the theoretical framework underlying these results is that of growth models with infinitely-lived representative agents who maximise the sum of discounted utilities, yet this social welfare function implicitly defines what is valued in the economy (what agents seek to maximise, *i.e.* what should be understood by net present value).

Sustainability criteria

There have been two main criticisms against using discounted utility as a social welfare function to characterize a sustainable development path. The first was initiated by Chichilnisky (1996), who axiomatised sustainable development, and the second was developed by Martinet and Rotillon (2007, 2009).

For Chichilnisky, a social welfare function characterising sustainable development should satisfy two principal axioms. The first, called “non-dictatorship of the present”, eliminates the usual criterion of the sum of discounted utilities that gives negligible weight to distant future generations through the discounting mechanism. The second, known as “non-dictatorship of the future”, eliminates the social welfare functions of the “green golden rule” type in which the utility at an infinite time is maximised, which results in protecting the totality of resource stocks. Under these two axioms, to which she adds the axioms of Pareto efficiency, linearity and completeness, she shows that the only social welfare function possible for a sustainable development is a weighted sum of the discounted criterion and the green golden rule. Unfortunately, this criterion does not provide a solution in certain simple models such as the one in which the natural resource is renewable and the discount rate is constant. Figuières and Tidball (2012) take up this problem and show that by limiting the class of admissible controls, a solution can be found that is quasi-optimal (because limited by the restriction). The natural extension of this approach consists in relaxing one or several of the axioms justifying this criterion. This is what Lauwers (2010) does in seeking the maximal Pareto-compatible anonymity condition. Alvarez-Cuadrado and Long (2009) abandon linearity and introduce another social welfare function, which they call the mixed Bentham-Rawls criterion, a linear combination of the standard discounted criterion and the maximin. As well as verifying the axioms of non-dictatorship introduced by Chichilnisky, it also avoids what could be called the dictatorship of the least-favoured generation by introducing the maximin as a component of the criterion. Asheim *et al.* (2012) abandon the strong Pareto axiom to construct a recursive social welfare function. We should also mention the work of Asheim and Zuber, who propose an Extended Rank-Discounted Utilitarian Criterion (ERDU) that treats all generations impartially (Zuber and Asheim, 2012; Asheim and Zuber, 2013). Lastly, Ayong Le Kama *et al.* (2014) show the existence of a social welfare function that satisfies anonymity and Pareto as well as two

new sustainability axioms called the “never-decisiveness of the present” and the “never-decisiveness of the future”, generalisations of Chichilnisky’s axioms of non-dictatorship. Under these conditions, this function allows to obtain solutions in growth models where Chichilnisky’s criterion does not. In the current state of research, it is clear that we are still far from reaching a consensus, from either a normative or a positive point of view, about “the” social welfare function that could characterise sustainability, but this research does give us a clearer understanding of the conditions under which we might hope to achieve this.

The other line of research into the characterisation of sustainability was developed by Martinet and Rotillon (2007, 2009). Pushing Solow’s (1993) point to an extreme, they start from the idea that, if sustainability exists, it requires to “preserve something in the long-term”, but they do not characterize it *a priori*, preferring to investigate whether invariant quantities can be found along the optimal paths defined by a classical representation of an economy with an exhaustible resource. The authors use Noether’s theorem to determine the conservation laws of dynamic systems (see Martinet, 2012, for details) and examine the conditions under which such an invariant might exist and how it could be interpreted as a sustainability indicator. They find that such invariant quantities may exist, but only under very restrictive conditions on preferences and technology. They conclude that the theoretical framework of neoclassical criterion optimisation is unable to characterise sustainability in a general way if one seeks to preserve something over time in the strictest sense of the term.

Insights for agricultural economists

As emphasised above, (environmental) economists are far from providing a unanimous sustainability criterion. Potential criteria, as well as being imperfect, are also far from being easy to implement for real life issues, and thus to the question of the sustainability of agriculture. This leaves us with the two traditional approaches to sustainability and the associated tools to measure sustainability. On the one hand, weak sustainability advocates the use of (shadow-) prices to value all capital stocks, including environmental assets, and compute genuine savings, an aggregate measure of investment in the sustainable productive capacities of the ecological-economic system. Notwithstanding the issue of defining the corresponding prices for the natural assets contributing to agricultural production (this includes the value of soils, biodiversity and ecosystem services such as pollination, pest control, and so on), the resulting indicator is not necessarily an indicator of sustainability when the economy does not follow an optimal constant utility path. Pricing nature may then be both a difficult and futile exercise from a sustainability perspective. On the other hand, strong sustainability recommends the preservation of natural capital stocks, but falls short in terms of theory and provides no framework to define which natural resources

should be conserved and at what level. What are the critical natural resources for a sustainable agriculture? Mixed-approaches, based on viability theory (Martinet, 2012) could be developed. The latter addresses the sustainability issue in quantitative terms by the means of indicators and thresholds representing the level under which the indicators should not fall over time (for example, maximum concentration of greenhouse gases or constraint on land use development in order to protect biodiversity). Using modelling approaches, and ecological-economics models of agricultural production in particular, it is possible to represent the set of sustainable economic and environmental outcomes of agricultural production systems. The frontier of such a sustainable production possibility set represents the necessary trade-offs between sustainability dimensions, and could be the basis for a social choice approach defining what should be sustained for future generations (Martinet, 2011, 2012).

Climate change economics and the green paradox

Climate change is caused by the accumulation of CO₂ and other greenhouse gases in the atmosphere, with CO₂ accumulation mainly due to burning fossil fuel. Greenhouse gas emissions are uniformly mixing, meaning it does not matter where in the world emissions take place. Hence, climate change poses a global externality. There are many studies trying to estimate the damages caused by climate change. This is not easy. For agriculture, for example, it is necessary to distinguish between different regions in the world, because the impact of global warming varies across regions. Moreover, it makes a significant difference whether or not the possibility of adapting to higher temperatures is taken into account. The same holds for forestry. Lastly, estimations depend on the expected degree of warming. At the aggregate level, Tol (2009) provides a table of estimated losses from several studies in terms of percentages of gross domestic product (GDP). They range from -5% (at 3 degrees warming) to +1% (at 1 degree warming). Furthermore, there are large differences across regions³. It can therefore be concluded that climate change should be considered a potentially crucial problem.

There are several ways to mitigate climate change: investing in energy efficiency so as to reduce demand for fossil fuel; stimulating a switch from demand for fossil fuels such as coal and tar sands to others such as gas which do less harm; stimulating the development of renewables, such as biofuels (even if their net effect on greenhouse gas emissions is ambiguous); taking measures to leave more fossil fuel unexploited; encouraging carbon capture and storage; moving from dirty to clean growth. Many of these can be obtained by imposing a well-designed tax on CO₂ emissions, which constitute the main source of the externality. However, in practice, it turns

³ See also Nordhaus (2011).

out to be rather difficult to implement such a policy, and government failure can be observed in many instances. It arises, for example, if dirty fossil fuels such as coal or tar sands are subsidised, or if renewables such as solar, wind energy or biofuels are subsidised. It also occurs if the carbon tax increases too quickly. Well-intended policies such as these aimed to stem the demand for fossil fuel neglect the supply aspect of fossil fuel, and this may lead to more rapid extraction of fossil fuel and the acceleration of global warming. This has been coined the “green paradox” (Sinn, 2008a,b). The idea behind it is simple and is explained in the next section. In the following sections, we discuss several modifications that can and should be made to the basic framework.

Hotelling’s rule with a backstop

Suppose the cost of extracting one barrel of fossil fuel does not vary with the existing stock of fossil fuel. There also exists a carbon-free backstop, a perfect substitute for fossil fuel. It can be produced in unlimited amounts at a constant unit cost, exceeding the unit extraction cost of fossil fuel. In a competitive environment, the constant marginal production cost equals the market price, if renewables are produced. Hotelling’s (1931) rule states that, as long as there is a supply of fossil fuel, the market price *minus* the *per* unit extraction cost grows at a rate equal to the (assumed exogenous and constant) interest rate. Indeed, unextracted fossil fuel is like a capital asset and should earn a rate of return. In this simple framework, fossil fuel and renewables are never on the market simultaneously. At some moment in time, the fossil fuel price will equal the price of the backstop, which then takes over. At that moment, the fossil fuel stock is fully exhausted. With this mechanism in mind we can consider the effect of a subsidy on the backstop. Its price gets lower, so that the price path of fossil fuel has to be lower as well. This implies that extraction of fossil fuel takes place faster: initially there is more fossil fuel use because of the lower price. Hence, initial emissions of CO₂ increase, causing the climate to deteriorate. Moreover, the period over which the resource is exhausted gets shorter. The same phenomenon takes place if there is a tax on fossil fuel that increases at a rate higher than the interest rate. These are illustrations of the green paradox. Policies intended to reduce fossil fuel use have an adverse effect: rather than mitigating climate change, they accentuate it.

Consider now the case where extraction costs depend on the remaining stock of oil reserves. In this case, the more oil has already been extracted, the more difficult it is to extract further; or, the more resource deposits have already been found, the more difficult it is to explore new deposits of the resource. Under this assumption, the situation changes significantly. A (large enough) subsidy on renewables will now have the effect that extraction costs at the moment of the transition are lower, so that more fossil fuel is left in the crust of the earth. Still, initially more fossil fuel

is extracted.⁴ This is why a distinction is made between the weak green paradox (extractions intensify in an early stage of the programme) and the strong green paradox (total discounted climate change damages increase). In the case of no stock-dependent extraction costs, total extraction is unaffected, but discounted total damages increase as emissions occur earlier. With stock-dependent extraction costs, total extraction decreases, but what happens to total discounted damages is ambiguous. One could even go a step further and look at the change in overall welfare, taking into account the distorting effect of the subsidy. For too rapid an increase of the tax rate, the reasoning is similar.

Extensions

Many important issues are not covered by the simple approach outlined above. Here we treat three of them in more detail.

Some fossil fuels such as coal can be considered as abundant and relatively cheap to extract. This does not mean that the green paradox paradigm does not apply⁵. In the market economy where externalities are not internalised, it may take a very long time to make the transition to renewables, but from a social welfare perspective, an early introduction is in order. This would require a high subsidy on renewables or a prohibitive carbon tax to ban the use of coal. This also raises the so-called substitutability issue⁶. Gas can substitute coal in electricity generation. It is also a good substitute for oil in many applications. But oil and gas are not substitutes in electricity generation, nor are oil and coal substitutes in producing petrochemicals. This has to be taken into account when designing climate policies.

It is necessary to consider the climate change problem and the green paradox phenomenon in a dynamic general equilibrium framework. This allows for the endogenous determination of the interest rate, which, as we have seen above, is a crucial variable in green paradox literature. Moreover, a development perspective on the global economy, including capital accumulation and technological progress, allows for a distinction between, on the one hand, economies in an early stage of development, where material consumption is likely to be more important than the negative effects of climate change, and, on the other hand, mature economies where this is the reverse. Van der Meijden *et al.* (2014) show that in a general equilibrium the green paradox is likely to be attenuated, although situations exist where it is reversed. Van der Ploeg and Withagen (2014a) consider the green paradox in an extended Ramsey growth model⁷ and provide a full description of the

⁴ See Van der Ploeg and Withagen (2012a).

⁵ See Van der Ploeg and Withagen (2012b).

⁶ See also Michielsen (2014).

⁷ See also Golosov *et al.* (2014).

optimal path of capital and CO₂ accumulation. They show that a subsidy on renewables leads to less fossil fuel left in the crust of the earth, but at the same time it has a distortionary effect, which may be especially harmful if the economy is still in an early stage of development, with a high marginal utility of consumption and lower marginal disutility from global warming.

A third extension concerns introducing multiple jurisdictions. It has to be taken into account that the world consists of multiple different countries or blocks of countries, each having their own preferences, with more or less weight attached to global warming. Hoel (2011) and Eichner and Pethig (2011) look into this and analyse the various possible outcomes of unilateral actions. It is found that country heterogeneity may have drastic effects on the optimal policy and the green paradox.

This section gives a brief account of the so-called green paradox⁸. A description of the basic mechanism has been given and some extensions have been briefly discussed. Many other related topics remain to be investigated or have not been treated here. They include learning by doing, strategic interaction, the modelling of damages, to name a few. An important issue, of course, is how relevant the green paradox is for actual green policies. Unfortunately only very few empirical studies exist (Di Maria *et al.*, 2014; Fischer and Salant, 2012). In view of the large scale introduction of solar and wind energy in some countries such as Germany, the policy relevance of empirical research is obvious.

Insights for agricultural economists

Are there green paradoxes related to agricultural and environmental policies? When considering public policies designed to mitigate the effects of agriculture on the environment, or other environmental policies such as biofuel-promoting policies or ecological conservation policies, it is highly probable. A first such paradox has been emphasised for biofuel policies. When agricultural production is reallocated from food, feed and fibre markets to energy markets (or when one changes the type of crops to produce energy crops, in other words, a direct land-use change), market substitution effects may trigger an increase in prices and an incentive to put new land into production (Havlik *et al.*, 2011). These indirect land-use changes may lead to land being cultivated that was storing a large amount of carbon (grassland or forests), emitted at once and creating a carbon debt undermining the performance of biofuel to mitigate climate change.

It has also been shown that a conservation policy based on setting aside land for natural reserves may have a type of green paradox effect: when

⁸ For more elaborate surveys see Van der Werf and Di Maria (2012) and Van der Ploeg and Withagen (2014b).

anticipated by agents, the policy that results in a reduction of land available for other purposes leads to an increase in land rent, and thus an increase in land price. When the land is actually put into a reserve, its price is higher than scheduled and less land can be protected for a given budget (Armsworth *et al.*, 2006). This effect occurs because land is a non-renewable resource, whose scarcity is increasing. Worse, in some cases, policies imposing constraints on some habitats, such as the preservation of grassland after a set date, may provide an incentive for holders to convert the habitat before the constraint applies.

Final comments

This article has presented three topics of non-renewable economics and discussed potential links with agricultural economics. We believe that many more insights for agricultural economists could be drawn from resource economics literature. Agriculture relies on natural resources and ecosystem services, such as land, soil and organic matter, water and phosphorus. It will be faced with many forms of scarcity and non-renewability in the future. In particular, the overexploitation of soil's productive capacity is shown to be an emerging concern (Montgomery, 2007; Pimentel and Burgess, 2013). 2015 has been declared the International Year of Soils by the Food and Agriculture Organization. Many issues related to the overexploitation of natural resources have already been examined by resource economists. This calls for strengthening collaborations between agricultural economists and resource economists.

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