

Green growth and the efficient use of natural resources*

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*Reprinted from

Energy Economics, 34(S1): S85–S93

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Reprint 2012-31

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ARTICLE INFO

Article history:

Received 24 January 2012
Received in revised form 12 June 2012
Accepted 30 August 2012
Available online 18 September 2012

JEL codes:

Q
C68
C81
D58
O44

Keywords:

Green growth
Environmental accounting
Environmental degradation
Environmental policy
General equilibrium modeling
Depletable resources
Renewable resources

ABSTRACT

The relatively new concept of “green growth” can be fruitfully connected to concepts and theories in neoclassical economics including market externalities, Ricardian and Hotelling rents, and policies that would correct externalities such as Pigovian taxes or a cap and trade system set to achieve emissions reductions consistent with cost benefit assessment. Partial equilibrium concepts have been extended to general equilibrium models, including their realization in relatively detailed empirical models that faithfully adhere to theoretical concepts of neoclassical economics. With such models we are then able to see how resource depletion and environmental degradation are affecting the economy, and how efforts to reduce the impact of these environmental and resource constraints could improve economic growth and performance. The foundation for traditional computable general equilibrium models are the National Income and Product Accounts (NIPAs), input–output (I–O) tables, and expanded Social Accounting Matrices (SAMs). The basis for extending these to include environmental and resource assets and goods are so called Integrated Economic and Environmental Social Accounts (IEESAs). While environmental effects are often considered to be “non-market,” many of the impacts of environment are often reflected in market accounts through damages that might include, for example, less labor (due to environment related health problems), reduced productivity of agroecosystems, or damage to infrastructure and other produced assets. The challenge is to make the environmental connection explicit so as to provide a guide to where changes in policies could provide benefit. However, some damages do not enter the accounts at all, and mainly this is because household labor and leisure time are generally not valued in traditional accounts. Hence the cost of illness in terms of reduced ability to contribute to household activities would be missed in the standard accounts. While the theoretical structure for expanding the accounts has been laid out in various reviews, the empirical challenge of doing so is substantial. Careful attention to expanding NIPA accounts, making it a regular part of government statistical agencies’ efforts would improve the foundation for analysis of potential “green growth” policies and measures.

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1. Introduction

Various terms have become recently popular in political circles to describe efforts to improve the environmental performance of the economy, including “green growth,” “green jobs,” and the “green economy.” While precise definitions differ (or may not exist), most users of the terms at least imply a switch to more reliance on renewable resources, which is then seen as more sustainable than relying on depletable energy and mineral resources. More broadly, the push to green economic growth expresses the intention to direct the economy toward technologies and consumption patterns that, while creating jobs and economic growth also reduce the impact on the environment. Less clear is whether green growth is concerned with the effect of environment and environmental policies on equity. If not, it

would argue that it should. However, the general issue of equity—is the current distribution of income equitable, and what policies and measures might improve equity—is probably so vast that it is usefully separated from green economy issues, which first and foremost bring to mind environmental and natural resource issues. Where policy and regulatory intervention is needed to redirect the economy toward “green growth,” and particularly where effective intervention requires coordination across many countries or the entire globe, political consensus requires attention to the perceived if not actual fairness of the outcome. And, technically, efficiency and distribution are not separable.

While the term “green growth” is quite new, from the perspective of environmental and resource economics the problems it addresses have a long history, and as such it is mostly old wine (some very old) in new bottles. Since Pigou (1932) and Coase (1960), economists have been concerned about potential environmental externalities as they might lead to over-use of environmental goods; whether and how they might come to be reflected in market decisions to improve

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economic performance; and the effectiveness and efficiency of tools public policy makers have to try and correct them.¹ Economists have also long been interested in potential problems associated with scarce resources. Here, the seminal contribution on exhaustible resources is that of Hotelling (1931), who concluded that with private ownership market forces would efficiently allocate such resources over time. Observations on pricing and efficiency of a renewable resource go back even further to Ricardo (1817), from which we get the term “Ricardian rent” reflecting the pricing of a scarce renewable resource. These papers are in the neoclassical tradition of rational agents, or in the case of Ricardo predating neoclassical economics, but the Ricardian rent concept has survived. More recently, the consolidation of different threads of economic theory and observation under the term behavioral economics as reviewed in Mullainathan and Thaler (2001) offers some cautions about trusting markets to deliver efficiency given the limits of human rationality. However, issues identified under the rubric of behavioral economics only add another source of potential market failure to be concerned about. This does not change the basic conclusion that in the absence of consideration of externalities there is at least the potential that intervention of some kind can improve economic performance.

One would also be remiss to ignore the current economic recession that afflicts many parts of the world, particularly Europe and the US. It is likely this condition that has led to a focus on linking environment to jobs and growth. Of course here, while there are many debates among macroeconomists about efficacy, Keynesian policy—stimulatory spending to spur an economy out of a recession—remains a principal tool of economic policy. In the absence of sufficient private demand, government spending is intended to stimulate economic activity, putting people to work (doing anything), until, with more money in people’s pockets and confidence in the economy, private spending takes over. From the standpoint of such “pump priming” it doesn’t matter what the spending is for, but if the money is spent on investments that are actually useful, then in addition to stimulation, the economy can reap additional benefits over the longer term.

I do not intend to address the possible role of using stimulatory spending to invest in the “green” economy—that is a major undertaking in itself. But here I note that a major key to economic growth is improved labor productivity—producing the same amount of goods with less labor. This can be accomplished through capital deepening—investment that raises the amount of capital per worker—and through labor (and capital) saving innovation. In a period of high unemployment it can seem almost perverse to be focused on labor-saving productivity and

investment—which would seem to “destroy” jobs. However, higher productivity is key to competitiveness and allows real wages and returns to capital to rise, and with higher income comes increased demand for goods that give rise to economic growth. In other words, there is no growth without improved labor productivity—we would never have escaped a life of subsistence had we not found ways to reduce labor needed for basic food and shelter. So economists generally separate macroeconomic problems of keeping the economy at full employment and issues of economic growth and productivity improvement over the longer term.

Goals of creating 10s of millions of high-paying jobs in green energy sound good when we are facing high unemployment, but such goals are at odds with long-term productivity improvement. Expenditure on energy accounts for only a few percent of the economy—and it is relatively capital intensive and so employment in energy is a few percent of the economy. The imagined 10s of millions of green energy workers are a much larger percentage of the labor force than currently, and thus energy costs would need to rise substantially to pay the wage bill. So the danger of focusing stimulatory funding on high-labor, job-creating green energy is that we direct the economy to energy sources that, once government subsidies and funding are removed, cannot survive in the market, even with proper pricing of externalities associated with the “brown” economy. In that case, the stimulatory funding may have done its primary job of stimulating the economy but left us with nothing more than if it had been directed toward digging holes and filling them in.

Leaving aside recession and unemployment, we must remember that the goal of an economic policy is the efficient provision of goods and services. That said, where those goods and services include “non-market” environmental services, the challenge of measuring the efficiency of outcomes is great. Even in conventional neoclassical theory the welfare criterion for an efficient outcome is not as clean as often portrayed. As pointed out by Samuelson (1955), since the welfare of a nation is not independent of the income levels of individuals in the country, and any intervention is meant to change the level of income, there is in fact no stable social welfare function. Acknowledging this leaves us without an objective welfare criterion. Even ignoring this critique, at best we can find potential Pareto improvements where an actual improvement depends on a policy design that may include compensation so that no one is worse off from the change and at least someone is better off.

My main point: Conventional economics has grappled with the issues of concern green growth is meant to consider. A, if not the, main thread of the discipline has been to consider ways in which governments might intervene to improve economic performance. That is not to say economics has all the answers, but at least it has sifted through the issues over many decades. While there may be room for theoretical advance, the principal obstacle I see to the challenge brought by green growth is to bring empirical analysis of the many environmental issues into focus—what can we say about where markets are failing, the magnitude of the failure, and the possible remedies?

What are the tools available and advances economists have made? On the empirical side, economists have extended analysis of the environment to incorporate it more fully into models of the economy based on firm neoclassical economic foundations—computable general equilibrium models. These mainstream tools of economic modeling had typically included only labor and capital as factor inputs, with natural resources only implicitly included in returns to capital. As such these resources were reproducible—more investment in these models leads to a greater capital stock, implicitly suggesting that land and more mineral resources could be produced at constant marginal cost, and thus depletion and resource limits would place no drag on the economy. While obviously not a physically accurate representation of the world we live in, in fact, through investment (lumping R&D with general investment) the world economy has been incredibly successful in effectively creating “more” natural

¹ An anonymous reviewer has questioned whether this concept of correcting externalities that improve economic performance is equivalent to the current political claim that such actions can spur growth. These early partial equilibrium environmental problems are largely static analyses, and so economic growth (over time) is not explicitly considered. In such a static analysis a bargained outcome that reaches a higher level of economic performance is “growth” in the context of a one-period (static) economy. In a dynamic setting, where the economy is growing and an uncontrolled polluting sector of the economy is also growing at the same rate of the economy, and marginal damages of pollution are increasing, then pollution damages will degrade economic performance at an ever larger share of the economy, slowing growth, properly measured. Hence, correcting this externality will improve growth. If the polluting activity is affecting market activities—e.g., the upstream polluter forces downstream industry to install costly water clean-up technologies, and it would be less costly for the upstream polluter to control pollution—then benefits of pollution control will be observed in measures of market economy growth. If the pollution mainly affects non-market activities—e.g., a downstream retirement home—these effects may not be seen in the market economy but would be seen in a properly expanded accounting system that valued the health and well-being of non-work time. In a less formal sense, if a regulator pursues a phased-in pollution control program and these benefits are only realized over time because of gradual phase-in or because of the stock nature of the pollutant, then this will result in improved economic performance over an extended period of time—improved growth. Of course, the key here is that these actions meet a properly evaluated cost-benefit calculus, and that the measures implemented to achieve the reduction are cost-effective. Thus, the distinction between improvement in growth versus economic performance in a static setting is at least fuzzy, if not non-existent.

resources though resource-augmenting technical change. While there is only so much land on earth and only so much known high-grade mineral resource, through R&D we have found ways to make each unit of land produce much more at no higher cost, and we have discovered new mineral deposits and invented ways to economically recover lower grade resources. The result has been that over the course of most of modern economic development—dating to the industrial revolution—food, energy, and mineral prices have mostly exhibited a long term declining trend, albeit with the exception of shocks where prices have temporarily spiked. This decline in prices occurs even though we are obviously depleting resources and utilizing more of the earth's surface so that, without technological change, we would be moving toward less suitable surface resources, even if renewable. But, if we really want to investigate the potential implications of resource limits, we cannot have a model that assumes there are none.

With the broad introduction above, I will in the remainder of the paper focus on the empirical advances and challenges in accounting for the environment in our management of the market economy. The next section discusses the challenge of measuring green growth. I then illustrate the role of renewable and exhaustible resources in growth in a simple economy, linking it back to the accounting structure. Finally, I describe recent advances in expanding models of the economy to better include natural resources and the environment and their effects on growth and efficiency.

2. Measuring green growth

One of the major criticisms leveled by those concerned about appropriate accounting for the environment is that the widely used measure of Gross Domestic Product (GDP) fails to account for resource degradation and depletion, and that therefore growth may be unsustainable. Several major panels have convened to investigate and recommend approaches for broadening the accounts, including the US National Academy of Sciences (Abraham and Mackie, 2005; Nordhaus and Kokkelenberg, 1999) and an international review conducted by the Commission on the Measurement of Economic Performance and Social Progress (Stiglitz et al., 2009). The later efforts include environmental considerations but address a far broader set of issues in moving the accounts toward measurement of well-being rather than production. Putting the problem in easy-to-understand terms, if you were to measure your family's well-being by how much you were consuming but ignored the fact that your level of consumption was maintained by drawing down or borrowing against assets, you would be misled when the day came that those assets were depleted and loan payments were due. Your consumption level is not sustainable. In fact, GDP is the wrong concept to focus on for this purpose. GDP is defined as the sum of aggregate household consumption (C), aggregate investment (I), government expenditure (G), and the difference of exports (X) and imports (M). As such, it is an accounting of the *annual flow of marketed* goods and services produced within a country in a year. The companion concept of Net National Product (NNP) defined as C plus I plus G plus Net Foreign Earnings less Depreciation is more appropriate, and under special circumstances is consistent with a concept of sustainable income. The proof and conditions under which there is a correspondence between NNP and sustainable income goes back to Weitzman (1976) and attention to it given in the wake of concerns about sustainability by Solow (1992). For purposes of green growth, an important condition for this correspondence is that it covers all goods and services, and so the omission of key environmental goods and services is a weakness. The main point: We need to focus on NNP rather than GDP and then see where it falls short.

In fact, the overlap of what is included in these two concepts is large, and for most economies the C + I + G component is so dominant that growth rates of either, especially over several years are very similar. But if one is concerned about sustainability the inclusion of depreciation is important. NNP would reveal if we were keeping GDP growth high by

using up produced (market) capital and not replacing it in any year where depreciation exceeded investment, whereas GDP would not. Albeit, if indeed we are drawing down capital eventually our ability to produce goods would fall and so would the GDP. If your family is sustaining consumption levels by drawing on savings or selling assets, you could only keep that up so long and eventually you would face lower consumption. The benefit of examining your asset balance is that you can take earlier action to bring consumption to a sustainable level, in line with earnings from wages and returns to assets. If you were to burn through all of your assets and take on debt, then your sustainable income would be less than if it you were spending only what you earned from wages and returns to assets. NNP, by including depreciation, includes a measure of the change in assets.

Why the strong focus on GDP in the media and popular press? One argument is that actual depreciation is very hard to measure and so just measuring goods and services produced in the economy is a more reliable measure (Nordhaus and Kokkelenberg, 1999). Focus on GDP is often directed toward business cycle phenomena—whether we are in or entering a recession—and that is a problem of short-term unemployment of resources much more closely related to production levels—whether we are fully utilizing the capital stock and labor resources. For such concerns GDP is an appropriate measure (Stiglitz et al., 2009). So understanding how we go about correcting measures of economic performance to make them “green” involves first understanding that the GDP concept is not the appropriate concept, and that other elements of the National Income and Product Accounts (NIPAs), appropriately expanded, should be the focus.

Here, the first thing to recognize is that many aspects of the environment are actually reflected in market accounts. Effects of air pollution in terms of damaged crops or illness that prevents people from working are seen as less agricultural output and less labor, respectively, and therefore less production of goods and services in measured GDP. The effects of depletion of resources will show up as gradual slowing of GDP as some combination of less of the goods produced from these resources (e.g., less oil, coal, natural gas) or more capital and labor devoted to producing them so that there is less capital and labor available to produce other goods. So here, the problem is not that GDP or the broader accounts fail to include the effects of resource depletion and environmental degradation but rather that they are not explicit about the contribution of depletion, degradation, and environmental change to the measured market production of goods and services. So like your family living beyond its means, if we as a society are depleting natural resources and degrading the environment, and those resources affect our ability to produce goods and services, the effects will show up in slower growth of consumption. But if we do not count depletion and degradation in NNP, then we may be living beyond our means, and as consumption starts sinking because our assets are depleting we may have no clue as to why they are falling.

Amending the asset accounts of the NIPAs has been identified as a main goal of Integrated Environmental and Economic Satellite Account (IEESA) system in the US and there have been various efforts in different countries undertaken by statistic agencies our outside analysts. The US Bureau of Economic Analysis (BEA) took a first stab at amending the US accounts, publishing in 1994 accounts for 1987. On their publication, Congress directed the BEA to suspend this work and seek external review of their approach, which led to a National Academy report cited above (Nordhaus and Kokkelenberg, 1999). The initial IEESA produced for the US had laid out an approach and identified the types of assets to include, but only provided actual values for some of the identified categories. Broadly the categories were a set of Produced Assets including “made assets” and “developed natural assets” and a set of Non-Produced Assets. Of course most of the capital stock normally accounted in asset accounts are produced assets, and so the IEESA in these cases, mostly attempted to separately identify those made assets and inventories related to environment and natural resources. This separate identification of

assets related to natural resources and the environment thus did not change the bottom line of the accounts for the most part. The categories included pollution abatement investment, water supply facilities, conservation investment, sanitary services and the like. The inventory accounts identified mainly inventories of agricultural crops. Developed natural assets included livestock, fish, crops not yet harvested, proved subsoil assets (oil, coal, gas, metals, and other minerals), and developed land. Non-produced/Environmental Assets included uncultivated wild biological resources (e.g., wild fish stocks, timber), unproven subsoil assets, undeveloped land, water, and air. More recently, the [World Bank \(2011\)](#) has made an enormous contribution to this discussion by developing extended accounts for most of the countries of the world.

As noted, the results did not affect the bottom line, almost by design, because it largely made explicit environmental and resource assets that were already accounted for in other Produced Assets components. Depletion of oil, gas, coal, and other subsoil assets represented some of the biggest numbers and could have had a more substantial effect on the accounts, but because estimates were only given for proved subsoil assets any effect was small, and even positive for some. How can depletable assets increase? Proved resources are more akin to a measure of inventory, where for the most part new resources are constantly being proved to replace those that were produced. So entries for depletion were mostly offset by capital formation reflecting the value of newly proved resources. Where newly proved resources were greater than depletion, the total stock actually rose resulting in positive adjustment for NNP. While the quantity and value of unproven depletable resources are very uncertain, we know for sure they are mostly being depleted because the process of replacing them occurs only over millions of years. So leaving blank the entry for unproven subsoil assets took away an entry that would have likely led to a negative effect on NNP and would be more in keeping with expectations about how depletion of resources could be undermining the sustainability of income.

Also, the BEA chose to value degradation of undeveloped land, water, and air at the actual amount spent reversing degradation in that year. As a result, the value entered for degradation was exactly offset by the entry for capital formation. So implicitly they assumed the quality of these resources was unchanged. Here, attempts are needed to actually measure the effects of air pollution and value them rather than use costs of mitigation as a measure of impact. In the case of land, any changes were often dominated by “revaluation” and other changes. The problem here is that for scarce assets that are growing scarcer we expect prices to rise, and so if that is the source of revaluation, there is no more land in any real sense. In this regard, the accounting problem is identical to that created by technical change. When completely new goods are invented that may improve our life dramatically, it is hard to appropriately calculate the added value. Air conditioning, air travel, instant messaging, and cell phones have no directly perfect comparison. If technical change reduces the cost of producing a known good, we can value that easily enough because the quality of the good is unchanged, but when both the quality or nature of the good and price are part of the package there is not a simple approach to measuring the value of that quality change. Similarly with revaluation of natural resources, we have multiple confounding factors: increased scarcity, degradation, and technical change as well as changing expectations about the future.

If innovation is making land more productive, that could result in a change in value—in fact a decrease in value if it made land less scarce—but one that should be a positive contribution to NNP.²

² Such innovation could lead to an increase or decrease in an open economy. If the productivity enhancement only applied domestically, or particularly favored domestic resources, one could see a general decline in land values for the world reflecting reduced scarcity. Meanwhile, domestically land rents could rise, more than offsetting the global decline. If the innovation was more generally applicable worldwide, then land rents would likely decline everywhere and the lessening of scarcity would show up as a negative revaluation.

Similarly, innovation may make previously inaccessible, depletable resources potentially available and hence the total “economic” resource larger. More effort is thus needed to sort out the cause of the revaluation and to deal with the amount and value of unproven resources. While many of the entries in the initial US IEESA were left as “not available,” subsoil assets and air and water quality were probably the most important in terms of value, but more or less by design, the methods chosen to deal with them resulted in little if any change to the bottom line. The initial US IEESA was a first attempt to demonstrate the concept, the framework set up was useful, and it helped identify important questions of how to proceed with valuation. Unfortunately, while creating more complete and regular IEESA accounts remains among goals of the US BEA, it has been relatively far down the list of priorities and has lacked funding. As a result there has been no attempt by the US BEA since 1994 to further the development of the accounts.

Probably the main issue demonstrated in the IEESA attempt in the US is that if one focuses on assets already valued in the accounts, then environmental accounting may simply identify the contribution of environmental change to changes in the value of assets without changing the bottom line. In other words, the market effect of environmental change is already reflected in asset values. Even so, this can be an important contribution. If your family assets are dwindling, not because they are being consumed but because of some outside force, knowing which asset is losing value and why may help you to correct the problem.

Where the accounts may miss completely the effect of resource depletion and environmental change is in the use of non-marketed resources in non-market activities. The best examples of non-marketed goods and services are self-provided household goods and services. The biggest missing resource is the value of household labor. A modern household that provides its own meals, is purchasing food, paying for water and electricity, and has purchased appliances needed to accomplish this household activity. So those parts of self-provided food service are measured in national accounts when they are produced and households purchase these goods. What is missing is a valuation of the household members' time used to prepare the meal. Even where food is self-produced, the main non-measured input is likely the labor involved in raising the food, although using market prices for that food may be a preferred way of indirectly valuing the labor.

The exclusion of household labor allows the possibility that GDP will change depending on whether household services are purchased or self-provided. Nannies, chauffeurs, purchased lawn care, and cleaning services, and the labor involved in providing purchased transportation are included in GDP because these people are counted as part of the labor force and are paid a wage. If these services are self-provided by the household, they are not. Thus, a trend toward increased monetization of household activities—more purchased and less self-provided services—adds significantly to GDP, but much of that addition is only shifting from self-provided to purchased service.³

Are there mis-measurement issues with natural resources (e.g., land and mineral resources) and the environment (e.g., air and water quality)—items that just are not valued at all, directly or indirectly? As noted above to the extent the services of natural resources and the environment are reflected in market goods, they are already measured in consumption and in many asset values. Favorable climate and clean air that lead to bountiful crop production and a healthy population mean more agricultural goods for consumption and a population that is able to provide labor services. Thus, measured market consumption

³ To be sure, such a shift would be expected to increase welfare—the choice to work more outside home would, under normal assumptions of rationality, reflect the individual's assessment that the market wages earned more than offset any cost of replacing those self-provided services in the home (or doing with less of them).

will be higher than if the climate is harsh and the air damaging to crops and health. Similarly, land that is in favorable climates, and hence more productive, has a much higher value. An economy that is degrading its climate and air or water quality will find it increasingly difficult to maintain production and consumption, and hence we will tend to see lower consumption levels than if the degradation had not occurred.⁴ Indeed, many methods for valuation of non-market goods actually rely on the fact that when the supply of the non-market good changes, there will be evidence of these changes in the market. Farmers will need to purchase more inputs to overcome yield losses or we will simply see yields decline. The market places a value on that yield loss, households spend more money on health care and hospital visits, additional costs will be borne to provide clean water or more incidences of illness related to poor water quality will be observed with consequences for labor and the economy.

But wait—are these examples of spending more money to correct environmental problems? Is environmental degradation actually leading to an increase in GDP because of all the extra spending to correct the problems created by resource degradation? This is mostly not true because allocation of more resources to maintain the same level of things like health or crop yields means fewer resources used to produce other goods. However, the accounting can go wrong when resources we *do not count* are used to make up for environmental degradation. So, for example, if environmental degradation affects the health of a family member and they are unable to continue self-provision of household services the loss of household services will not be counted, whereas if they cannot go to work, that will show up as lower labor productivity and less output, unless the economy makes up for losses due to environmental degradation by shifting labor from self-provision of household services to paid labor. In that case, the environmental degradation would then perversely show up as an increase in market consumption. Again, take our family example, if the household makes up for illness in the family by hiring household help (and that results in an increase in paid hours worked in the economy) the air pollution damage would then be seen as a GDP or NNP increase.⁵ However, this depends on there being an actual increase in market labor. If the supply of labor is completely inelastic, then the additional labor hired by this family will simply crowd out some other activity, and there will be no net increase in measured GDP or NNP. So to account properly for the impact of the additional demand for labor due to environmental degradation we need to know something about the labor supply elasticity—how much more labor will be supplied to the market, meaning loss of non-market labor/leisure. Of course, if we counted the value of non-market labor in the accounts, then any reduction there would be registered as an offset to increased market labor. The conclusion here is that failure to measure household labor, which at first appears to be a completely separate issue from environmental accounting, can actually lead to misleading GDP changes due to environmental change.

In the example of air pollution above, we focused on the effects of the pollution on the current accounts—what it was doing to health and the provision of services in the current year. There also may be effects that are reflected in asset values. Here, one of the more problematic aspects of the accounts is that there is no human capital asset. Labor is seen as purely a flow of services, yet clearly there are environmental health effects that lead to death or long-term illnesses. These reduce labor available for the economy in the current period, and may demand additional resources allocated to care, but these

also imply reduced labor and additional medical care in future periods and so these ought to show up as a “depreciation” of human capital.

The potential for a variety of stock and flow effects of environmental change were described generically in a review of green GDP accounting (Nordhaus and Kokkelenberg, 1999) and are repeated below in Fig. 1. Following the outer solid circle, anthropogenic pollutants (and possibly natural sources of these same substances) contribute to increasing stocks of polluting substances in the environment, and those stock levels affect economic assets which in turn affect the flow of services from these assets. For a broadened Green NNP accounting depreciation or degradation of economic assets (or appreciation and improvement if pollution were reduced) changes in the value of these assets should be included. Changes in the stock of assets should also be reflected in the accounting of current economic activities. An example would be emissions of long-lived greenhouse gases that accumulate in the atmosphere and change the climate, where this change in climate leads to damage of coastal infrastructure. The loss of coastal infrastructure then reduces measured consumption in the current year and over what would have been the life of the infrastructure. Or, following the outer dashed circle, the accumulating pollutants may affect current economic activity directly, such as if climate affects crop yields. If these lower crop yields were expected to continue land values would also be affected. The middle solid circle of the figure admits the effect of short-lived pollutants, that while not accumulating in the atmosphere, may affect economic assets and again, through this channel, current economic activity—acid deposition leading to deterioration of buildings and the service flow from them, or pollution that results in death, for example. The interior circle also represents short-lived pollutants that affect current economic activities directly—high levels of tropospheric ozone or particulate matter that damage crops or cause short-lived respiratory problems, for example. If these short-lived pollutants disappeared, the pollution and resulting environmental damages would go away very quickly, however, the pollution may be related to longer run investments in power plants and transportation systems that are not expected to go away, and are thus also reflected in related asset values such as housing prices in polluted areas or cropland values.

Where the economic activities and assets are valued in the market, the actual damage and expectations about future damage should be reflected if investors look forward. While that is a big “if,” it is also one of the additional requirements for a direct correspondence between NNP and sustainable income. This problem also potentially affects traditional produced assets. If investors expect a tight climate

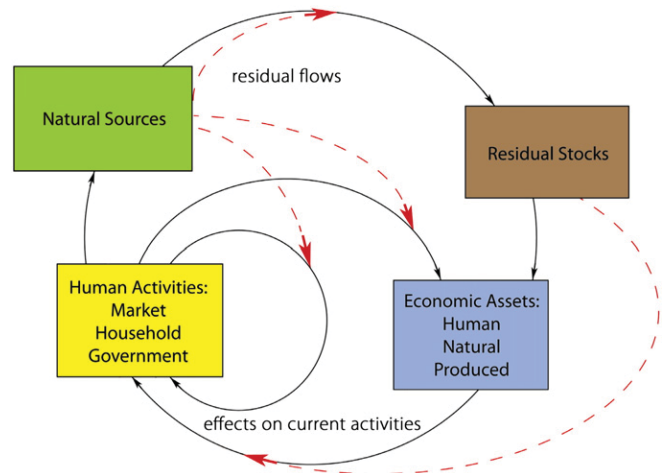


Fig. 1. Human activities, residuals, and economic assets. Based on: Nordhaus and Kokkelenberg (1999).

⁴ Assuming an efficient level of environmental quality was provided.

⁵ If paid hours worked in the economy do not increase then the addition of wages paid by this family will be offset by fewer wages paid somewhere else and the net effect will be zero, the same as if the household did not make up for the loss through purchased services. However, if the extra demand results in more labor supplied to the market, this will show up as an increase in economic consumption.

policy in the near future, the value of coal power plants would fall. That should, if counted correctly, show up as rapid depreciation. But doing this correctly, even for traditional produced assets, is a problem that dogs statistical agencies responsible for these accounts. If markets do not fully or correctly incorporate the future effects, then the valuation problem is muddled because models or other assessment would need to make these valuation changes. These models would need to determine where the market was (partially) taking these effects into account so as not to partially double count.

The main conclusion of this section is that GDP is not the right concept for most concerns about green growth, and that, instead, the NNP concept is more relevant. While NNP is incomplete in terms of covering environmental and resource issues, many of the environmental and resource depletion effects should already show up in measured NNP, but they are likely not explicit. Efforts to expand accounting for environmental and resource effects to create a Green NNP would be reflected in two ways: (1) effects are already recognized as part of an expenditure or asset and can be identified without affecting the total, and (2) others that are not included at all in existing measures, and must be added. Here the large omissions are household labor, and valuing human capital. It may seem odd at first, that concerns about environment and natural resources would lead one to be concerned about these omissions but because health effects may be among the most important environmental effects, and some with long term consequences—exposure to lead for example—these need to be tracked. In addition, this full accounting would then avoid the problem that if environmental change is decreasing the amount of market goods and services available, and we make up for it by working even harder, we then are not fully seeing the loss in measured market production and consumption.

Improved accounting can us give us a bottom line—with a measure of NNP, appropriately broadened—to a Green NNP, we have an indicator that can be related to sustainability. It will fall if it turns out that we are maintaining consumption levels at the expense of depleting assets (including natural resource assets). But an equally important contribution of expanded accounts is that in making explicit where environmental or resource depletion are affecting the economy, and how big are different effects we are then alerted to where problems may exist, and which are ones are most worth tackling. But, improved accounting does not itself correct the problem of unpriced externalities and the like. That requires pricing these externalities or otherwise correcting market forces that may be leading to less than ideal outcomes.

3. Renewable and exhaustible resources

One of the mantras of green growth is the need to move to renewable resources and away from depletable resources. It would seem self-evident that use of depletable resources is unsustainable whereas a resource that renews itself—a flow and not a stock that can be drawn down—could be used sustainably if harvest did not exceed regrowth or replenishment. But switching away from depletable resources simply because they are depletable is not necessarily consistent with sustainable *growth*. For a theoretical derivation of various aspects of resource depletion see, for example, [Hartwick \(1977\)](#), [Solow \(1986\)](#), or [Dasgupta and Heal \(1980\)](#). To illustrate this let us consider the ever-popular, among economists, Robinson Crusoe economy, after the character in the 1719 novel by Daniel Defoe. The setup gives us one man who must make decisions about how to allocate limited resources, and with no contact with the outside world. Thus, there is no trade—he must produce everything he needs—and there is no ability to bail himself out by taking out a home equity loan. There are many versions developed to illustrate different elements of a neoclassical economy. In our Robinson Crusoe economy, imagine there are limited forest resources that can be a source of food, energy, and building materials. These resources are renewable. Our island

also has an easily recoverable deposit of fossil fuel, a depletable resource. Scarcity is what makes economics problems interesting, and the scarcity we have on our island is that the forest resource is sufficient for food and energy needs, but insufficient to also provide material for a shelter. Robinson could have a sustainable income, using only the renewable resource to supply him with food and fuelwood for cooking and keeping warm, but it is a reasonably meager existence. But suppose he considered using the depletable fossil resource for energy. Let us assume that he would now have an excess flow of renewable forest product with which he could, over time, build a shelter. The shelter improves his life, and also reduces his need for energy to keep himself warm. Further assume that, with the shelter built, the savings in energy would be sufficient so that even if he exhausted the supply of fossil fuel he would have enough forest product flow to make the occasional repairs to the shelter. Should he make use of the depletable resource? Here we are ignoring any potential environmental effects of fossil fuel use, and so, clearly, using the fossil fuel allows his economy to grow. The economy now provides food, energy and shelter, and even if he eventually exhausts the fossil fuel he can sustain this higher level of income. If he does not deplete the fossil resource his economy is sustainable, but it does not grow, and the sustainable level of income is forever lower than if he were to use the fossil resource.

The resource endowments and technology requirements of our island economy were carefully constructed to generate the result we got to illustrate the point that it may be to our advantage to deplete some resources to get to a higher sustainable income. Whether it is advantageous to use a depletable resource depends on many factors, including the cost of extracting it relative to the costs of alternatives. In our island economy this would be the labor involved in either activity. If the fossil resource was very labor intensive it may not have made sense to use it because Robinson may then not have had enough time to produce the food he needed to stay alive even though the forest resource was sufficient to produce the food. Then the fossil resource has no real economic value unless elements of the economy or technology change to make it economically feasible to exploit. If the renewable resource was not meaningfully limited, there might be no need to use the depletable resource. On the other hand, if the fossil resource were very easy to get relative to cutting wood for energy, Robinson might be better off using the fossil resource, giving him some spare time to develop tools that would make harvesting the forest easier. In this case, the scarcity is his time not the renewable resource, and the problem with the renewable resource is the cost (amount of time) needed to harvest it. His use of the depletable resource gives him the time to create an innovative tool to better use the abundant but otherwise costly renewable resource.

These different possibilities illustrate economic trade-offs very similar to those we need to make in the real economy between depletable energy resources and renewable resources. In the example, growth and a higher sustainable level of income is achieved because the savings made by using the fossil resource are invested, and those investments lead to higher productivity. A lazy Robinson might have used the fossil resource and never bothered to develop tools, in which case, he experiences growth, but when the fossil resource runs out he loses the growth and goes back to a lower level of income. Robinson, as the lone islander, might make that choice—he might prefer less work in the near term, taking the risk that he may have to work harder if the depletable resource runs out. If he were concerned about a future generation—a future shipwreck—if he depleted the resource and did not make an investment, leaving behind some tools for the next generation, then Robinson II would never have the option of a sustainable higher level of income.

We can then also illustrate our previous economic accounting principles for our island economy. Here let us take the case where the renewable resource is not meaningfully limited, but costly to access. Consider two cases where Crusoe either uses the time saved

to invest in developing tools or does not. As currently measured, consumption is the same in both cases. But GDP would be higher in the case where he developed tools—because the investment would be counted but we are not counting the value of leisure and so it looks like we are getting the higher GDP for nothing. GDP does not, by definition, count depletion of the fossil resource. Our measure of Green NNP should. If he completes the tool before exhaustion of the resource, then the fossil resource becomes useless to him anyway because it is then, let's say, more costly than the renewable resource. If there is some chance of exhausting the fossil resource before he completes the tool, then we need to have some expected value of the depletion, and in an expanded measure of NNP that depletion would be subtracted. In the widely-used current approach to accounting, depletion is not subtracted and measured NNP would thus be just $C + I$. So we now see a case where our measure of NNP is incomplete by not accounting for depletion, and is overestimating our sustainable income.

In the expanded GDP accounting that includes leisure, GDP would be the same in both cases, because we value leisure at the opportunity cost of producing the investment good. So that makes it clear that the investment good is a reallocation of leisure time, and not completely free. But in the leisure case there is no chance of developing a harvest tool, and so the full economic value of depletion of the fossil resource should be subtracted from an expanded measure of Green NNP. Whatever the result, it is going to be no less and likely more than in the case where there is only a chance of not developing the tool in time. So our expanded definition of Green NNP that includes both leisure and depletion will be no higher and likely lower than in the case where the tool was not developed. How would we go about valuing that depletion? It is the discounted value of lost future income from the resource. Suppose in our simple case, the fossil resource lasts for just one period. Then the depletion value is the discounted present value of the labor savings from period 2 until his expected rescue or death from his perspective. If instead, from a social accounting perspective, we expect an infinite number of future generations of shipwrecks to replace each as they die, then it would be the discounted sum over infinity. Whatever this number it is going to be a subtraction from GDP and so our Green NNP will show a lower sustainable income.

Clearly, if he is only concerned about himself, and if we altered our assumptions so that there was certainly enough of the resource to last his lifetime or until past his rescue then the depletion value would be zero. The resource is not meaningfully limited even though it is technically depletable. Of course that is not very realistic in our world where we expect the human population to continue. But if it really only takes one period of labor savings to develop the innovative tool we need, and that is the only new technology option that is potentially available, then if the fossil resource is very large the value of depletion is very small until we gradually approach full depletion. There are two ways to think about offsetting the investment we could make in tool development. We could offset it with a very small initial investment toward the development of the new tool that grew as we approached the date when we needed it so that by then it would be fully developed. The other way to look at it is that the value potential for the tool development—the blueprint—less the discounted cost of actually developing the tool just offsets depletion, and as we approach fossil exhaustion, the value of the blueprint increases because the date of its actual use grows closer.

What if there is no blueprint? In this case, the Hotelling result on depletion comes into play. He should deplete so that the present value of depletion is equal across all relevant time periods. Our expanded GDP including leisure would show the leisure benefits of using the fossil resource. NNP would include depletion. There is no feasible tool development and so no possibility of investment. But the labor savings would show up as greater consumption because of leisure time accounting. NNP would thus be higher than if he did

not exploit the fossil resource. In the Hotelling result the depletable resource is never fully exhausted but just meted out slowly over time in ever smaller amounts.

From this example, we can see several important issues in expanded accounting that complicate the issue. For a more complete discussion see, El Sarafy (1997). The value of depletion depends strongly on our expectations about the future. Uncertainty exists, and how we value depletion depends on what we expect to do. What is the demand from future generations? How much of the uncertain depletable resource do we have? Will we invest in potential technology or not? What are our expectations of when those technologies will be available and what will they cost? Is there really no feasible alternative? And, is there some way in which we can enforce intergenerational concerns—here that is the basic externality or possible contradiction between a social goal of sustainability and preferences. Crusoe I may not consider or care about Crusoes II...n. If they overlapped, then there becomes the possibility of some exchange where future Crusoe I could imagine extracting some value from II that would create incentives him to leave wealth for II and so on. But if Crusoe I values leisure more than future Crusoes there may be nothing they would be willing to pay him to preserve assets, and hence sustainability would not be a market outcome. In this case, the goal of sustainability may not be consistent with preferences of some of the Crusoe generations. We would need to invent a social planner, who would tax consumption enough during these generations so that they invest rather than simply consume, leaving future generations poorer. These last points demonstrate that getting the accounts right does not insure sustainability. And, for the real world there is not much we can actually do to prevent some future generation from depleting resources and just consuming them, leaving subsequent generations with, at best, a lower sustainable income. But, getting the accounts straight is the first step to understanding where we are.

4. Examples of implementing expanded accounting in models

While efforts of national statistical agencies to produce integrated economic and environmental accounts have been limited and spotty, research efforts to integrate environmental and resource issues have proceeded. Computable general equilibrium (CGE) models, one class of economic model used to investigate environmental and resource issues, are structured on NIPA data used in national accounting systems. And so these efforts have proceeded to expand the economic accounting to represent at least some of the environmental and resource components along the lines sketched out above. They have also sought to improve representation of distributional effects—among countries, states, and households of different income levels or demographic characteristics. And, these results begin to emphasize some of the tradeoffs in distributional effects and efficiency. I will briefly discuss some of the key developments with reference to work with which I am very familiar—that undertaken in the MIT Joint Program on the Science and Policy of Global Change in the development of the Emissions Prediction and Policy Analysis (EPPA) model and various versions of the model (Paltsev, et al., 2005). A key in this work is to create supplemental physical accounts that link economic values to physical quantities of resources. This allows tracking over time of depletion in physical terms, or to associate pollution emissions or quality variation and change of physical resources.

This work has included separate tracking of resources (both exhaustible and renewable) and feedbacks of environmental change on economic welfare of agents in the economy. Here welfare includes effects on market consumption and on non-market leisure time. As such, the potential effects of externalities on the narrower market economy, on a broader definition of the economy to include valuation of non-work activities of people, and allocation of scarce resources

over time can be evaluated within a sound economic framework. Some examples are Babiker et al. (2003) who considered the interaction of a carbon tax with existing market distortions; Matus et al. (2007, 2011), Nam et al. (2010) who investigated the market and broader welfare effects of the health effects of air pollution; Babiker et al. (2009) who examined the allocation over time of scarce pollution allowances and fossil resources in a forward looking economic model; Reilly et al. (2007) who examined climate and pollution effects on agriculture, forestry, and pasture; Antoine et al. (2008) who integrated hunting, fishing and wildlife viewing recreation values into the accounts; and Gurgel et al. (2011a), who priced the value of carbon in soils and vegetation. Thus, in this work, resource exhaustion, limited flows of renewable resources, and negative environmental feedbacks all create a drag on economic growth. Where this drag is due to unpriced/nonmarket pollution effects, the potential exists to improve economic performance with policies that price pollution or otherwise reduce pollution levels. Where resource exhaustion or limits on renewable resource flows exist the principle solution is improved technology (to access more dispersed or diffuse resources or use them more efficiently) or technology alternatives that are less expensive and rely on a more abundant resource. While much of this work relies on the “representative agent” and therefore has a unique social welfare function for a nation, it has represented multiple agents for different regions as well as within regions (e.g., Jacoby et al., 2010; Rausch et al., 2010) which at least then introduces the complication of global or national efficiency when different nations or households are affected differently by a policy change.

In creating a model that simulates environmental effects forward the approach used in the EPPA model is to expand the Social Accounting Matrix (SAM) as shown in Fig. 2. The key additions beyond the standard SAM are shaded. One set of additions are the Household Services production sectors. These use intermediate inputs—we’ve shown medical services for the household activity that mitigates pollution health

effects (Matus et al., 2007, 2012; Nam, et al., 2010)—and for outdoor activities we have shown gear and hotel room purchases (Antoine, et al., 2008). These household production sectors may also use other household services as “intermediates.” Here we show household transportation as an input into Outdoor Recreation. However, these inputs are simply removing items that were previously reported simply as consumption and showing them as now related to environmental and resource activities of the household. The main addition is the accounting for household labor used in these activities, as that creates value added that was not previously accounted. Otherwise the aggregation of different goods and delivery to final consumption would just equal what was removed from final consumption. We also show pure leisure, unrelated to any specific activities. The other area of addition is the explicit separation of Natural Resources. Here we have shown oil and land resources as examples, but the EPPA model includes several categories of land and multiple types of energy resources—crude oil, coal, gas and indeed oil sands, shale oil, and multiple types of gas deposits.

The work on air pollution health effects is a useful starting point. Here Matus et al. (2007, 2012) and Nam et al. (2010) have analyzed the economic damage from air pollution in the US, Europe, and China for the period from about 1970 to 2000 to 2005. Including these effects does not change measures of market income, however, what it does is reduce measured welfare by diverting resources from other activities to abating health effects of air pollution. Thus, for Europe, Nam et al. (2010) found that market consumption could have been 169 billion € higher in 1975 if none of the health effects of air pollution they observed had been present. Welfare (consumption plus leisure) would have been €293 billion, and these rose to 217 and €354 billion, respectively, by 2005. However, because these costs were a lower share of consumption and welfare, the growth rate corrected for these costs was actually somewhat higher. Uncorrected growth in consumption was 2.59% per year and corrected it was 2.66%. The uncorrected growth in welfare was 2.69% per year and corrected it was 2.73% per year. So by this

		INTERMEDIATE USE						HOUSEHOLD SERVICES			FINAL USE				OUTPUT	
		1	2	...	j	...	n	Pollution Health Effects	Outdoor Recreation	Other H.H. Activities	C	I	G	X-M		
DOMESTIC PRODUCTION	1															
	2															
	:															
	i								Hotel							
	:								Gear							
	n								Medical Services							
H.H. PROD.	Pollution Health															
	Recreation															
	Other H.H.								HH Transport							
IMPORTS	1															
	2															
	:															
	i															
	n															
LEISURE																
VALUE-ADDED	Labor								H.H. Labor	H.H. Labor						
	Capital															
	Indirect Taxes															
	Natural Resources															
	Oil, others															
	Land, etc															
INPUT																

Fig. 2. Expanded Social Accounting Matrix (SAM) for environmental and resource effects (after Nam et al., 2010).

calculation even though there was a substantial burden on the economy due to air pollution and it grew over time, correcting for it leads to a rosier outlook—more rapid real economic growth in terms of what it provided households.

Gurgel et al. (2011b) and Reilly et al. (2012), looking forward over the century considered the effects of pricing carbon emissions. If only emissions from fossil fuels were priced, the result was to encourage the use of biomass energy, a shift from depletable fossil resources to renewable resources. However, that shift had implications for land use and hence carbon emissions from land use change. They then extended carbon pricing to land carbon, avoiding deforestation and encouraging reforestation. That led to significant carbon reductions and land uptake, but reduced the amount of biomass energy that could be economically harvested, and substantially increased crop and livestock prices. With energy and land carbon policy, crop prices rose by 30 to 50% compared with small decline or slight rise (+/− 10%) without policy. Livestock prices rose by 2.2 to 3 times with the full carbon policy on land and energy, compared to increases of 10 to 30% without policy. The lessons here—even though biomass is renewable—its use for energy or other new products competes with traditional demand for food and forestry products, and ecosystem services—here carbon storage.

5. Conclusions

Green growth, green jobs, and the green economy have become politically popular terms recently. In political discourse their use turns the negative association with the cost of environmental control into a positive, promising growth and jobs. Focusing on growth and jobs is particularly attractive in a period where economic growth is lagging and economies are gripped with recession and high unemployment. There is a strong foundation for green growth in neoclassical economics that dates back many decades. Traditional environmental economics has concerned itself with externalities—disposal of pollutants or effects on resources where the user does not bear the full cost of pollution or his resource use. These are classic cases where internalizing the externality can improve economic performance. However, many of these effects will show up in market consumption. If continued pollution so degrades the environment and causes illness and death, those can eventually have effects on traditional measures of the market economy. However, it is important to have a proper measure of economic performance, focusing on well-being rather than simply the production of goods and services, as that can be misleading.

Various panels have called for an expansion of measures of economic activity that would broaden the accounts and give a better picture of how well-being was changing rather than simply how production of goods and services are changing. Important in this approach is to focus not only on a GDP concept but on an NNP concept that includes an evaluation in the change in value of assets, thus accounting for depletion, degradation, and depreciation as well as investments that may extend or increase economically useful amounts of natural resources. To do this poses some difficult empirical issues but then would provide some evidence of those environmental and resource utilization issues that had strong effects on the bottom line—via an expanded NNP concept—as well as on how they were affecting the economy. In moving in this direction, there are many potential pitfalls, possibilities for double counting, or missing effects completely. And, it remains important to recognize that business cycles that result in unemployment have different sources and remedies than the issue of the sustainability of growth over time, and the measures used to evaluate these need to differ appropriately. While there may be overlap between the remedies for short run business cycle concerns and in assuring longer-term sustainability, designing such policies requires great care. Finally, “green” is almost certainly a relative concept and we need to be cautious about jumping on a bandwagon, labeling some things green and some things not green. Virtually any human activity is going to affect the planet in

some way, especially at the scale of that activity in terms of the population level and our ability to alter the environment. Finding paths of development that have lower impact involves a careful consideration of valuation of those impacts in comparable terms.

References

- Abraham, K.G., Mackie, C. (Eds.), 2005. *Beyond the Market: Designing Nonmarket Accounts for the United States*. : Panel to Study the Design of Nonmarket Accounts, National Research Council. National Academy Press, Washington DC.
- Antoine, B., Gurgel, A., Reilly, J.M., 2008. Will recreation demand for land limit biofuels production? *J. Agric. Food Ind. Organ.* 6 (2) Article 5. Available at: <http://www.bepress.com/jaifo/vol6/iss2/art5>.
- Babiker, M., Metcalf, G., Reilly, J., 2003. Tax distortions and global climate policy. *J. Econ. Environ. Manage.* 46, 269–287.
- Babiker, M., Gurgel, A., Paltsev, S., Reilly, J., 2009. Forward-looking versus recursive dynamic modeling in climate policy analysis: a comparison. *Econ. Model.* 26 (6), 1341–1354.
- Coase, R.H., 1960. The problem of social cost. *J. Law Econ.* 3 (1), 1–44.
- Dasgupta, P.S., Heal, G.M., 1980. *Economic Theory and Exhaustible Resources*. Cambridge University Press, Cambridge.
- Gurgel, A., Paltsev, S., Reilly, J., Metcalf, G., 2011a. An analysis of US greenhouse gas cap-and-trade proposals using a forward-looking economic model. *Environ. Dev. Econ.* 16, 155–176 <http://dx.doi.org/10.1017/S1355770X10000495>.
- Gurgel, A., Cronin, T., Reilly, J., Paltsev, S., Kicklighter, D., Melillo, J., 2011b. Food, Fuel, Forests, and the Pricing of Ecosystem Services. *Am. J. Agric. Econ.* 93 (2), 342–348.
- Hartwick, J.M., 1977. Intergenerational equity and the investing of rents from exhaustible resources. *Am. Econ. Rev.* 66, 972–974.
- Hotelling, H., 1931. The economics of exhaustible resources. (1931) *J. Polit. Econ.* 39 (2), 137–175.
- Jacoby, H.D., Babiker, M.H., Paltsev, S., Reilly, J.M., 2010. Sharing the burden of GHG reductions. Chapter 24 In: Aldy, J.F., Stavins, R.N. (Eds.), *Post-Kyoto International Climate Policy: Implementing Architectures for Agreement*. Cambridge University Press, Cambridge, pp. 753–785.
- Matus, K., Yang, T., Paltsev, S., Reilly, J.M., Nam, K.-M., 2007. Toward integrated assessment of environmental change: air pollution health effects in the USA. *Clim. Chang.* 88 (1), 59–92.
- Matus, K., Nam, K.-M., Selin, N.E., Lamsal, L.N., Reilly, J.M., Paltsev, S., 2012. Health damage from air pollution in China. *Glob. Environ. Chang.* 22 (1), 55–66.
- Mullainathan, S., Thaler, R.H., 2001. Behavioral Economics. *Int. Encycl. Soc. Behav. Sci.* 1094–1100.
- Nam, K.-M., Selin, N.E., Reilly, J.M., Paltsev, S., 2010. Measuring loss in human welfare caused by air pollution: a CGE analysis for the European region. *Energy Policy* 38 (9), 5059–5071.
- Nordhaus, Kokkelenberg (Eds.), 1999. *Nature's Numbers: Expanding the U.S. National Accounts to Include the Environment*. : Panel on Integrated Environmental and Economic Accounting, Committee on National Statistics, Commission on Behavioral and Social Sciences and Education, National Research Council. National Academy Press, Washington DC.
- Paltsev, S., Reilly, J.M., Jacoby, H.D., Eckaus, R.S., McFarland, J., Sarofim, M., Asadoorian, M., Babiker, M., 2005. *The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4*. MIT Joint Program for the Science and Policy of Global Change, Report No. 125. Cambridge, MA, (Aug.), 2005.
- Pigou, A.C., 1932. Part II, Chapter IX: Divergences between marginal social net product and marginal private net product. *The Economics of Welfare*. MacMillan and Co., London.
- Rausch, S., Metcalf, G., Reilly, J., Paltsev, S., 2010. Distributional implications of alternative U.S. greenhouse gas control measures. *B. E. J. Econ. Anal. Policy* 10 (2) (Symposium).
- Reilly, J., Paltsev, S., Felzer, B., Wang, X., Kicklighter, D., Melillo, J., Prinn, R., Sarofim, M., Sokolov, A., Wang, C., 2007. Global economic effects of changes in crops, pasture, and forests due to changing climate, carbon dioxide, and ozone. *Energy Policy* 35, 5370–5383.
- Reilly, J., Melillo, J., Cai, Y., Kicklighter, D., Gurgel, A., Paltsev, S., Cronin, T., Sokolov, A., Schlosser, A., 2012. Using Land to Mitigate Climate Change: Hitting the Target. Recognizing the Trade-offs. *Environ. Sci. Technol.* 46 (11), 5672–5679.
- Ricardo, D., 1817. *On the Principles of Political Economy and Taxation*. John Murray, London: Albemarle-Street.
- Samuelson, P., 1955. Diagrammatic exposition of a theory of public expenditure and taxation. *Rev. Econ. Stat.* 37, 350–356.
- Sarafy, El, 1997. Green accounting and economic policy. *Ecol. Econ.* 21, 217–229.
- Solow, R.M., 1986. On the intertemporal allocation of natural resources. *Scand. J. Econ.* 88, 141–149.
- Solow, R., 1992. *An Almost Practical Step Toward Sustainability. Resources for the Future*, Invited Lecture. Washington DC. Oct. 8.
- Stiglitz, J.E., Sen, A., Fitoussi, J.-P.L., 2009. Report by the Commission on the Measurement of Economic Performance and Social Progress. <http://www.stiglitz-sen-fitoussi.fr/en/index.htm>.
- Weitzman, M., 1976. On the welfare significance of national product in a dynamic economy. *Q. J. Econ.* 90, 156–162.
- World Bank, 2011. *The Changing Wealth of Nations: Measuring Sustainable Development in the New Millennium*. International Bank for Reconstruction and Development (IBRD), Washington DC.

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2012-30 The Role of Stocks and Shocks Concepts in the Debate Over Price versus Quantity, Parsons, J.E. and L. Taschini, *Environmental and Resource Economics*, doi: 10.1007/s10640-012-9614-y (2012)

2012-31 Green growth and the efficient use of natural resources, Reilly, J.M., *Energy Economics*, 34(S1): S–S93 (2012)

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