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Endogenous Growth and Negative Externalities

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ERRATA CORRIGE

The following footnote substitutes for the footnote (2) of the paper:

[2] The idea that growth can be fed by negative externalities was originarily formulated in an evolutionary context in Antoci and Bartolini (1997). In order to show its logical robustness, the idea has subsequently been studied in the context of two very different neoclassical growth models. In Bartolini and Bonatti (1997) a non-storable output is a perfect substitute for the resource. The dynamics of the economy under different laws of motion of the resource is analized. It is shown what kind of law of motion give rise to multiple equilibria. An interpretation is provided of this law of motion, in terms of the role played in growth by different social values and mass-psychology. In Bartolini and Bonatti (1998), a non-storable output can be used as a perfect substitute for the resource or to satisfy needs different from those satisfied by the environmental good. Also analysed is the impact of technical progress on labour input in the economy. The present paper yields perhaps the most remarkable results because it shows that negative externalities can generate endogenous growth. We show that in an AK growth model if working time is a control variable, the model is no longer able to generate endogenous growth, unless negative externalities are introduced.

The following articles should be included in the bibliogragraphy

Antoci A. and Bartolini S. (1997), *"Externalities and growth in an evolutionary game"*, Discussion Papers n. 10, Università di Trento, Dipartimento di Economia

Bartolini S. and Bonatti L. (1997), *Negative externalities as the cause of growth in a neoclassical model*, Discussion Papers n. 9, Università di Trento, Dipartimento di Economia

Bartolini S. and Bonatti L. (1998), *Growth as a coordination failure*, Discussion Papers n. 5, Università di Trento, Dipartimento di Economia

Introduction

The aim of this paper is to present a view on growth which differs from the dominant paradigm, with its insistence that self-sustained growth is fuelled by positive externalities. We instead emphasise the role played in the growth process by negative externalities:[1] the expansion of private production erodes the quality and reduces the endowment of resources to which all individuals have free access, thereby forcing them to increase their consumption of private goods in order to satisfy their needs. This further erodes the free resources, giving rise to a self-fuelling process.

A coordination failure is at the origin of this process. Acting entirely autonomously, households seek to defend their welfare against the deterioration of commonly owned resources by keeping both their labor supplies and saving rates relatively high, despite their increasing private wealth. By so doing, each household contributes to an increase in current and future production, with a detrimental--though negligible--impact on the future quality or quantity of the free resources. In the absence of incentives for the full internalization of these externalities, individual activities have a substantial aggregate effect on free resources. Perpetual growth is the outcome of this self-fuelling process. Since growth results from a coordination failure, it tends to be excessive, and steady-state rates of growth may be higher than socially desirable.

Legitimate interpretations of the mechanism described in this paper can be formulated both in terms of the damage wrought to environmental assets by productive activities, and in terms of the undermining of the institutional and non-material bases of communal modes of life by the enlargement of the sphere of action dominated by private enterprise. In both cases, individuals must increasingly rely on privately produced goods in order to avert a drastic decline in their well-being.

This paper is based on ideas with a long and interdisciplinary history behind them. Obviously, it would be beyond its scope to conduct a thorough survey of the contributions made to this history by anthropologists, sociologists, psychologists, philosophers, economic geographers, economic historians, and

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[1] As an ample variety of positive externalities have revealed fruitful to explain important mechanisms generating endogenous growth, we suggest that a wide range of negative externalities should be considered for their role in the growth process.

economists – economists of development in particular.[2] However, of the twentieth-century economists who have helped to shape these ideas, mention should at least be made of Polanyi (1968) and Hirsch (1976). The work of these authors has strengthened the view that economic development and growth are both the effects and causes of the erosion of traditional institutions and cultures, the decline of which releases the energies that fuel the growth process, with its destructive impact on such institutions. This erosion plays a crucial role in the mobilization of human resources and in the formation of the attitudes toward thrift essential for a population's saving propensity and capital formation.[3]

The model presented below explores the explanatory and predictive potentialities of these ideas in the simplest possible way. Its focus is on the determinants of labor supply and thrift, and its implications and predictions are often complementary to those of current growth models. In other instances, it may shed light on stylized facts which modern growth theory cannot easily explained or has somehow overlooked.

We share with the literature on sustainable growth its concern for the potential impact that current economic activities may have – by depleting social and environmental assets – on long-term growth performances and future well-being. The emphasis in the literature, however, is on whether unbounded growth is possible in the presence of natural resources negatively affected by the growth process,[4] and not

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[2] Among studies related to this research project see Antoci and Bartolini (1997), which derives some of the results of this paper in the context of an evolutionary game.

[3] A recent example of the crucial role played in growth episodes by human resource mobilization and rising saving rates is provided by the Asian 'Tigers', where in many cases, rates of activity and dependent employment have doubled in the space of ten years (see e.g. Krugman,1995). While the modelling tradition has concentrated on pull factors (in Lewis, 1954, and in Todaro, 1969, the pull factor is the wage differential between the modern and the traditional sector), a large body of literature has stressed push factors. Among them, the decline of traditional institutions of the rural sector is considered a major determinant of those migration flows into urban areas that make possible the formation of an industrial workforce.

[4] In Musu (1994), sustainable growth is consistent with a modified AK model, assuming that there is no increase in pollution as production increases because of higher capital stock. In the absence of a lower limit, below which environmental quality cannot fall without entailing irreversible catastrophe, Martin and Rotillon (1996) analyse under what conditions on the utility function the AK model is able to generate sustainable growth. In the presence of such a limit, Aghion and Howitt (1998) show that growth is not sustainable with a AK production function.

on the role as the 'engine' of growth played by the progressive degradation of these assets. In other words, the literature does not seem entirely aware of the extent to which the declining endowment of free resources is able to boost economic growth. By contrast, we focus precisely on the manner in which work attitudes, saving propensity and consumption habits become more favourable to growth as access to free resources diminishes.

The paper is organized as it follows. Section 1 discusses some of the points that motivate the model. Section 2 presents the model and derives the optimizing behavior of the agents. Section 3 characterizes the equilibrium paths of the economy, showing that it is only in the presence of negative externalities that perpetual growth is possible. Section 4 dwells on certain implications and possible extensions of the model. The appendix gives another example of an economy which can exhibit a strictly positive long-run growth rate only in the presence of negative externalities, together with characterization of the path selected by a benevolent planner under these circumstances.

1. Motivations

Growth and working time in the long run

By endogenizing the decision on the time spent working, our model makes it possible to deal with a crucial issue in long-term growth: the allocation of productivity gains between leisure and consumption. Growth models in which the labor supply is exogenous assume precisely what they should explain: that increases in productivity are utilized mainly to augment output, and only marginally to reduce working time. If the reverse occurs, growth (in the sense of increased per-capita output) may not take place. Current endogenous growth models find it difficult to preserve perpetual growth when the possibility of a labor/leisure choice is explicitly considered.[5] We show in this paper that if a Ramsey-Rebelo AK model is augmented by treating the units of time devoted to work, h, ("capital operating time") as a choice variable, the resulting Akh model does not generate endogenous growth in the absence of negative externalities.[6] In

[5] Baldassarri et al. (1992) show that the models of Romer (1986) and Lucas (1988) admit endogenous growth only if leisure is not a choice variable (see also Solow, 1995).

[6] In Rebelo's (1991) AK model , the absence of diminishing returns to capital can be made plausible by interpreting K in a broad sense to include human capital (see also Barro and Sala-i-Martin, 1995). It is even more plausible to let labor enter the production function both as a reproducible factor whose quality depends on previous investment and as an

this case, an economy with the prospect of becoming richer by accumulating capital tends to reduce the saving rate, even if the production function is such that for given levels of technology and labor effort the marginal productivity of capital is not decreasing in K. This is because the return on capital investment is reduced by the less time devoted by individuals to work as the capital stock grows larger and the economy becomes more productive.

As well as ruling out the possibility of unbounded growth, inclusion of the labor/leisure choice in a AK model which ignores the negative externalities generated by economic growth yields the counterfactual prediction that working time will be highly responsive in the long run to technological advances. Indeed, the tendency for labor input to decrease is weak, and it displays very important exceptions.[7] Obviously, satisfactory assessment of the extent to which total working time reacts to productivity improvements also requires analysis of how productivity changes affect home work (see Greenwood and Hercowitz, 1991; Benhabib *et al*., 1991). This is especially true in the light of the historical trend toward increased female labor-market participation distinctive of the advanced countries during the twentieth century. However, the fact that the production of certain services is no longer confined to the family is part of the general and progressive weakening of communitarian modes of life that has accompanied modern economic growth. Furthermore, widespread in contemporary societies is the perception that people suffer from a shortage of time in the midst of affluence.[8]

Growth models which include the labor/leisure choice as a control variable (see, for example, Barro and Sala-i-Martin, 1995) explain the low long-term elasticity of per-capita working time with respect to productivity advances by assuming that in the long run the income effect only weakly predominates over the substitution effect induced by the increased remuneration of labor. That is to say, standard explanations rely

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input whose quantity depends on demand and supply. In other words, physical capital tends to increase together with the quality of the working population, but not necessarily with the time that this population devotes to work: in our model, h can be interpreted as the capital (in the broad sense inclusive of human capital) operating time.

[7] In the USA, labor input per head of population (hours) was 710 and labor productivity (GDP per hour worked) was 8.64 in 1938. Analogous figures were 756 and 12.66 in 1950, and 741 and 29.10 in 1992 (see Maddison,1995). According to Schor (1993), in 1987 Americans worked for around one month per year more than they did in 1969 (+163 hours).

[8] Among the attempts to explain this “famine of time”, see Linder (1970), Hirschmann (1973), Cross (1993).

on the peculiarities of individual preferences. The symptoms of widespread discontent with the excessive role played by work in people's lives should prompt a search for complementary explanations as to why productivity gains are not massively transformed into leisure increases.

The explanation proposed in this paper rests on the need of individuals to substitute for diminishing free resources. In response to technological progress, the same individual tastes are consistent with a drastic long-term fall in working time when negative externalities are ignored, while they do not generate any significant working time reduction once these externalities have been taken into account. Observed long-term reactions of per-capita working time to productivity advances depend on a coordination failure and not on the tastes of individuals, who would prefer lower levels of market activity in exchange for more free time and more resources. The presence of negative externalities caused by the growth process is an incentive for individuals to devote productivity increases mainly to the production of substitutes (to the point of increasing the labor supply) because their uncoordinated efforts do not take account of the social cost of increased production, thus fuelling the mechanism whereby increases in output cause a deterioration in the free resources which stimulates increases in output. As the economy grows and free resources deteriorate, the value of private consumption for households increases relatively to the value of time, and the return on capital investment is not depressed by households' willingness to work less. The growing labor productivity brought about by the rising capital stock is not used to reduce the time devoted to work, because the deterioration of free resources makes it more urgent to increase private consumption.[9]

Growth and thrift in the long run

An economy that has the prospect of increasing its private wealth by accumulating capital tends to keep the saving rate constant as households anticipate that the future endowment of the free resource will be negatively affected by the growth process, and therefore increasingly substitute private goods for free resources in their consumption activity. Indeed, social wealth also includes those commonly owned assets whose progressive degradation accompanies the growth of capital stock. In our model, the impoverishment due to the declining quality of free resources tends to offset the negative effect on the saving rate due to the increase in private wealth. As an example of how the gradual erosion of communal institutions in favour of

[9] It is precisely in order to focus on this point that a mechanism generating endogenous technological progress is not included in the model, the intention being to analyse how negative externalities influence decisions concerning labor supply and capital accumulation in the presence of technological progress, regardless of the mechanism that generates it.

more individualistic lifestyles may keep the saving rate high, one may cite the major effect on saving propensity exerted by the declining importance of the family in providing support to the elderly which typically accompanies the evolution of an advanced society.[10]

Growth as a substitution process

As growth proceeds, agents increasingly derive welfare from private rather than common consumptions. This conclusion may strike sociologists as familiar, since they often associate growth with the "creation of new needs" and with a "change in patterns of consumption". These expressions tend to be interpreted in terms of an endogenous change in preferences. In our model, the creation of new needs and change in consumption patterns constitute the engine of growth, but in a context of invariant preferences. This is because new needs are viewed as increases in demand for substitute goods generated by a diminution in free consumptions, while changes in patterns of consumption concerns the passage from common (free) goods to private (costly) ones. Consequently, the traditional view that increasing quantities of goods become available as growth proceeds may be incomplete. The image conveyed is one of luxury goods which become standard goods for the next generation, and absolute needs for the one that follows thereafter. Our model suggests that this is only partially true, since also involved are free goods whose endowment and quality are progressively reduced. The point is an obvious one in an environmental interpretation of the concept of 'free resource': meadows, woods, clean beaches, unpolluted air and water, silence, and so on, are all examples of free goods which may deteriorate or become scarce. It is often the case in advanced economies is that, in order to enjoy what could be obtained for free thirty or forty years ago, agents must now purchase a house in an exclusive area in the countryside or at the seaside, or buy an expensive holiday in some tropical paradise, etc. However, a sociological interpretation of free goods is also possible, given that many of them relate to social relations and seemingly grow scarcer with growth. With this broader interpretation in mind, the concept of 'substitute' may help to explain changes in lifestyles, as well as in patterns of consumption.

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[10] Pay-as-you-go pension schemes – which have replaced the family as the principal source of support for the elderly in most Western societies – still incorporate an important solidaristic element, since they are widely used to perform intragenerational and intergenerational tranfers. The current trend toward reducing their role in favour of more individualistic ways to provide for the elderly could be interpreted as another step in the erosion of communal institutions. Those who advocate this reduction expect it to boost aggregate saving.

According to Hirsch (1976), growth in advanced economies is largely due to an increase in defensive consumption: that is, consumption induced by the negative externalities produced by growth, which is similar to the concept used here of substitute consumption. After Hirsch, the notion of defensive consumption was taken up by the debate on corrections to GNP in order to improve it as a index of welfare. The literature on defensive consumption contains a large number of interesting examples, but the idea that seems to inspire all authors, and Hirsch in particular, is that reactions to a situation of general decay may be very general.[11] Individuals may compensate for the deterioration in everything that is public with a concern for everything that is private, giving rise to the contrast typical of "affluent societies" (Galbraith's well-known observation).

Growth and increased pressure on environmental and social resources

The model predicts that a larger population size and a greater impact of a given level of production on free resources tend to boost long-run per capita growth, but at the cost of a declining steady-state level of households' welfare. In fact, everything that exerts greater pressure on the free resource and accelerates its decline induces individuals to react by working and saving more. Thus, according to the model, policies that reduce population growth and the environmental impact of productive activities restrain the long-term per capita growth rate of the economy.

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[11] The empirical literature on defensive consumption displays a number of conceptual difficulties--evidenced, for example, by the variety of definitions of defensive expenditure--which derive in part from a failure to understand that the concept of defensive expenditure is a sub-case of the concept of substituted good (which is clearly codified). In the set of substitutes it is the sub-set of substitutes for environmental goods (i.e. for the free goods subject to negative externalities). In the opinion of these authors, however, it is difficult to give plausible statistical substance to the concept, owing to the difficulty of identifying spending for defensive reasons among the items in the GNP, constructed on other criteria. The strategy followed is generally highly restrictive, in that only classified as defensive is spending which is certainly and wholly such: spending on environmental purification, on land reclamation, on pollution-related diseases. The estimates obtained are not negligible, but on the admission of the authors themselves they are enormously under-estimated. For a growth model including defensive expenditure, see Beltratti (1996). In this model, however, the presence of defensive expenditures cannot generate a self-propelled process of growth, since (i) a rise in defensive expenditures does not increase the level of economic activity by inducing individuals to work harder, and (ii) the flow of use of the environmental asset is fixed (it is not affected by the level of production).

It is also worth noting that the prediction that population increase will raise the rate of growth of per capita income is entirely consistent with the predictions made by models of endogenous technological change (see Grossman and Helpman, 1991; Aghion and Howitt, 1992; Kremer, 1993). However, our model has normative implications regarding the desirability of population increases which are at odds with those stressed by models of endogenous technological change, since our prediction depends on the increase in negative externalities due to congestion (increased pressure on environmental and social assets), rather than on positive externalities due to scale effects.[12]

Growth and institutional shocks

The model predicts that an institutional shock which causes a collapse of free resources will accelerate growth. This acceleration is only transitory and in the long run the economy will resume the steady-state per capita rate of growth determined by its structural features. As a permanent effect of this acceleration, the economy tends to be endowed with a higher capital stock at any future point in time. However, the net expected impact of such a shock on households' lifetime well-being is negative, since as the economy moves back to steady state, people suffer from the welfare decline due to the fall-off in the endowment of environmental and social assets.

More than one historical episode could be cited as examples of institutional shocks of this kind. Perhaps the best known example, however, is provided by the 'enclosures', the process whereby the private ownership of land was extended in Britain. The enclosures broke up the communal institutions of land use and deprived vast numbers of the rural population of their means of subsistance, uprooting them from agricultural under-employment and forcing them into urbanization or vagabondage. In our terms, the enclosures constituted a collapse of free consumption,[13] and historians widely recognize that they were a pre-condition for the formation of an industrial labor supply.

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[12]In models of technological change an increase in population spurs technological change and economic growth by increasing the size of the market, because the cost of inventing a new technology is independent of the number of people who use it. According to Kuznets (1960) an increase in population boosts technological progress by favouring intellectual contacts among people and labor specialization. In this way, greater population density can explain the disproportionally larger number of innovations in cities.

[13] Transition since the end of state socialism in East Europe can be interpreted as another social experiment in growth set in train by the collapse of institutions allowing the free consumption of (low quality) goods and services.

Explanations *à la* Polanyi of the role of institutional shocks in determining growth accept the neo-institutionalist emphasis on the importance of the extension of private property. But they give an explanation of its role in determining growth which differs entirely from that couched in terms of the increased efficiency, accumulation and technical progress brought about by the internalization of externalities.[14] In Polanyi's context, which we shall attempt to formalize, the extension of exclusion rights may trigger growth because it restricts rights of free access to resources. The two explanations are not incompatible: the explanation in terms of a decline in free consumption may point to a further reason why private property generates growth. After all, the mechanism *à la* Polanyi may be considered to be the reverse side of the neo-institutionalist mechanism: the attribution of exclusion rights to someone, alters his/her decisions concerning the use of the resource, which becomes subject to his/her right but also reduces someone else's right of access to that resource. Polanyi emphasises the general equilibrium reaction to this reduction: increased participation in the labour and product markets.

Growth, discount rate and long-term welfare

One prediction of the model is that the long-term welfare of individuals tends to decline as they discount the future less heavily: the greater the concern of living individuals about the future, the more they will worsen the prospects of future generations. This apparent paradox depends on the fact that rational individuals more anxious about the future are inclined to save more in order to safeguard their welfare (or the welfare of their descendants) in anticipation of a deterioration in the free resources. In doing so, they accelerate both the long-run growth rate of the economy and the deterioration of social and environmental assets, thereby reducing their long-term well-being (and the well-being of their descendants) because the increased availability of produced goods does not compensate for the poorer quality of free resources. More intense and uncoordinated efforts by individuals to safeguard their future welfare may reduce the long-term welfare of all agents as an unintended outcome of their individual strategies.

This result reverses the conventional environmentalist explanation that the problems of sustainability depend on the selfishness of the present generation – that is, on its too high discount rate (see Pearce, 1993). This explanation can be inconsistent: one cannot argue that economic growth depends on the accumulation of productive assets – which is boosted by a low rate of time preference – while also claiming

[14] In North's growth theory, around 10,000 years of human economic progress have been driven by the establishment of rights (first communal and then private) on resources (see North and Thomas, 1973; North, 1981).

that the problems of social and environmental sustainability – which can be exacerbated by high growth rates – are made more serious by a high discount rate (see Vercelli, 1992). In our approach, the problem is not intergenerational conflict, but coordination failure among individuals belonging to the same generation. Given the public-good character of environmental quality, this failure requires appropriate policy responses.[15]

Growth and its desirability

It should be noted that even in an economy in which growth involves the further deterioration of free resources, and mainly concerns their substitution with produced goods, a higher rate of growth may lead to greater welfare. Although growth is based on a destructive process, a limited increase in the growth rate may generate Pareto-improvements. It seems plausible, in fact, that the social and environmental costs of industrialization are more than offset by, for instance, the decline in child mortality or by increased life expectancy. However, in the presence of negative externalities, growth tends to exceed the threshold beyond which its destructive effects predominate over its beneficial impact on welfare. As a result of a coordination failure, growth "goes too far", bringing about an excessive use of labor and the deterioration of free

[15] This call for collective action is consistent with the hypothesis that "even for those dimensions of environmental quality where growth seems to have been associated with improving conditions, there is no reason to believe that the process is an automatic one", since "the stongest link between income and pollution in fact is via an induced policy response" (Grossman and Krueger, 1995, pp.371-372). In its turn, this policy response is driven by citizen demand. In the recent debate on the so-called 'environmental Kutznets curve', i.e., on the hypothesis that the relationship between per capita income and environmental degradation takes an inverted U-shaped form, also Arrow et al. (1995) claim that economic growth is no substitute for environmental policy. Moreover, they note that "reductions in one pollutant in one country may involve increases in other pollutants in the same country or transfers of pollutants to other countries" (Arrow et al., 1995, p.92). Estimating a dynamic model, De Bruyn et al. (1998) show that economic growth has a direct positive effect on the levels of emissions, thus supporting the radical standpoint, according to which the idea that economic growth can be good for the environment is 'false and pernicious nonsense' (see Ayres, 1995). However, it should be emphasised that sustainability is not simply a function of the levels of emissions and resource depletion, since it depends on the capacity of natural systems to absorb wastes and renew resources (see Kaufmann and Cleveland, 1995).

resources. This coordination failure is obviously due to market incompleteness: missing markets for scarce resources generate undesirable growth.[16]

Hence, the existence of substitute consumption may worsen welfare, compared with the case in which there is no opportunity for substitution.[17] In other words, the reaction of agents to a worsening in their living conditions may cause their further deterioration. This is a coordination failure: the model describes a world of individuals whose uncoordinated efforts to improve their position may give rise to a general worsening of individual positions. This might be a factor in explanation of the "broken promises of growth": dissatisfaction with the world created by the advanced economies, which people perceive as stressful, fraught with economic difficulties, and characterized by the deterioration of the social and natural environment. Analyses of subjective data, like the perceptions by individuals of their own welfare, conclude that the correlation between growth and well-being seems, in the most optimistic of evaluations, "very slight"[18]: growth does not make people feel significantly better.

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[16] This amounts to claiming that a market system may generate excessive growth on account of the fact that it is incomplete. We would emphasise the difference here with respect to the endogenous growth literature, where markets are incomplete (given that there are positive externalities) and growth is sub-optimal (if markets for positive externalities existed, steady state growth rates would be higher). This implies that the completeness of markets generates growth. In our model, by contrast, the completeness of markets lowers the steady-state rate of growth rather than enhancing it.

[17] In the literature on sustainable development, the degree of sustitability between 'man-made' capital and natural capital is considered crucial for sustainability. If they are perfect substitutes, the condition for sustainability is that the aggregate stock of capital ('man-made' plus natural) should not decline ('weak' sustainability) (see, for instance, Hartwick, 1986). If they are not perfect substitutes, sustainable development requires that there be no net damage to environmental assets ('strong' sustainability) (see, for instance, Pearce *et al.* , 1990, Daley, 1991). Both concepts of sustainability implicitely assumes that a high degree of sustitutability can be welfare improving for future generations. In contrast, our model shows that the possibility of substituting man-made goods for environmental assets can give rise to a self-reinforcing process that leads to a long-term worsening of individual well-being.

[18] The expression is Oswald's (1997), who makes the most optimistic evaluation of the data on individuals' perceptions of their own happiness. More pessimistic is Easterlin (1974, 1995), for whom happiness is the same in rich and poor countries, and growth does not increase well-being.

The most general policy implication of the existence of Pareto-worsening growth dynamics is that there may be socially undesirable growth mechanisms whereby growth is the outcome (and the cause) of social and environmental deterioration. When growth is of this type – that is, based on high social costs – it is unlikely to give rise to an improvement in welfare (and neither, probably, to social stability). This paper counsels great caution with regard to growth policies able to achieve their goals but at high social and environmental costs. Welfare-generating processes and social institutions that do not work through the market may be complex and fragile. Fuelled by their degeneration, and at the same time provoking their sometimes irreversible crisis, a growth dynamic may determine a non-transitory deterioration in the welfare of the populations concerned.

2. The model and the optimizing behavior of agents

We consider an economy in discrete time with an infinite time horizon. There is a large number I of identical households with finite lifetimes: they have a strictly positive and constant probability $\omega, 0 < \omega < 1,$ of dying in each period. Thus, the probability of dying in each period is assumed to be independent of the age of the individual; and it is also assumed that the mortality rate of a large group of individuals does not fluctuate stochastically even though each individual's lifespan is uncertain. This implies that at the end of each period a constant number $(1 - \omega)\mathrm{I}$ of households dies and is replaced by an equal number of newly born individuals.

Households' utility

The period utility function of the representative household, U_t, is additively separable between consumption and leisure:

$$\mathrm{U}_t = \beta f(x_t) + (1 - \beta) g(l_t), 0 < \beta < 1, \; f' > 0, \; f'' < 0, g' > 0, g'' < 0, \tag{1}$$

where x_t is the amount of services generated by a consumer activity in period t, and l_t is leisure. Households generate x_t by combining a resource to which all individuals have free access in every period and a consumer good that can be privately appropriated:

$$x_t = \mathrm{R}_t \mathrm{C}_t, \tag{2}$$

where R_t is the endowment (or an index of the quality) in t of the free resource, and C_t is the amount of a produced good consumed in t. Note that there is non-rivalry in the consumers' use of R_t, from which no consumer can be excluded, since it has the nature typical of a public good. The intuition underlying (2) is that individuals are unable to gain any utility from the consumption of private goods if they have no access to some free resource (air, environment etc.). However, households may respond to a deterioration in the free resource by using increasing quantities of private goods in substitution for it, thus restricting the worsening of their welfare.

Production

There is only one good Y_t produced in this economy. Each household produces this single good according to the technology

$$Y_t = AK_t h_t, \ A > 0, \tag{3}$$

where A is a parameter measuring the state of technology, K_t is the stock of capital existing in t, and $h_t = 1 - l_t$ are the units of time spent working in t by the household (the total amount of time available to each household in period t is normalized to be one). Capital can be interpreted in a broad sense, inclusive of all reproducible assets, and h_t can be defined as the capital operating time.

Capital

The stock of capital evolves according to

$$K_{t+1} = Y_t + (1-\sigma)K_t - C_t, 0 < \sigma < 1, \ K_t \geq 0, K_0 \text{ given,} \tag{4}$$

where σ is a capital depreciation parameter. For the sake of simplicity, we assume that the individuals born in t inherit K_t from the households that have just died.[19]

Free resource

The motion of the free resource is governed by

$$R_{t+1} = \rho R_t + \gamma, 0 < \rho < 1, \gamma > 0, R_0 \text{ given,} \tag{5a}$$

or, alternatively, by

$$R_{t+1} = \rho R_t + \frac{\gamma}{\alpha I Y_t}, \alpha > 0, R_0 \text{ given.} \tag{5b}$$

In (5a) the evolution over time of the common resource R_t is not affected by the volume of productive activity, while (5b) captures in simple manner the idea that the ability of the free resource to regenerate declines with the level of aggregate production, whose impact on R_{t+1} depends on the technological

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[19] All the results of this model also hold if one assumes that households take accumulation decisions with a view to the welfare of their descendants, thereby linking individuals in infinite lived dynasties.

parameter α. Given that the economy is populated by a large number of households, the negative effect of a single household's output on the future endowment of the resource is negligible.

Households' objective

In each period, the representative household must decide on h_t and C_t in order to maximize the discounted sequence of utilities that it expects during its lifetime:

$$\sum_{i=0}^{\infty}\theta^{i}U_{t+i}, \ \theta \equiv \zeta(1-\omega), 0<\zeta\leq 1, \tag{6}$$

where ζ is a time preference parameter. Expectations are rational, in the sense that they are consistent with the true processes followed by the relevant variables.

Optimizing behavior

Maximizing the Hamiltonian $H_t = \sum_{i=0}^{\infty}\theta^{i}\left\{U_{t+i} - \lambda_{t+i}\left[K_{t+i+1} - AK_{t+i}h_{t+i} - (1-\sigma)K_{t+i} + C_{t+i}\right]\right\}$ with respect to C_t, h_t and K_{t+1}, where λ_{t+i} is the multiplier, we obtain the following conditions that an optimal path must satisfy:

$$\beta R_t \frac{df(.)}{dx_t} = \lambda_t, \tag{7a}$$

$$(1-\beta)\frac{dg(.)}{dl_t} = AK_t\lambda_t \tag{7b}$$

and

$$\lambda_t = \lambda_{t+1}\theta\left(Ah_{t+1} + 1 - \sigma\right). \tag{8}$$

An optimal path must also satisfy the laws of motion (4) and (5), and the transversality condition

$$\lim_{t\to\infty}\theta^{t}\lambda_t K_t = 0. \tag{9}$$

According to conditions (7), the marginal utility of leisure must be equal for optimality to the increment in utility obtainable by devoting one additional unit of time to work. The latter depends on both the endowment of free resource available in t, which influences the utility that the household can obtain by consuming the private good, and the stock of capital available in t, which affects the marginal productivity of labor.

The intertemporal trade-off faced by the household along an optimal path is captured better if (7) and (9) are used to rewrite (8) as

$$R_t \frac{df(.)}{dx_t} = \sum_{i=1}^{\infty}\theta^{i}(1-\sigma)^{i-1}Ah_{t+i}R_{t+i}\frac{df(.)}{dx_{t+i}}. \tag{10}$$

Equation (10) states that along an optimal path the marginal utility of consuming an additional unit of a private good must be equal to the increment in the discounted sequence of future utilities that the household can expect to obtain during its lifetime by accumulating an additional unit of capital. Obviously, the future productivity of capital depends on the time that the household decides to devote to work, and on the state of the technology.

3. Equilibrium paths

In this section we give an example[20] which shows that this economy can achieve a strictly positive long-run growth rate only if there are negative externalities, i.e. if the motion of the free resource is governed by (5b).

Let us specify the following functional forms for the utility function in (1):

$$f(x_t) = \ln(x_t - m), m > 0, \tag{11}$$

and

$$g(l_t) = \ln(l_t). \tag{12}$$

In (11), C_t and R_t are substitutes, in the sense that $\frac{\partial f(.)}{\partial C_t}$ is decreasing in R_t holding C_t constant,[21] and m represents a subsistence level of consumption: $f(x_t) \to -\infty$ as $x_t \to m$.

Equilibrium as the evolution of the resource is not affected by productive activities

Using (4), (7), (8), (11) and (12), one can obtain the system of equations that together with (5a) govern this economy in the absence of negative externalities:

$$\frac{K_{t+1}(1-h_{t+1})}{\theta(Ah_{t+1}+1-\sigma)} = K_t(1-h_t) \tag{13}$$

and

$$K_{t+1} = AK_t h_t + K_t(1-\sigma) - \frac{A\beta(1-h_t)K_t}{(1-\beta)} - \frac{m}{R_t}. \tag{14}$$

By writing the system (5a), (13) and (14) as

$$\frac{Z_{t+1}}{(1+\mu_t)} = \rho Z_t + \gamma K_t, \; Z_t \equiv R_t K_t, \mu_t \equiv \frac{K_{t+1}-K_t}{K_t}, \tag{15}$$

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[20] See the appendix for another example.

[21] The other example outlined in the appendix shows that unbounded growth is possible in the presence of negative externalities even if C_t and R_t are complements, i.e. even if $\frac{\partial f(.)}{\partial C_t}$ is increasing in R_t holding C_t constant.

$$\frac{(1+\mu_t)(1-h_{t+1})}{\theta\left(Ah_{t+1}+1-\sigma\right)}=(1-h_t) \tag{16}$$

and

$$1+\mu_t = Ah_t + (1-\sigma) - \frac{A\beta(1-h_t)}{(1-\beta)} - \frac{m}{Z_t}, \qquad 17)$$

it is evident that (15)-(17) has no fixed point such that $\mu_{t+1}=\mu_t=\mu>0$: in the absence of negative externalities, this economy cannot grow forever at a constant rate. The unique steady state of the economy when R_t evolves according to (5a) is characterized by

$$\bar{\mu}=0, \tag{18a}$$

$$\bar{R}=\frac{\gamma}{1-\rho}, \tag{18b}$$

$$\bar{h}=\frac{1-\theta(1-\sigma)}{\theta A}$$

(18c)

and

$$\bar{K}=\frac{m/\bar{R}}{A\bar{h}-\sigma-\frac{A\beta(1-\bar{h})}{(1-\beta)}}. \tag{18d}$$

It is worth noting in (18c) that the elasticity of $\bar{h}$ with respect to the state of technology, A, is unitary: in the long run, a once and for all technological improvement causes a fall in the units of time devoted to work of the same proportion. One can also check for reasonable parameter values that the system which is obtained by linearizing (5a), and (13)-(14) around (18) exhibits saddle-path stability.[22] Moreover, the stable arm converging to (18) is the unique optimal path of this economy.[23]

Even if the production function is such that for given levels of technology and labor effort the marginal productivity of capital does not decline as K_t is raised, it is never optimal to allow capital to grow

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[22] Linearizing (13)-(14) around (18) yields the following characteristic equation:
$\xi^2-\left\{\frac{\theta A(1-\bar{h})\left[(1-\beta)(A\bar{h}+1-\sigma)-A\beta(1-\bar{h})\right]+(1-\beta)(2-\sigma+A)}{(1-\beta)[1+\theta A(1-\bar{h})]}\right\}\xi+\frac{A+(1-\sigma)}{1+\theta A(1-\bar{h})}=0,$ where ξ_1 and ξ_2 are the characteristic roots. Letting $A=.5625, \gamma=1, \theta=.8, m=\sigma=.2, \beta=.5$ and $\rho=.75$, one obtains $\bar{h}=.8, \xi_1=.962$ and $\xi_2=1.299$.

[23] Explosive paths of K_t and h_t can be ruled out because they violate the transversality condition, while implosive paths can be ruled out because--as K_t approaches zero--consumption must fall to a level that is inconsistent with the optimality conditions.

forever. This is because leisure can be substituted for consumption. Indeed, an economy that has the prospect of becoming richer by accumulating capital tends to reduce the saving rate because the return on capital investment is lowered by the shorter time that individuals will devote to work as the capital stock grows larger and the economy becomes more productive.

Equilibrium as the evolution of the resource is affected by productive activities

In the presence of externalities, the economy moves along the path governed by (5b), (13) and (14). Again, this system can be rewritten as (16), (17) and

$$\frac{Z_{t+1}}{(1+\mu_t)} = \rho Z_t + \frac{\gamma}{\alpha I A h_t}. \tag{19}$$

By setting $\mu_{t+1} = \mu_t = \mu$, $Z_{t+1} = Z_t = Z$ and $h_{t+1} = h_t = h$ in (16), (17) and (19), one can solve for the steady state of this economy in the presence of negative externalities:

$$\tilde{\mu} = \theta(A\tilde{h} + 1 - \sigma) - 1, \tag{20a}$$

$$\tilde{Z} = \frac{\gamma(1+\tilde{\mu})}{\alpha I A \tilde{h}[1 - \rho(1+\tilde{\mu})]}, \tag{20b}$$

$$\tilde{x} = \frac{\beta A(1-\tilde{h})\tilde{Z}}{(1-\beta)} + m \tag{20c}$$

and

$$\tilde{h} = h(A, \gamma, \alpha, m, \beta, \sigma, \rho, \theta, I).^{24} \tag{20d}$$

In general, we have $\tilde{\mu} \neq 0$:[25] the long-run per capita growth rate of this economy can be strictly positive. Moreover, it is possible to check for reasonable parameter values that the system which is obtained by linearizing (16), (17) and (19) around (20) exhibits saddle-path stability:[26] the stable arm converging to the long-term equilibrium is the only path consistent with (7)-(9).

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[24] $h(.) = b/2a + \sqrt{(b/2a)^2 - c/a}$, where $a = \gamma\theta A^2[(1-\beta)(1-\theta) + \beta] + m\alpha I(1-\beta)\rho\theta A^2$,

$b = \gamma\theta A[\beta A - 2(1-\beta)(1-\theta)(1-\sigma)] + m\alpha I(1-\beta)A[1-\rho\theta(1-\sigma)] - \gamma\theta\beta(1-\sigma)A$,

$c = \gamma\theta(1-\sigma)[(1-\beta)(1-\theta)(1-\sigma) - \beta A]$ (it is reasonable to assume that c<0).

[25] It is apparent in (20a) that $\tilde{\mu} = 0$ if and only if the parameters' values are such that $\tilde{h} = \frac{1-\theta(1-\sigma)}{\theta A}$.

[26] The economy governed by (16), (17) and (19) evolves according to the following system of difference equations in h_t and Z_t:

$$\frac{I A \alpha h_t Z_{t+1}}{I A \alpha h_t \rho Z_t + \gamma} = \frac{\theta(A h_{t+1} + 1 - \sigma)(1-h_t)}{(1-h_{t+1})},$$

$$\frac{I A \alpha h_t Z_{t+1}}{I A \alpha h_t \rho Z_t + \gamma} = A h_t + 1 - \sigma - \frac{\beta A(1-h_t)}{(1-\beta)} - \frac{m}{Z_t}.$$

An economy that has the prospect of increasing its private wealth by accumulating capital tends to keep the saving rate constant as households anticipate that the future endowment of the free resource will be negatively affected by the growth process, which induces them to increasingly substitute the private good for R_t in their consumer activity. As the capital stock grows, and as the free resource deteriorates, the value of C_t for households increases relatively to the value of time, and the return on capital investment is not depressed by the willingness of households to work less. The increasing labor productivity brought about by the rising capital stock is not used to reduce the time devoted to work, because the deterioration of R_t makes it more urgent to increase private consumption. In other words, growth is a self-fuelling process caused by a coordination failure. Acting entirely independently of each other, households seek to defend their future welfare against the deterioration of the free resource by increasing their ability to consume private goods in substitution for R_t. They can do so by keeping both their saving rates and their labor supplies relatively high. Accordingly, they cause a further deterioration of R_t, thereby fuelling the process. Perpetual growth is the outcome of this self-fuelling process.

4. **Implications of the model and possible extensions**

Some implications

There are various implications of the mechanism described above.

1) In the absence of negative externalities, optimizing households react to technological progress by reducing their working time: in the long run, a technological improvement leads to a fall in the units of time dedicated to work of the same proportion. This is not the case in the presence of negative externalities even if preferences are exactly the same. The increased output obtainable with given quantity of K_t and L_t thanks to a permanent improvement in the level of technology (higher A) tends to

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The characteristic equation of the system obtained by linearizing this system around (20) is the following:

$$\zeta^2 + \left\{\frac{IA\alpha\tilde{h}\rho\tilde{Z}}{IA\alpha\tilde{h}\rho\tilde{Z}+\gamma} + \frac{\theta(\tilde{h}A+1-\sigma)+(1-\tilde{h})A[1+\beta/(1-\beta)]}{\theta(A+1-\sigma)}\right\}\zeta +$$

$$+\left\{\frac{\theta(\tilde{h}A+1-\sigma)+(1-\tilde{h})A[1+\beta/(1-\beta)]}{\theta(A+1-\sigma)}\right\}\frac{IA\alpha\tilde{h}\rho\tilde{Z}}{[IA\alpha\tilde{h}\rho\tilde{Z}+\gamma]} = 0,$$ where ζ_1 and ζ_2 are the characteristic roots. Letting 1=A=I= $\gamma=\alpha, \theta=.8, m=\sigma=.2, \beta=.5$ and $\rho=.6$ yields: $\tilde{h}=.7265009, \tilde{Z}=6.28905,$ $\tilde{\mu}=.2212, \zeta_1=-1.2279$ and $\zeta_2=-.7327$.

accelerate the deterioration of the free resource, thereby eliminating the incentive to use the higher labor productivity to obtain more leisure.[27]

2) As capital and labor grow more productive as a result of technological progress, the economy tends to be characterized by a higher long-run growth rate of capital and output, which compensates for the faster degradation of R_t. Therefore, a permanent improvement in technology tends to be associated with a higher steady-state rate of saving.[28] Note that at steady state the saving rate does not decrease even if private wealth (capital) grows larger. This is because social wealth also comprises R_t, which declines at steady state as K_t is accumulated.

3) Steady-state growth consists in the progressive substitution of goods that can be privately appropriated for commonly owned goods whose endowment is declining.[29]

4) Both a larger population size (larger I) and a greater impact of a given level of production on the free resource (larger α) tend to boost long-run per capita growth, but at the cost of a declining steady-state level of household welfare.[30] In fact, everything that exerts greater pressure on the free resource and accelerates its decline induces individuals to react by working and saving more. Thus, according to the model, policies which reduce population growth and the environmental impact of productive activities restrain the long-term per capita growth rate of the economy.

5) It is worth noting that an institutional shock causing a collapse of the free resource (a once and for all fall in R_t) accelerates growth. This acceleration is only transitory and in the long run the economy will resume the steady-state per capita rate of growth determined by its structural features. As a permanent effect of this acceleration, the economy tends to be endowed with a higher capital stock at any future point in time. However, the net expected impact of such a shock on households' lifetime well-being is

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[27] Letting 1=A=I= $\gamma = \alpha, \theta = .8, \mathrm{m} = \sigma = .2, \beta = .5$ and $\rho = .6$, a 10% increase in A yields a 1.01% increase in $\tilde{\mathrm{h}}$, to a 23% increase in $\tilde{\mu}$ and to a 6% increase in the steady-state (gross) rate of saving.

[28] See the previous note.

[29] In a steady state with $\tilde{\mu} > 0$, we have both $\mathrm{Y_t} \to \infty$ and $\mathrm{R_t} \to 0$ as $\mathrm{t} \to \infty$.

[30] $1 = \mathrm{A} = \gamma, \theta = .8, \mathrm{m} = \sigma = .2, \beta = .5$ and $\rho = .6$, we have $\tilde{\mu} = .2212$ and $\tilde{\mathrm{U}} = -.377$ with $\mathrm{I} = \alpha = 1$, while $\tilde{\mu} = .2216$ and $\tilde{\mathrm{U}} = -.378$ with $\alpha = 1.0204$ and $\mathrm{I} = 1$ or with $\mathrm{I} = 1.0204$ and $\alpha = 1$.

negative, since as the economy moves back to steady state individuals suffer from the welfare decline due to the fall in R_t.[31]

6) As individuals discount the future less heavily (higher θ), steady-state welfare tends to decline.[32] Households more anxious about the future are inclined to save more in order to safeguard their welfare (or the welfare of their descendants in a dynastic framework) in anticipation of deterioration in the free resource. In so doing, they accelerate both the long-run growth rate of the economy and the deterioration of R_t, thereby lowering their steady-state utility (and the utility of their descendants).

7) In this economy, indeed, a higher long-run rate of growth of per capita output may be associated with a lower steady-state level of utility[33]. A benevolent planner would enjoin households to save less and to enjoy more leisure than they would be inclined to do if they acted in full autonomy, thus lowering the steady-state rate of growth (see the Appendix).

Possible extensions

A huge amount of empirical and theoretical research is required to find systematic evidence consistent with the growth paradigm outlined in the paper and to enrich its formal foundations. On the theoretical agenda, we give priority to extension of the model in two directions. Technological progress – both in the form of advances which boost the productivity of labor and capital, and in the form of improvements which reduce the impact of production on free resources – should be treated as the outcome of agents' behavior conditioned by institutional constraints and public policies. Furthermore, a highly

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[31] Let the parameters' values be $1=A=I=\gamma=\alpha, m=\sigma=.2, \theta=.8, \beta=.5$ and $\rho=.6$, and suppose that the economy is at its steady state. In the absence of shock, the economy will grow at a constant rate $\tilde{\mu}=.2212$.

Linearizing the system that governs the motion of the economy around the steady state, one can compute that a 1.59% fall in Z_t will cause an immediate acceleration of growth $(\mu_t=.258)$ as the economy starts moving back to its steady state (after 4 periods, the capital stock is higher than it would be without the shock: $\prod_{i=0}^{3}(1+\mu_{t+i})=2.2549>(1+\tilde{\mu})^4=2.224$). This acceleration is accompanied by a 5.26% fall in the sequence of discounted utilities of the first 4 periods after the shock.

[32] Letting $1=A=I=\gamma=\alpha, m=\sigma=.2, \beta=.5$ and $\rho=.6$, we have $\tilde{\mu}=.2212$ and $\tilde{U}=-.377$ with $\theta=.8$, while $\tilde{\mu}=.27$ and $\tilde{U}=-.4$ with $\theta=.82$.

[33] See the preceding note.

promising line of inquiry would be examination of how wealth and income distribution interacts with the growth mechanism described here.

Appendix

1) Another example of an economy exhibiting endogenous growth only in the presence of negative externalities

Let $g(l_t)$ still be given by (12) and specify $f(x_t)$ as

$$f(x_t) = \sqrt{x_t}\ . \qquad \text{(A1)}$$

(4), (7), (8), (12) and (A1) can be used to obtain the equation that together with (15) and (16) governs this economy in the absence of negative externalities:

$$1 + \mu_t = \mathrm{Ah}_t + (1 - \sigma) - \mathrm{Z}_t \left[\frac{\beta \mathrm{A}(1 - \mathrm{h}_t)}{2(1 - \beta)} \right]^2 . \qquad \text{(A2)}$$

Again, it is evident that the system consisting of (15)-(16) and (A2) has no fixed point such that $\mu_{t+1} = \mu_t = \mu > 0$: in the absence of negative externalities, neither can this economy grow forever at a constant rate. The unique steady state of the economy with a strictly positive capital stock and with R_t evolving according to (5a) is characterized by (18a), (18b), (18c) and

$$\overline{\mathrm{K}} = \frac{(\mathrm{A}\overline{\mathrm{h}} - \sigma)(1 - \beta)}{\overline{\mathrm{R}}} \left[\frac{2(1 - \beta)}{\beta \mathrm{A}(1 - \overline{\mathrm{h}})} \right]^2 . \qquad \text{(A3)}$$

One can check for reasonable parameter values that the system obtained by linearizing (15)-(16) and (A2) around this steady state is saddle-path stable, which suggests that this economy has a unique optimal path.

In the presence of externalities, this economy moves along the path governed by (16), (19) and (A2). Solving for the steady state of this economy in the presence of negative externalities, one obtains (20a), (20b),

$$\tilde{x} = \left[\frac{\beta \mathrm{A}(1 - \tilde{\mathrm{h}})\tilde{\mathrm{Z}}}{2(1 - \beta)} \right]^2 \qquad \text{(A4a)}$$

and

$$\tilde{\mathrm{h}} = \mathrm{b/a} - \sqrt{(\mathrm{b/a})^2 - \mathrm{c/a}}\ , \qquad \text{(A4b)}$$

where $\mathrm{c} = \dfrac{\mathrm{A}\beta^2\theta\gamma}{\alpha \mathrm{I}(1 - \beta)^2}$, $\mathrm{b} = \mathrm{c} + 2(1 - \theta)[1 - \rho\theta(1 - \sigma)]$ and $\mathrm{a} = \mathrm{c} + 4(1 - \theta)\rho\theta\mathrm{A}$. Letting $\mathrm{A} = \mathrm{I} = \gamma = \alpha = 1$, $\mathrm{m} = \sigma = .2, \theta = .8, \beta = .5$ and $\rho = .6$ yields $\tilde{\mathrm{h}} = .5591$ and $\tilde{\mu} = .0873$. One can check that the steady state characterized by (20a), (20b), (A4a) and (A4b) is the unique steady state of this economy, and that the system obtained by linearizing the system of two difference equations governing the motion of the economy in a neighborhood of this steady state is saddle-path stable. Also in this case, the model has the implications discussed in the text.

2) The optimal path selected by a benevolent planner in the presence of negative externalities

A benevolent planner would internalize the negative externalities caused by productive activities. For simplicity and without loss of generality, we normalize the large number of households to be one. Therefore, maximizing the Hamiltonian

$$H_t = \sum_{i=0}^{\infty} \theta^i \left\{ U_{t+i} - \lambda_{t+i}\left[K_{t+i+1} - AK_{t+i}h_{t+i} - (1-\sigma)K_{t+i} + C_{t+i}\right] + \zeta_{t+i}\left[R_{t+i+1} - \rho R_{t+i} - \frac{\gamma}{\alpha AK_{t+i}h_{t+i}}\right]\right\},$$

with respect to C_t, h_t, K_{t+1} and R_{t+1}, where λ_{t+i} and ζ_{t+i} are the multipliers, we obtain the following conditions that the optimal path must satisfy:

$$\beta R_t \frac{df(.)}{dx_t} = \lambda_t, \tag{A5a}$$

$$(1-\beta)\frac{dg(.)}{dl_t} = AK_t\lambda_t - \frac{\gamma\zeta_t}{\alpha AK_t h_t^2}, \tag{A5b}$$

$$\lambda_t = \lambda_{t+1}\theta\left(Ah_{t+1} + 1 - \sigma\right) - \frac{\theta\gamma\zeta_{t+1}}{\alpha AK_{t+1}^2 h_{t+1}} \tag{A6a}$$

and

$$\zeta_t = \zeta_{t+1}\theta\rho + \theta\beta C_{t+1}\frac{df(.)}{dx_{t+1}}. \tag{A6b}$$

The optimal path must also satisfy the laws of motion (4) and (5b), and the transversality conditions

$$\lim_{t\to\infty} \theta^t \lambda_t K_t = 0 \tag{A7a}$$

and

$$\lim_{t\to\infty} \theta^t \zeta_t R_t = 0. \tag{A7b}$$

Note that ζ_t captures the increment in the discounted sequence of future utilities that the representative household can expect to obtain during its lifetime thanks to a marginal increase in the current endowment of the free resource. Comparing (A5b) with (7b) shows that the benevolent planner also takes account of the negative effect of a marginal increment in working time on the future endowment of the free resource, and therefore tends to choose more leisure than each household would choose were it acting in full autonomy. Similarly, (A6a) can be compared with (8): in evaluating the expected effect on households' lifetime welfare of accumulating an additional unity of capital, the benevolent planner also takes account of the expected loss in discounted utilities due to the future decline in the free resource caused by the increased production. Considering (A5a) and (7a), this implies that the propensity to save tends to be depressed because a benevolent planner is able to dictate the optimal policies. It is evident that both the reduced working time and the depressed saving rate give rise to a lower steady-state rate of growth.

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