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LONG-TERM CONSEQUENCES OF POPULATION GROWTH: TECHNOLOGICAL CHANGE, NATURAL RESOURCES, AND THE ENVIRONMENT

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1. Introduction

This chapter surveys the long-term implications of population growth and its interaction with technological change, resources utilization and the environment. We ask: what are the key determinants of the processes of population growth and technical change and how do they interact with each other? Under what conditions can the people of the world enjoy rising living standards, and if they do, does population have to stabilize for this to be feasible? How do the answers to these questions depend on the relationship between human progress and the natural environment? Will growth be limited by lack of resources or negative environmental repercussions? Will the development of the world economy necessarily mean the despoiling of the environment?

This is a wide brief and we make it manageable by concentrating on what we see as the core analytical issues and using these to provide a framework with which to assess the empirical literature. While formulating a satisfactory overarching framework is virtually impossible, we think the evidence and the theory provides certain strong intuitions about the right way to see the issues and, in particular, to evaluate their welfare and policy implications. One of our main purposes is to elucidate these central issues and intuitions.

The questions which we address are arguably the earliest to be carefully studied in economics, yet they remain amongst the most controversial. Since ancient times social thinkers have speculated about the tensions between the size and growth of populations and the resources available for them. Such speculation has usually led to dire predictions most famously associated with the name of Thomas Malthus. While we touch on the classic “Malthusian debate”, since this critically involves the nature of the relationship between technical progress and population change, the main concerns of the chapter are the issues raised by “neo-Malthusians” – those concerned with the fragility of the environment, the impact of economic and population growth on the “natural capital stock” and the “sustainability” of development.

The economic history of the nineteenth and twentieth centuries has not been kind to Malthus in his prediction that the finiteness of resources and basic procreation behavior would trap society into a situation of economic stagnation. The result of this was a serious neglect of any such issues in the formal theory of growth which developed in the 1950s and 1960s. The 1970s changed this. In this decade much attention was focused on resource extraction and exploitation. This literature concentrated on the extent to which the finiteness of certain natural resources (oil, minerals, etc.) could place a bound on per capita income. The results were encouraging: under certain, arguably reasonable, assumptions about technical change and production technology (which we discuss in Section 2.3.2) society could substitute man-made for natural capital in such a way as to allow for a sustained growth in living standards. The dire predictions of Forrester (1971) and Meadows (1974), which received so much public attention, were relatively mechanistic extrapolations which ignored exactly the issues, which seemed of central importance to economists (see the discussion of Solow
(1974b) or Koopmans (1979), or from another (but equally balanced) perspective, Deneen (1988). The experience of adjustment to higher fuel prices, for example, the increased efforts to develop alternative energy sources, seemed to largely vindicate the economists views. Apocalyptic pronouncements, such as the forecast of Ehrlich (1970) that 65 million Americans would die of starvation in the 1980s, were made to appear foolish. As Michaels (1993) points out, “in fact 60 million Americans dieted during the period”.

Since the 1970s, however, the argument has shifted to a form which is not so easy to dismiss as that pertaining to finite resources. The more recent concerns focus not on whether or not the economy can find a suitable substitute energy source for coal, for example, but rather on the far more ambitious and elusive question of how economic processes and human activities are embedded in the global environment and the implications which population and income growth and economic activity have for this relationship.

Economy–environment interactions go in both ways and are subtle, pervasive, and mostly suppressed in economic analysis. The recent literature has brought these issues to the surface and into sharper focus. Their empirical implications and importance are, however, highly contentious. We suggest a way of integrating these issues with standard models of economic growth. While such a formalization is severely limited (due to a very inadequate understanding of the nature and dynamics of environmental processes), it is exceedingly helpful in elucidating the crux of the interaction between environmental phenomena, demographic processes and the nature of technical change. As Partha Dasgupta (1993c) puts it, “modern economic analysis has for some while provided us with a language in which to discuss the private and social management of environmental resources. In some cases the prescriptions are sharp and precise; in others they are outlines, but only because of the deep uncertainties we face about the nature of ecological processes and about our own values, and not because we do not have a precise language in which to think through them”. This framework has the additional advantage of bringing the tools of welfare economics to bear on the issues.

The interaction between the environment and the economy is obviously multifaceted. One cannot, for example, hope to capture the ramifications of the exploitation of local commons and the economic impact of climate change in a single model. We deal with this by using different models, each tailored to address an issue, or issues, which we feel to be central. Far from being a limitation of our approach, this is an advantage. In particular, we argue that the environmental problems, and their interaction with population growth, faced by developing economies are often qualitatively different from those facing developed economies. Many key environmental issues for the poor nations of the world, such as lack of potable water, inadequate sanitation, and air pollution due to the use of biomass fuels, are best solved by economic development. In these cases there is no trade-off between environment and growth. This is important since environmental improvement is often regarded as a luxury which poor nations cannot afford. We argue, along with the World Bank (1992), that there are strong
complementarities between policies to improve the environment, influence population growth and promote development in general. We also echo their conclusion that, in terms of orders of magnitude for human welfare, these problems are the most serious environmental problems facing the world.

We also argue that there is a more fundamental sense in which development and efficient utilization of the environment are complementary. This stems from the fact that both a major cause and symptom of underdevelopment is dysfunctional social and political institutions (as we argue in Section 3.3, this is one lesson of the recent revival of growth theory). Development necessitates institutional innovation and transition in order to stimulate capital accumulation and technological change, and institutions which impede these key aspects of development are highly unlikely to be able to implement efficient ownership structures or desirable policies with respect to resource use or the environment.

The situation is different in developed economies. While problems of local commons and inadequate property rights are also important, the main environmental problems are pollution, toxic waste disposal and worries about the global commons. While there are still local issues, such as for example, protection of natural habitats, these seem minor in comparison to those faced by developing countries. This seems to be the key reason why global environmental problems loom so large in the debate in developed economies. This is ironic since, if anything, poor countries face larger risks and will certainly find it more difficult to adjust to the economic impact of climate change. It is not that global problems do not affect poor countries, but rather that other problems are more tangible and pressing.

While we make this the main focus, this is a fledgling field with tremendous controversy amongst experts over the pertinent facts. Both the effects of economic growth and population growth on the natural capital stock are in dispute, as is the reverse relationship. Indeed, the perspective we adopt is that the main issues are empirical. In our theoretical treatment we stress that the evolution of population, technology and resource usage are all the jointly endogenous outcome of the decisions of agents in the economy. Much of the literature ignores one or other facets of this joint relationship. The literature is full of misleading and erroneous causal associations between population growth, income growth, and resource use.

Consider, as an example, the over use of local common resources in the presence of rapid population growth. It is tempting to attribute causality from population pressure to resource over-use, and indeed this may be read from a regression equation. We argue that both phenomena (rapid population growth and environmental degradation) are two consequences of poverty and underdevelopment and related institutional and policy failures. Both are a result of the actions of poor people attempting to cope with the situation in which they find themselves. The most plausible explanations for rapid population growth in developing economies link this to poverty, high infant mortality, and inadequate institutions (lack of insurance and saving possibilities, markets, and social infrastructure) and thus to the very roots of underdevelopment itself. Birdsall
and institutions are frequently to blame for environmental stress. A recurrent theme throughout the paper, for example, is the need to clarify and enforce property rights. While communities have developed institutions to ensure the efficient allocation of common resources (Ostrom (1990) provides insightful examples), it is these very institutional structures that are often disrupted in the process of development. Salient examples of policies affecting the environment are subsidies in Brazil to ranching which has caused a large amount of deforestation (seeBinswanger, 1989 or Feder, 1977, 1979), and migration incentives in Indonesia (for example, Barbier et al., 1989). Repetto (1988) lists other related examples. The subsidization of fuel inputs in Eastern European countries before the fall of communism led to the adoption of fuel intensive technologies which tended to produce high levels of pollution. Agricultural policies which depress the prices for farmers undermine profitability and reduce the adoption of more efficient and durable farming practices. The World Bank (1992) estimated that in a sample of five African countries logging fees represented only 33% of the costs of replanting. Similarly, charges for irrigation are far below efficient levels. Apart from these, there is a sad litany of major development projects which had severe, and largely unanticipated, environmental impacts.

We draw from this a relatively optimistic conclusion that tackling the central problems of underdevelopment is likely to be effective in solving both environmental problems and in initiating the demographic transition. What is critically important is that the problems are correctly identified and addressed. In the above examples it is underdevelopment, both in terms of low per capita income and in terms of social and political infrastructure (for example, the lack of representative, open and democratic political institutions) which is the heart of the problem.
It is also apparent, however, that to the extent that markets are incomplete and institutional responses inadequate or inappropriate the scope for potential Pareto improvements is large and no trade-offs have to be faced until all inefficiencies are eliminated. It is in an economy with complete and perfect competitive markets where equilibrium allocations are efficient (or in situations where some concept of constrained efficiency is appropriate) that real trade-offs occur. In such a world, society may have to choose between consumption of physical commodities and environmental resources, or between consumption per capita and aggregate population. We do little more than raise such issues. They clearly present all the well-known intractable normative questions of ordinal welfare economics. Our view is that there is much to be done before economists have to face these issues and that the real job is to find ways of implementing potential welfare improvements. This requires a careful study of the type of potential inefficiencies surrounding both the processes of population growth, technical change and that of resource utilization.

We adopt a remorselessly choice theoretic approach throughout the chapter and it is clear that this may have disadvantages. Indeed, as T.W. Schultz (1974) has remarked in a similar context, "I anticipate that many sensitive, thoughtful people will be offended by these studies (which) may seem far beyond the realm of the economic calculus". Especially with respect to the modeling of choices about fertility and family, the nature and specification of both the constraint set and the objective function are difficult. Many factors seem pertinent to the conditioning of fertility choices, some of which are: the availability of contraception, social norms and marriage patterns, the division of labor between males and females. Similarly, specification of the objective function seems equally fraught with complexity: do parents care about the welfare of their children, or how this welfare is generated, do they desire children for themselves or for what they can get out of them? The vexed nature of preferences becomes even more problematic at the level of social choices about population.

From the long-run perspective of human evolution, however, adopting the choice theoretic approach seems by far the most promising methodological approach. In prehistory hominid groups experienced moderate fertility. Both modern hunter-gatherers and our closest kin in the animal world, the sub-human primates, exhibit low fertility, certainly far below the physiological possible maximum (see Davis (1989) for an interesting perspective). One might ask: why? A plausible explanation is that, given the rudimentary nature of their ability to provide food for themselves, they deliberately controlled population to find some equilibrium with resources. This changed around 10,000 B.C. when humans began to settle and develop agricultural societies. Both situations have plausible economic explanations. The settling of previous itinerant populations, the domestication of animals and systematic cultivation of crops, created an enormous expansion of output. At the same time the division of labor changed. This is not to deny the existence of exogenous forces on population, for instance the development and diffusion of diseases or parasites (though the evolution of these themselves is clearly not exogenous to the organization of human society, McNeill
(1976)), but it suggests that the best method to understand the implications is through the lens of choice theory, at least if we take an eclectic enough position about the relationship between individual motivations and the interaction between individual and social constraints. The evidence also suggests that the crucial determinant of actual fertility is "desired" fertility (Pritchett, 1994) so that choices matter.

We see this approach as being complementary to others. Demographic processes are modeled in evolutionary biology. While the objective functions and constraints may be unusual for economists (such as stress on "reproductive success", "fitness", and "adaptive traits"), the conceptual framework is often surprisingly similar (see Cronk, 1991). As in the economics literature, there is no automatic stress on optimality. Previously adaptive behavior may persist even after it no longer confers any advantages (such as a preference in humans for sweet foods which previously helped to select nonpoisonous food), just as social behavior may persist due to norms and conventions long after it has become dysfunctional or redundant.

The derivation of behavior from individual preferences also allows us to treat welfare issues explicitly. One of our major conclusions concerning population growth is that we need to better understand the nature of inter-familial and inter-generational preferences. In lieu of such knowledge, the voluminous philosophical literature on optimal population growth, for example, is largely sterile.

In the next two sections we provide an overview of some of the facts about population growth, development and resources. It is difficult to come away from these with a firm understanding of these processes. The relationship between demographic phenomena and the economy is highly complex and does not yield to simple generalizations (see Caldwell, 1990; Birdsall and Griffin, 1988), and that between the economy and environmental features perhaps even more uncertain. For instance, Slade (1987) concludes her wide ranging survey by stating, "it should be abundantly clear that all attempts here to draw conclusions about the effects of resource scarcity on the growth of population and economic well-being at the macro level failed". We stress that little can be concluded from the aggregate evidence about the relationship between population and economic development or about the more complex relationship between these variables and resource exploitation and the environment. This is in line with the theory, which we discuss in Section 3.4, which suggests that the relationship is ambiguous and contingent on the exact structure of society and the responses and behavior that population growth or development induces.

As a salient example of this, consider the relationship between the level of per capita income and population growth. Birdsall (1989) concludes that "the exceptions suggest the importance of factors other than average income which affect demographic variables – factors that operate at the individual and family level: education, availability and distribution of health services, women's status, access to family planning, prevailing religious views, a country's population policy, and so on". These same complexities have foiled the attempt to construct "threshold" levels of economic and social indices which might signal the onset of demographic transition (see Caldwell, 1990;
Coale and Watkins, 1986). Similarly, while there are many examples of variegated and even seemingly alarming environmental problems, the evidence does not allow one to conclude that there is in any sense a crisis, or that, as we argued above, properly interpreted, development and growth have deleterious effects on the environment. The evolution of population, the environment, per capita income, and resource extraction are inexorably intertwined with the whole process of economic, political and social change which we call development, and this process does not yield to simple monocausal explanations or sweeping generalizations.

The introduction concludes by outlining our approach in more detail and then providing an overview of the paper.

1.1. Population past and population present: a review

Before commencing on the analytical heart of the paper, it is important to have some feel of the historical processes at work and the evidence. We first describe the facts about the evolution of population and its main determinants. We then focus on a key issue for this paper, the econometric evidence concerning the aggregate relationship between population growth and the level of per capita income. In Section 3.4 we turn in detail to more disaggregated studies.

In synthesizing the literature, we are fortunate in being able to call on authoritative summaries due to Cassen (1976), McNicholl (1984), World Bank (1984), National Research Council (1986), Kelley (1988), Birdsall (1988, 1989), Srinivasan (1988, 1992), Caldwell (1990), and Jha et al. (1994). In this section we wish to give a sense of what is known. While what is known is far less than one would wish, this section will orientate our discussion in the rest of the paper. The literature is full of shrill and vitriolic rhetoric and Cassandra-like warnings of impending doom, one of the more scholarly sources being the work of Keyfitz (1991a,b). Our reading of the evidence supports the more agnostic view prevalent in the recent scholarly literature on population growth (good examples being Kelley (1988, 1991)). We also try to persuade the reader that this seems the best approach to thinking about natural resources. Kelley (1988) suggests that the agnostic view has four essential aspects: “First, population growth may have positive as well as negative aspects, second, both direct and indirect linkages are important in connecting population and economic growth, third, several problems typically attributed to population are due largely to other causes, and finally, the role of population is sometimes to exacerbate other problems and to reveal their symptoms sooner and/or more dramatically”.

At first glance the size of the issue is enormous. It took millions of years for the population of the planet to reach one billion, 120 years to add a further billion, 35 years for the next, 15 years for the next, and another 13 years until the five billion mark was reached. Current estimates (World Bank, 1992) predict that world population will level off at around 12.5 billion in about 2150. Different scenarios give sta-
tiorary populations between 10.1 and 23 billion. Although these forecasts are debatable, given the uncertainties surrounding base-line population estimates as well as those of fertility and mortality rates in many developing countries, nobody disagrees that there will be considerable increases in population, even if all societies were to reach replacement fertility today. This latter phenomena has been called “population momentum” by Keyfitz (1982), who calculated that a developing country with a representative age structure could still expect population to grow by about one third after replacement fertility was attained. The World Bank has predicted that most developing countries would reach replacement fertility between 2005 and 2025 (though for some countries in the Middle East and Africa it is later). This is based on most countries already having experienced significant fertility declines (though this is not true of all countries, Nigeria for instance). As Sen (1993) points out, the number of people added to world population between 1980 and 1990 (923 million) is approximately the same as the population of the entire world at the time of Malthus.

The historical evidence is in fact relatively supportive of Malthus’s hypothesis for the period before 1800. The evidence presented in Lindert (1985) and Weir (1989) (see also World Bank, 1984) suggests that Malthus was basing his theory on sound evidence. The prediction that living standards would grind along at subsistence levels seems born out. Life expectancy was probably about the same in 1600 as it had been 2000 years before (World Bank, 1984). Population growth was positively related to wage increases and seems to have led to a consequent reduction in wages and fertility – the classic Malthusian cycle. This changed some time in the late 18th century (as Keynes put it, “the Malthusian devil was chained”). The industrial revolution heralded a period with both rising population and rising per capita income.

While in seventeenth century Britain fertility rose and mortality fell, fertility was much lower than that of contemporary developing economies, and mortality much higher. In Western Europe, marriage rates were low and those who married, married late. The mean rate of marriage in the seventeenth and eighteenth centuries in Belgium, France, England, Sweden and Germany was 25. In 1871, 50% of women aged 25–29 in Ireland were unmarried, while in England the figure was still a high 36%. The main reason for this appears to be that to marry young, people had to set up a separate household and this required resources. The greater relative poverty in Ireland explains the difference with England. The crude birth rates of European countries when their demographic transition took off were far lower than those of currently developing economies. Similarly, mortality was much higher. From this it follows that population growth rates were in aggregate very modest compared to those currently or recently experienced. In England, population growth peaked at 1.6% in the 1820s, and in France it never exceeded 1% in the nineteenth century. The demographic transition has now evolved so far that several countries have dropped below replacement fertility levels which itself has caused concern (Keyfitz, 1986).

The picture in the contemporary developing countries is different. Starting after the first World War mortality began to decline. The main cause seems to be the large im-
provements in medical science and practice (one famous example being the effect of the control of malaria on mortality in Sri Lanka). These mortality declines took place at much lower levels of income than those in western countries. For example, in 1982 life expectancy in India was 55, while its per capita income was below US$300 (in 1982 prices). In 1900, life expectancy in England, the United States and Sweden was below 50, and yet their average income was over US$1000 (in 1982 prices, see World Bank, 1984). It is also worth noting that the literacy rate of India was below 40% in 1982, while in these European countries it was over 80% in 1900. They were also (or maybe as a result) not immediately followed by significant falls in fertility. While these have now taken place, the rates of population growth experienced since World War II are unprecedented historically. For developing countries as a whole population growth rates rose from 2% in 1950 to 2.4% in 1965, mostly as a result of the falling death rates. Since then, rates of fertility have fallen faster than mortality, and current growth rates are, on average, over 2%, with considerable regional variation. In Africa, for example, the rate is 3% (the United Nations forecasts that the proportion of world population in Africa, which was 11% in 1980, will increase to 26% by 2100). Moreover, the declines in fertility rates have been much faster than those experienced by the developed countries. The average decline is dominated by that in China (which accounts for one third of all people in developing countries), although the East Asian countries have also experienced fast falls in fertility. However, there has hardly been any fall in fertility in Sub-Saharan Africa.

In an interesting comparison between European fertility declines during the period 1882–1900 and those of Taiwan and Thailand (which began in 1963 and 1970 respectively), Knodel and van der Walle found large differences. European economies began their transition to low fertility with a fertility rate which was two thirds of the Asian level and much higher infant mortality (between 150 and 200 first year deaths per 1000 live births as opposed to figures of 49 and 77 in Taiwan and Thailand respectively; see World Bank (1984)).

The empirical evidence overwhelmingly suggests that fertility and mortality are negatively related to per capita income, though, as mentioned above, this is not uniformly the case. For instance, there are many counter-examples to the claim that fertility will only fall when per capita income increases. Lutz (1990) provides an examination of one such case – Mauritius – of particular interest since the fertility rate declined spectacularly by 50% in less than a decade. Other famous examples are the states of Kerala and Tamil Nadu in India (see Sen, 1993) and Sri Lanka, all of which are close to achieving replacement rates of fertility. This demonstrates that a whole vector of variables, not closely correlated with per capita GDP, affect both fertility and mortality.

These facts describe the contours of the “demographic transition” both historically, as it happened in the developed countries, and as it is currently occurring in developing countries. There is a strong sense here that, while the details matter, on balance fertility, mortality and the rate of population growth, all fall as economies develop and
per capita income rises. This is due, not just to some simple relationship between income level and fertility and mortality, but also to the social and economic changes that accompany and are an intrinsic part of this process of development. Innovations and changes in institutions can disrupt simple correlations between variables.

The empirical consensus is that, despite many assertions to the contrary, there is no robust relationship between the rate of population growth and economic growth. This has been confirmed by a large number of works beginning with Kuznets (1966) and Easterlin (1967). Kelley (1988) provides an authoritative survey of this literature. He notes that “while several models predict a negative net impact of population growth on economic development, it is intriguing that the empirical evidence documenting this outcome is weak or nonexistent”. More recent work, with better data and more sophisticated econometric techniques, has found a small negative relationship.

Important recent examples are Bloom and Freeman (1988), Brander and Dowrick (1994) and Kelley and Schmidt (1994). These studies are sophisticated in trying to recognize the joint endogeneity (for example, by using instrumental variable techniques for estimation) of the series under consideration and in controlling for other factors in attempting to statistically isolate the relationship. They also broaden the scope of earlier work by assessing the influence of not just population growth, but also possible separate effects of fertility and mortality. Changes in these, while both sources of changes in population growth, might plausibly affect economic growth in differing ways. Indeed, Bloom and Freeman find that the breakdown of a rate of population growth into fertility and mortality is important. A particular growth rate of population has a smaller effect on income growth if it results from low fertility and low mortality. Using the Heston-Summers data set, Brander and Dowrick (1994) do find a negative relationship between population growth rates and birth rates and economic growth. However, the coefficients in their regression equations are typically insignificant statistically. The results are stronger for developed than for less developed countries, and stronger for recent rather than earlier years. They also find that investment is negatively, and significantly related to birth rates. Population growth tends to be unrelated to income and investment which is why Brander and Dowrick concentrate on birth rates. It is not clear, however, how robust these results are.

An important recent study by Kelley and Schmidt (1994) also finds evidence of a negative relationship between the rates of population and per capita income growth for the 1980s, while confirming the insignificance of the relationship for the 1960s and 1970s. They find, in contradistinction to Brander and Dowrick, that this effect is much more pronounced for developing countries and in fact is sometimes positive for developed countries. When they disaggregate this effect, Kelley and Schmidt find that it is accounted for by the emergence in the 1980s of a negative effect from the number of births (net of infant deaths) on income growth. This paper is also interesting because it provides the first corroborating evidence supporting the results of Simon (1986) who has found a statistically significant positive effect of population density on
income growth. They also find a pure size effect emerges in the 1980s. They further find that population growth exerts a negative effect on the saving rate.

The problem with interpreting all of this evidence is that, even if a robust negative relationship between population growth and income growth should emerge, we need to understand whether this is really causal or just a joint facet of the dynamics of technological change and demographic transition. As Cassen (1976) puts it, “in general a large amount of specification is needed to yield a prediction about the sign of the simple correlation between the growth of population and that of total of per capita income. Those found in practice are of negligible interest. And they are quite immaterial to the question of whether, in the given circumstances of a particular country, per capita income would grow more or less rapidly were population growing more slowly”. He goes on to conclude that “the one thing we can infer from these correlations is that whatever the influence of population on economic growth, it is relatively small in comparison to other influences”.

1.2. Growth, development, demography and resources: a perspective

Having considered the salient demographic evidence, we now proceed to assess the environmental evidence. Where possible we integrate this with demographic trends (as some empirical work has explicitly attempted to do). We wish to concentrate on environmental and renewable resources since these are the resources which seem most critical to human welfare. A large theoretical literature (which we review in Section 2.3.2) has examined the interconnections between exhaustible resources and growth. A number of empirical investigations have been conducted to try and estimate to what extent, if any, the world is running out of these resources, or the sense in which they might become a constraint on human activities. That this empirical literature exists is a testament to the fact that exhaustible resources differ from other environmental resources in that they tend to be owned and allocated on the basis of well defined property rights and, moreover, traded in markets at prices which we can observe. Contrast this to the problem of generating data on whether or not natural habitats are becoming more scarce.

1.2.1. Exhaustible resources

The consensus is that there is in fact little evidence that any serious scarcity is developing. Nordhaus (1994b) has estimated that real oil prices in 1986 were at the same level as in 1900. In Meadows et al. (1972), world supplies of lead in 1970 were put at 91 million metric tons. Beckerman (1993) reports that world consumption of lead between 1970 and 1989 was 98.5 tons, and yet in 1989 world reserves were estimated to be 125 million tons. There are many such examples. Simon (1981) also argues that there has been a decline in the real cost of resources and uses this as evidence that
worrying about shortages or increased scarcities are unfounded. One would expect that, if the world were suffering a resource crisis, relative prices would be rising. MacKellar and Vining (1987) in their comprehensive review found that no simple general answers were possible to questions such as: "Are natural resources becoming more scarce? Are conservation and population control policies called for?"

The evidence suggests that as long as resources are priced, so that prices can reflect scarcity and give incentives for substitution and conservation, then there seems to be little prospect that resources will constrain living standards. Exhaustible resources must eventually disappear, though there is of course the possibility of recycling to extend their life. Chandler (1984) estimates, for example, that the world steel industry uses scrap metal for 45% of its input requirements. Despite exhaustibility, it does seem possible to be optimistic, though, about the effect of pricing on the discovery of new resources and substitutes. For example, when Zaire, producer of about half of the world's production of cobalt, restricted supply by 30%, prices rose from $11 per kilo to $35. This led to an extensive introduction of substitutes and US demand fell by 50% (Goeller and Zucker, 1984). National Academy of Sciences (1986) list many other examples.

It is sensible to attempt to measure scarcity of these resources by looking at their long-term price movements (Barnett and Morse (1963) is a classic example). Although the evidence is mixed on balance, there seems to be no evidence of increasing scarcity. Thus far, depletion has been successfully met by new supplies being discovered (or becoming economical) or substitutes being developed (Slade, 1982, 1987). While the reliance of the world on petroleum is important, MacKellar and Vining (1987) point out that the potential supply from nonconventional sources (such as oil shale) is vast.

1.2.2. Renewable resources

On the topic of this section there are many preconceptions. Two types of problems are commonly raised when discussing the interaction of population growth, development in general and environmental resources in a wide sense.

Firstly, that growth can only be sustained by using up resources and depleting the environment beyond its ability to regenerate, and, secondly, as per capita income increases, the flows of wastes and pollutants increase as well, and the earth "sinks" and the natural ability of the environment to regenerate and absorb waste, will become overburdened.

There are two facets to these arguments. Firstly, a positive claim that the environment puts an upper bound on feasible per capita output and, worse, if damaged irreparably, may lead to the planet becoming uninhabitable. Second, that even if growth in per capita income is feasible, it cannot lead to increased human welfare if the environment is destroyed in the process.

Many caveats apply to these simple propositions. Development involves not just increases in total and per capita output, the composition is also important. For exam-
ple, later stages of development are characterized by the increasing importance of service industries which are much less resource intensive. Price incentives also stimulate the adoption of new "clean" technologies. The evidence we report below substantiates this intuition. As societies develop, the relative valuation of produced goods and the amenity services of environmental resources changes in ways which are conducive to conservation (this is a possible foundation for the environmental "Kuznets curve" which we discuss below). Moreover, the arguments implicitly assume an enormous myopia in human decision-making and disregard for the welfare of future generations which needs theoretical clarification and empirical substantiation.

We also argue that this common perception about growth and the environment is altered by widening what one means by the environment. Serageldin (1993) estimates that one billion people do not have access to clean water, 1.7 billion do not have access to sanitation, and 2–3 million children die annually because of diseases associated with this lack of water and sanitation. The World Bank (1992) estimates that 300 million to 700 million women and children suffer from severe indoor air pollution from cooking fires; lack of sanitation is the major contributor to 900 million cases of diarrheal diseases each year which cause the death of three million children; and two million of these could be prevented if adequate sanitation and clean water were available. Lack of sanitation has direct as well as indirect economic costs. For example, the World Bank (1992) also calculated that about 1% of the GDP of Jakarta in Indonesia was spent simply on boiling water. Another striking example is that in the first ten weeks of a recent cholera epidemic in Peru, losses in agricultural exports and revenues from tourism were more than three times the amount the whole country invested on improving sanitation and water supply facilities in the whole of the 1980s (World Bank, 1992). Certainly these numbers are subject to wide margins of error and biases, however, they do give an indication of the order of magnitude of the problem.

Economic growth has a big impact in reducing these environmental problems. The World Resources Institute (1990) estimates that, in 1985, while on average only 39% of people in the poorest quintile of countries had access to safe drinking water, on average 87% of people in the richest quintile had such access. Similar findings apply to sanitation.

Despite examples of this type, there seems to be a strong presumption that growth is inconsistent with environmental preservation. We argue that resource use is a natural part of a dynamic path. LDCs have much larger ratios of environmental resources to either physical and human capital, and it seems sensible that they would wish to exploit the former to obtain both of the latter. What is more crucial is the extent to which this use is efficient. This rests not on the growth rate per se, but rather on the economic, social, and political institutions of society. Even without growth in per capita income, resource usage may easily be disastrous without the correct set of institutions and incentives.

It is also thought that population growth has large adverse impacts on environ-
mental resources. The World Bank (1992) concluded: “Population growth increases the demand for goods and services, and, if practices remain unchanged, implies increased environmental damage. Population growth also increases the need for employment and livelihoods, which – especially in crowded rural areas – exerts additional direct pressure on natural resources. More people also produce more wastes, threatening local health conditions and implying additional stress on the earth’s assimilative capacity”.

We would like to know what the evidence is on these issues. The great difficulty in compiling this section is the tremendous variety of environmental phenomena. To make the discussion more manageable, we introduce the standard distinction between local and global environmental phenomena. This is not simply for convenience, but also because the distinction turns out to have important implications for policy. Local environmental problems seem far more amenable to policy solutions such as defining property rights. Global problems seem to require much more direct intervention, and possibly more problematical, international cooperation. A recurrent theme is the problem of valuing such resources. While some are relatively tangible and yield to analysis, others, such as “biodiversity”, are less so. Nevertheless there are good examples suggesting even this is important. For example, several US pharmaceutical companies have recently signed agreements with the government of Costa Rica to exploit forests for medical products. A Costa Rican research institute is prospecting for indigenous plants and organisms which may be useful to Merck and Company. Merck is supporting the project financially with payments going to sustain natural habitats (New York Times (1992), as quoted in Chichilnisky (1993b)). At the same time, however, the government of Panama are allowing the construction of the Pan American highway to proceed through the Darien Gap to link Colombia to Central America. The experience of Brazil, for example, suggests that this could have a disastrous effect on the remaining forests.

Having made this distinction and discussed the evidence about resource use, we then assess what role population plays in all this.

Local environmental phenomena. As Dasgupta and Måler (1995) stress, in 1988 about 65% of the people in countries which fit the World Bank’s definition of low-income lived in rural environments. This figure is only 6% for industrialized economies. The livelihood and well-being of these people is directly linked to the environmental resource base (for example, Jodha (1986) estimated that 15–25% of poor family income in seven states of India came directly from common property resources). As they put it, “the dependence of poor countries on their natural resources, such as soil and its cover, water (lakes and aquifers), forests, animals, and fisheries should be self-evident”. The critical resources are renewable ones. These include land, forests, fish and bird populations, even animal species.

It is easy to find what appear to be startling data about the deterioration of local environmental resources in developing economies and close correlations with demo-
graphic trends. For instance, the population of Nepal has increased from 8 million in 1950 to 17 million in 1980, while at the same time the area of land forested has fallen by two-thirds (Myers, 1986). Though one should treat these numbers with circumspection (it is problematic to define unambiguously “forested land”), this gives a classic example of the types of interrelationships which have received attention. How should one interpret this? It is good to recall that startling figures for deforestation could be produced for currently developed countries. In Britain, for instance, it was the Tudor ship-building industry and the use of charcoal for fuel which caused this, both of which yielded to technical change. Nobody suggests that the process of deforestation was inimical to the economic or social development of Britain.

Even without directly considering population, there are many disturbing estimates of environmental degradation worldwide. Mabbutt (1984) estimates that 40% of productive drylands are under the threat of desertification. It has been estimated that 400 million people in Africa are suffering from acute problems of water shortage (see Dasgupta and Mäler, 1995). It is perhaps interesting to recall that North Africa, now mostly desert, was the “bread basket” of the Roman Empire. Barbier et al. (1989) study many other such examples. Salinization of irrigated land is a serious problem in many areas of the world. The vanishing of the Peruvian anchovies in 1972 has been blamed on overfishing (Clark, 1978). It has also been estimated that Asia lost tropical forests at an annual rate of 1.2% between 1980 and 1990 as compared to 1% in Africa and Latin America, and that an extraordinary 80% of Africa’s pasture and range areas are exhibiting signs of damage (World Bank, 1992). At this level these examples tell us little which is critical in determining whether resources are used well or not. For instance, it is quite possible that an efficient extraction policy can run a fish stock to zero (Dasgupta and Heal, 1979). It is difficult to know about the efficiency of particular outcomes without a detailed knowledge of the costs and benefits.

Consider the issue of deforestation. Shifting cultivation accounts for about 45% of all forest clearing according to Postel (1984). Postel also estimates that 75% of all wood gathered from forests in developing countries is used for fuel – even though wood is an inefficient source of fuel. This suggests that poverty is the root cause of deforestation. At higher income levels individuals shift to kerosene or gas and also adopt more capital-intensive and sedentary agricultural techniques than “slash and burn”. In Gambia and Central Tanzania, firewood has become so scarce that the average household requires 250–300 worker-days to meet its needs (National Research Council, 1986). This represents an extraordinary relative price for fuel. However, this case, while startling, seems atypical. In general, the critical problem with deforestation is the common resource nature of forests in many poor economies, and it is the abundance of forest resources which leads to their common access. Sedjo and Clawson (1984) convincingly argue that this issue is the key one in determining the efficiency with which forest resources are utilized. As their value rises, the incentives to define property rights and utilize the resources more efficiently increase (as in Demsetz, 1967). This is one interpretation (though not an uncontested one) for the motivation
behind the enclosure movement in pre-industrial Britain, for example (see Polya, 1944).

These problems do not loom so large in developed nations where local commons barely exist anymore and forests have been felled (except insofar as they suffer from the atmospheric effects generated by deforestation). What is difficult to extract from this data is the extent to which these patterns of resource extraction and depletion represent a socially inefficient path of development. Even if they do, as is perhaps plausible, the important issue is what types of policies does this suggest and what are the main causal factors.

Global environmental problems. (a) Global warming. Perhaps the best example of a global environmental issue is global warming. Greenhouse gases warm the Earth by reducing the radiation of heat into space and thus increase the net inflow of radiative energy. The most important of these gases is water vapor which is largely unaffected by human activity (Schmalensee, 1993). These gases are vital in sustaining life on Earth and the relative temperatures of the Earth, Mars and Venus can be largely explained by differing concentrations of greenhouse gases (Manne and Richels, 1992). The concentration of another important greenhouse gas, CO₂, has increased by 27% since the beginning of the Industrial Revolution and is rising at 0.5% a year. Although natural sources of emissions are ten times more important than human emissions, this build up, found by examining ice core samples which give relatively reliable data (see Houghton et al., 1990), is generally attributed to human activities. These activities are primarily burning fossil fuels (which accounts for 85% of the total) and from changes in land use (mostly deforestation), which accounts for about 12%. While the US has contributed about 20% of recent emissions of CO₂, most forecasts suggest that the majority of future emissions will emanate from outside the OECD (primarily India and China). For example, Manne and Richels (1992) report that industrialized countries accounted for 64% of total carbon emissions in 1990, but that this figure will fall to 30% in 2100. Other greenhouse gases have also accumulated. The concentration of methane is increasing by 0.7% per annum, and that of nitrous oxide 0.25% per annum. Again this is generally attributed to human activity. The main effect of this build up of gases is to increase the amount of solar radiation trapped by the atmosphere and thus increase the average surface temperature of the Earth. Climate models predict that a doubling of the atmospheric concentration of CO₂ will raise the average surface temperature by 1.7–5°C. The Intergovernmental Panel on Climate Change (IPCC) predicted that unchanged emissions would cause the Earth's surface temperature to rise by 3–6°C by 2100 (relative to 1900). As Nordhaus (1993b) points out, "these projections are worrisome because climate appears to be heading out of the historical range of temperatures witnessed during the span of human civilizations".

The dynamics of the climate and atmosphere are highly complex and poorly understood (Broome (1992), Cline (1992) and National Academy of Sciences (1992) provide accessible discussions). Both the sources and sinks of greenhouse gases are not completely understood. Of especial importance are feedback effects (such as the abil-
ity of oceans to absorb both gases and heat) which cause the time lags between gas build-up and temperature rises to be "long and variable". The scientific consensus is that some global warming must take place if there are not drastic cuts in gas emissions, but there is a large amount of uncertainty about the time horizon over which this will take place and the extent of the increase.

From an economic viewpoint, this aspect of uncertainty is the simplest part of the analysis. Even more uncertainty surrounds the likely economic impact of such climate change (see Nordhaus, 1993b). A clear implication seems to be that agricultural production will relocate, with the "wheat belts" of North America and Asia moving further north. Global warming may have strong distributional implications for countries and this may be important in terms of negotiating international agreements. However, as Nordhaus (1993a) reminds us, there have been many famous and misdirected attempts to provide a climatic theory of economic history. Human beings have shown a remarkable ability to adapt to inhospitable climate conditions, and there seems to be no real evidence that global warming will have disastrous aggregate effects. Anderson (1981) has argued that historically, long-run climate changes have been offset by economic adjustments. Nordhaus (1991) notes that only a very small portion of US GDP is sensitive to the climate. The one exception to this is possible flooding of low-lying coastal areas and the complete submersion of some islands barely above sea level. This may be a real problem for countries such as Bangladesh, the Netherlands and Maldives. Estimates of the increase in sea levels due to warming range from 0.6 to 4.0 meters (Hekstra, 1989). Problems will be greater in developing countries where there is much more reliance on agriculture and natural resources which may be temperature sensitive (such as the ecosystems of various types of forest). Another important issue is whether international trade will be able to help countries adapt to the possible adjustment problems (Reilly and Hohmann, 1993).

Nordhaus (1991), Cline (1992) and Frankhauser (1993) have all estimated the economic impact for the USA, in terms of current real GNP, of climate change. The estimates are losses of 1.1% of GNP for a 2.5°C warming (Cline), 1% of GNP for a 3°C warming (Nordhaus and Frankhauser). Nordhaus (1994a), using a survey of experts, arrived at an estimated loss of 1.8% of world output resulting from a 3°C rise in temperature. Several authors (in particular Nordhaus (1991) and Jorgenson and Wilcoxen (1991), see also the useful surveys of Ayres and Walter (1991), and Clarke et al. (1993)) have also conducted sophisticated intertemporal cost-benefit analyses of controlling greenhouse gas emissions (by the use of carbon taxes). These studies suggest that while the optimal policy involves positive tax rates, it does not demand strong measures (this should be evident from the rather modest estimates of the damages).

Manne and Richels (1992) show that the present value of costs of controlling carbon emissions depends very sensitively on forecasts about technological change in energy supply and conservation. Applying large taxes on current emissions is wasteful if carbon emissions would in any case be stabilized by technical change. They concentrate on computing the costs of carbon emissions under different scenarios about
the availability of new technology and alternative fuel sources. They estimate that stabilizing emissions at 1990 levels until the year 2000 and then initiating a 20% cut would cost 1–2% of GDP per annum for OECD countries. For the US this is 2.5%. Even this policy still implies that carbon concentration doubles relative to the beginning of the Industrial Revolution by 2100. To stabilize the concentration of CO₂ at 1990 levels would entail a 70% cut in current emissions. This doubles the losses for the OECD economies. Manne and Richels stress the huge potential payoff to research which increases our knowledge about the nature and effects of climate change. They also show that great care is required in designing effective policies. For example, carbon taxes may well have perverse effects since they will encourage a switch to “cleaner” fuels such as oil and gas and nuclear energy, but the world stocks of these are much smaller than those of coal, and nuclear power has the potential to be environmentally disastrous.

(b) Pollution and the environmental Kuznets Curve. There has also been much recent interest in comparing the incidence of various forms of pollution to the level of economic development. The World Bank (1992) publicized the notion of the “environmental Kuznets curve” where pollutants were often in low levels of concentration for low-income countries, increased for middle-income countries, and then fell again with higher incomes. The idea of an environmental Kuznets curve has been carefully examined by Grossman (1993) and Grossman and Krueger (1994). Their results show that not all measures of environmental quality are affected in the same way by economic growth. Concentration of lead and cadmium in river basins and concentration of coarse suspended particles in urban air improve monotonically with per capita income (other results are ambiguous, Grossman and Krueger find that the concentration of mercury, arsenic and nickel first increases, then decreases, and then increases again once per capita income rises above $13,000). Other pollutants have the inverted U shape — sulfur dioxide (generated during the burning of fossil fuels), fecal coliform (bacteria found in human and animal feces that indicate the presence of pathogens), the oxygen regime of rivers (level of dissolved oxygen which is important for the health of local ecosystems), nitrate concentrations (mostly reflecting agricultural runoff), and other types of “suspended particulate matter”. Turning points are very different for different pollutants. Some pollutants show no sign of improving — estimated emissions of carbon dioxide and nitrous oxides have continued to rise with income.

Grossman (1993) argues that the strongest link between pollution and income is via induced policy response, and may be due to income effects on consumer preferences. The evidence supports the “policy response” hypothesis. US public and private expenditures on pollution control and abatement represent 2% of GNP (OECD, 1990). These expenditures rose by 3.2% a year on average between 1972 and 1987, compared to the average growth rate of GNP of 2.6%. The situation is the same in other OECD countries (see Beckerman, 1993). Other explanations are related to the changing structure of production as economies develop, in particular the movement toward
service industries, and income effects from higher per capita income on the demand for the amenity services of the environment.

Important factors conditioning effective policy are, according to Grossman (1993), "salience of environmental damage, the cost of avoiding such damage, and the degree to which the harm inflicted by the pollution coincides in its geographic and temporal extent with the political jurisdiction of the bodies empowered to establish property rights and enforce regulations".

1.2.3. The role of population

There is clear evidence of environmental degradation in many developing countries. Is there also evidence that this is directly exacerbated by population growth? It is difficult here to identify the role of population growth separately from the role of per capita income, though one can imagine that there are separate effects. For example, if an increase in population growth led to a fall in per capita income (as suggested by simple interpretations of the recent econometric evidence of Bloom and Freeman (1988) and Brander and Dowrick (1994)), then this would give a way of identifying these separate effects.

There has been some interesting formal econometric work on the interrelationships between population growth and the environment, though it is based on very noisy data. Allen and Barnes (1985) found that higher population growth rates were associated with higher rates of deforestation throughout the world. Their results imply that a reduction of one percent in the rate of population growth will cause a reduction in annual rates of deforestation of between 0.33 and 0.5 of one percent. Jha et al. (1994) use data from the Food and Agriculture Organization to estimate the relationship between the annual rate of deforestation 1975–1986 and population growth rates. They find a significant positive relationship, though smaller than Allen and Barnes. Of course such correlations do not uncover causal relationships and so the counterfactual calculations must be treated with caution. Deforestation has also been found to directly contribute to global warming. There are two effects at work linking deforestation to global warming. First, the deforestation itself generates greater emissions, and, second, the destruction of forests reduces the ability of the atmosphere to regenerate. Bongaarts (1992) estimated that population growth will account for 35% of projected global increase in CO₂ emissions between 1985 and 2050. Cross-country regressions of CO₂ emissions from land use changes, particularly deforestation, against population growth rates also show a strong positive relationship. Jha et al. (1994) estimate that a one percentage point reduction in population growth rates is associated with a 0.32 percentage reduction in CO₂ emissions from land use changes.

The FAO (1993) assumes that the ratio of forest land to total land area is a logistic function of population density. They then use this relationship to forecast deforestation rates. They assume that population growth causes deforestation, but other factors (stage of development, technology etc.) which they do not control for must be impor-
tant in this relationship. Cropper and Griffiths (1994) recently find an environmental Kuznets curve for deforestation in non-OECD countries. The curve is significantly affected by population density which shifts the relationship upwards. Their results imply that both population density and population growth have a positive effect on deforestation holding per capita income constant.

Though there does seem tentative evidence that population growth has an adverse effect on deforestation and greenhouse gas build-up, this work is very partial. There are severe conceptual and econometric problems to be resolved before using these results to motivate policy proposals. We therefore hesitate to draw the conclusion that population policy can be motivated on these grounds. Birdsall (1992) argues that the effect of feasible reductions in population growth rates (based on World Bank scenarios) on emissions of greenhouse gases and global warming are small. She estimates that such reductions might reduce fossil fuel emissions by 10% by 2050. These are small relative to projections that emissions will triple over this period. She does, however, make an interesting calculation which is, although the total impact may be relatively small, population policy may actually be a cost effective way of reducing emissions relative to direct taxes on carbon emissions. We would argue, however, that given the uncertainties surrounding such calculations, thinking of population policy in this way is probably a conceptual error.

As Jha et al. (1994) put it, slowing “population growth by itself is unlikely to halt or even slow the rate of environmental degradation and depletion of forest, marine, and water resources. Other policies that limit access to common property resources, manage rural–urban migration, regulate greenhouse gas emissions, and eradicate poverty will be needed... However, rapid population growth will certainly make it more difficult for countries to improve the environment with a given set of policies and interventions”.

There is less clear evidence of environmental stress in developed economies. There seems to be little direct connection between population growth and environmental issues in developed economies since individual choice sets are not connected to them as intimately as in poor countries.

We can conclude this section in no better way than quoting at length one of the central conclusions from the 1992 World Development Report. “The reason some resources – water, forests, and clean air – are under siege while others – metals, minerals, and energy – are not, is that the scarcity of the latter is reflected in market prices and so the forces of substitution, technical progress, and structural change are strong. The first group is characterized by open access, meaning that there are no incentives to use them sparingly. Policies and institutions are therefore necessary to force decision-makers to take account of the social value of these resources in their actions. This is not easy. The evidence suggests, however, that when environmental policies are publicly supported and firmly enforced, the positive forces of substitution, technical progress, and structural change can be just as powerful. This explains why the environmental debate has rightly shifted away from concern with the physical limits of
growth, toward concern about incentives for human behavior and policies that can overcome market and policy failures.

1.3. Our approach

To what extent is it possible to draw definitive conclusions from the empirical work as it stands? While there is clearly much uncertainty surrounding the qualitative and quantitative properties of the dynamics under consideration, there are certain conclusions that one can reach. Firstly, there is no evidence of adverse effects of population growth on economic growth. This suggests that in formulating models we want to allow either for a neutral effect, or for offsetting positive and negative effects. Secondly, models of development need to incorporate the elements of the demographic transition. Thirdly, the evidence suggests that market mechanisms have been remarkably effective in allocating finite resources which are priced in markets, however, we need to be open minded about the nature and efficiency of the evolution of environmental resources. Finally, in studying the interactions between population growth, resources and environment, we need to be scrupulously careful to isolate the causal relationships otherwise we cannot say anything interesting about welfare or policy.

Unfortunately, for a large class of phenomena, the theory orders what we would like to know, not what we conclusively do know. We try and understand the joint phenomena both positively and normatively via the tools of intertemporal welfare economics. This bears fruit in analyzing issues pertaining both to population and the environment. For example, while it is often said that population growth reduces income growth, and this proposition is true in some simple growth models, this in itself says nothing about the desirability or otherwise of this result. If population growth is the conscious outcome of individual decisions, then it is possible that individuals will willingly make these types of trade-offs (see Lee (1990) for an example). One position is that if this is a Pareto optimal situation, then there is little to be said (see Ng (1986) for a strong affirmation of this view). The same goes for environmental "degradation" and resource use. On the other hand, one might view this as evidence that Pareto optimality is a woefully blunt tool in this context. As is well-known, in standard welfare economics the fact that an allocation of resources is Pareto efficient is only a necessary condition for it to be socially optimal. Such models assume that the population, constant or changing, is exogenous, so that there is a fixed pool of people the welfare of whom can be compared under different allocations. When population is endogenous, it becomes moot as to whether or not Pareto optimality, as conventionally defined, is even necessary for social optimality.

Now consider the environment. Perhaps the clearest distinction between economists and environmentalists is that economists can conceive of a dynamic path which runs a renewable resource to zero as being optimal. This position is typically regarded as preposterous by environmentalists. Along an optimal transition path it seems highly
likely that resources will be run down and exploited. The perspective of welfare economics suggests that concentrating on the preservation of environmental resources directly is confusing ends with means (see Solow (1992, 1993); Dasgupta (1993c) and Dasgupta and Mäler (1995) all make similar points). What we are interested in is welfare and not the preservation of any particular environmental asset per se. Preservation becomes vital when the asset is essential to production or human welfare. This attitude conditions our approach to the topic of "sustainable development" in Section 4.1.

What we attempt to do is to think about the type of joint dynamic behavior of population, resource usage and technical change that we would expect to see along an equilibrium growth path. We do this in different models, not only because a general model is of too high a dimension to handle, and also because, as we have already argued, neither population growth nor resource usage really lend themselves to a general model. We are still too uncertain about critical features of these phenomena. We then repeatedly ask several key questions. Firstly, what are the asymptotic implications of this path for population and resources? Secondly, how does this behavior relate to the empirical evidence. Thirdly, can per capita income grow unboundedly or will it be constrained by lack of natural resources or similar Malthusian phenomena? Finally, is this path inefficient, and, if so, what are the fundamental sources of these inefficiencies?

In the course of the analysis, we do not devote much space to the pros and cons of various intertemporal welfare functions. Both the population and environmental literatures are plagued by this. In discussing dynamic paths, we deliberately do not commit ourselves to any particular social valuation function without seeing what is implied. In this we follow Koopmans (1967) who puts the issue in the following way, "ignoring realities in adopting "principles" may lead one to search for a non-existent optimum, or to adopt an optimum that is open to unanticipated objections". This approach has recently been stressed by Dasgupta and Mäler (1995). To our mind the best way to proceed is to examine the equilibrium allocations corresponding to different sets of assumptions and see if these coincide with our ethical notions. An implication of our perspective is that we will be critical of the rather arid theoretical literature on optimal population growth with exogenous fertility. As we shall see, there are some classic examples of social welfare functions which generate intuitively ludicrous results. Much of the hand wringing about the form of society's objective function vanishes once fertility is made endogenous, and, in any case, as we have stated, we do not feel that a priori arguments about intertemporal welfare functions are convincing.

This topic also raises the interesting issue of how to construct aggregate measures of welfare which encompass environmental changes. It is in this context that the idea of Net National Product has been constructed taking into account the value of environmental and resource degradation. The effects of this can be large. For example, Repetto et al. (1989) estimated that, once environmental degradation was taken into account, the growth rate of Indonesia over the period 1971–1984 was 4% rather than
the 7% based on standard national accounting techniques. Mäler (1991) and Dasgupta and Mäler (1990) have shown how intertemporal welfare economics and shadow pricing provides the conceptual framework for this analysis. While we do not attempt such derivations here, it should be clear that our analysis of the issues is very much in the same spirit.

This approach unifies our attitudes to population, technological change and environmental resource use and helps identify their potential welfare implications which might justify policy intervention. In the end this is what the topic is about. The debate about both population growth and the environment and the interaction between them focuses on the necessity of policies to stem population growth and the desirability of controls on environmental degradation. Consider initially population growth. While there are certain situations, for example, the dyastic economy we study in Section 2.1, where the rate of population growth which is chosen by private agents is the first-best one (identical to the one which would be chosen by a social planner), this turns out to be a far from general proposition. The assumptions necessary to induce dyastic preferences are restrictive (such as fully operational gift and bequest motives), and moreover they seem to rule out some of the key phenomena which are thought to be of importance in the determination of population growth in poor countries. It is quite plausible then that the rate of population growth may not be first-best. It is still possible, however, that it may be Pareto efficient (bearing in mind the problematical nature of this concept with endogenous population), but welfare economics gives us a set of tools to understand situations in which it may not be. For example, as we discuss in Section 3.4.2, either externalities or noncooperative behavior within the household can lead to rates of fertility and population growth which are inefficient under reasonable interpretations of the Pareto criterion.

Consider now the welfare issues surrounding technological change. In Section 3.3, we put into perspective recent developments in this area. Much of the work (following Romer (1986) and Lucas (1988)) has stressed external effects stemming from the public good and nonrivalrous nature of abstract "knowledge", "ideas", "technology" or "human capital". Such a perspective generates the strong implication that in laissez faire equilibrium innovation and investment will be socially inefficient (although, as we shall see, the empirical strength of these phenomena is hotly debated). The framework tells us what can go wrong and what can be done about this.

The same set of tools provide the best approach to the environment. Environmental resources provide one of the best examples of externalities since they are typically not traded in markets (the atmosphere being a good example). It is this which generates the presumption that they may be inefficiently exploited or utilized. Thinking of the environment in this way allows us to separate the issue of the efficiency of environmental preservation from the other central issues of this paper, such as whether or not there is a population problem, or whether or not development must lead to the inefficient destruction of the environment, which are so confusingly conflated with it in much of the literature.
In the present paper, we restrict our scope to outlining the conceptual issues and do not deal with detailed policy proposals. Designing policies requires a much more detailed specification of the structure of economies than is tractable for conceptual analysis. In practice one must deal with the complex interaction of numerous market failures and second-best problems. Bovenberg and van der Ploeg (1993a–d) provide an interesting first-step in modeling some of these issues in the context of environmental policy. Similar issues arise with population policy. One must design policies affecting the costs and benefits of fertility, which seems to be more amenable to such policy than mortality. We also warn that without an understanding of the dynamics of population growth, simple policies may have unanticipated side effects. Another strong argument for such incentive policies is that the most important candidates for such policy (for example, subsidization of human capital accumulation, building health and social infrastructure) seem to have strong rationales on other grounds and so there are strong complementarities, as we argue below, between population and other policy. Again this must be done in a general equilibrium context where other deviations from the first-best allocation of resources need to be taken into account. We do not undertake any analysis of this sort here (see Chomitz and Birdsell (1991) for a good discussion of the issues).

1.4. Overview of the paper

To keep the discussion relatively self-contained, we proceed in the next several sections with a development of a sequence of canonical models. These provide the framework to begin systematic study of the joint dynamics of growth, population and resource use. The models are often not very instructive in this regard. For example, the basic neoclassical model, due to Solow (1956) and Swan (1956), regards population growth and technical progress as exogenous and ignores environmental and resource issues altogether. These models are instructive, however, in building our intuition regarding the forces at work in the growth process and in understanding why the treatment of population and technology in these models is so unsatisfactory.

Our approach is primarily analytical and, in order to help the reader in understanding the motivation for a particular model or piece of analysis, we provide summaries of the "plot" at appropriate places, reminding the reader what we have established thus far and where the argument is headed.

Having developed the basic growth model, we investigate the positive and normative aspects of population policy. We raise the issue of the optimal rate of population growth by first thinking about the issue of the optimal size of population in a static model. Extending this to determine the optimal level of population at each point in time then generates naturally an optimal rate of population growth. We concentrate on the implications of various technological assumptions (such as the degree of returns to scale) and the form of the social objective function. We argue that the underlying in-
ter-generational linkages between agents are crucial for the foundations of any particular objective function and hence the nature of desirable policy.

We then introduce both exhaustible and renewable resources into the analysis. We consider the nature of intertemporal equilibrium and again the positive and normative issues surrounding the dynamic path. We then re-examine the positive and normative issues of population growth. The analysis is very tentative, especially with respect to renewable resources. We emphasize that there is high uncertainty about the nature of the dynamics, involving nonlinearities, threshold effects, and irreversibilities, which are extremely difficult to model satisfactorily. There are also important complementarities between different resources. For example, forests control water run-off and flooding which stabilizes topsoil elsewhere. One cannot hope to capture these rich interactions with the type of aggregate model we study, but one can hope to direct attention to what is crucial and what we need to know.

In Section 3, we move to endogenize population and technical change. Both of these steps represent fundamental improvements on the basic neoclassical model, although they clearly complicate the models considerably. In Section 3.1, we present a condensed discussion of the issues involved in endogenizing fertility, mortality (though we only touch on this topic), and thus the rate of population growth. Our treatment is conditioned by the in-depth treatment of the issues elsewhere in the Handbook (see the chapter by Nerlove and Raut). Our aim is rather to apply versions of these models to the issues at hand. We begin in Section 3.2 by introducing endogenous population growth into models where resources are explicitly accounted for. Such a model no longer allows simple causal statements about the effects of population growth to be made. Section 3.2.1 examines a simple model of the joint dynamics of population and environmental resources. In Sections 3.2.2 and 3.2.3, we discuss models emphasizing the complementarities between population dynamics and resource use. These are both models of "no trade-off" situations where addressing the real problems, in 3.2.2 a classic "local commons" problem, and in 3.2.3 a public goods problem, solves not only the resource problem but also the population problem. In Section 3.3, we review recent theories of endogenous technical change. In Section 3.4, we discuss the considerable literature which models the interrelationships between population and economic growth, in particular different causal channels through which population growth influences development. Section 3.5 then discusses the implications of recent theories of technical change in economies with exhaustible and renewable resources. In Section 3.5, we present the most general discussion, assessing the implications of the joint endogeneity of population and technical change in the presence of natural and environmental resources.

In Section 4, we then provide an assessment of several contentious topics in the literature and in particular use the models of the paper to discuss the issues of discounting and sustainable development. We briefly discuss the importance of uncertainty and the implications of introducing international issues. Section 5 then offers our conclusions.
2. Long-run development with exogenous population and exogenous technical change

We begin our formal treatment of the issues addressed in this chapter with very simple familiar economies and propositions. Section 2.1 develops classical positive and normative results from growth theory when both population growth and technological change are exogenous, with infinitely-lived agents, a single produced good (i.e. a one-sector economy), and with no natural resources. Section 2.1.1 introduces the main normative and positive issues. In Section 2.1.2, we broach the question of optimal population for the first time, introducing the issues in a simple static setting and using it to clarify the key issues. We then extend the ideas (in Section 2.1.3) to examine the existence and characteristics of the optimal rate of growth of population in the growth model of Section 2.1.1. Section 2.2 extends the results from Section 2.1 to overlapping generations models where individuals live for only a finite number of periods. In Section 2.2.1, we analyze positive and normative issues in a version of the celebrated model due to Diamond (1965a). Section 2.2 derives the optimal rate of population growth in the overlapping generations model. Section 2.2.3 then discusses relationships between generations and their implications for the issues analyzed earlier.

In Section 2.3, we introduce renewable and exhaustible resources. In Section 2.3.1, we add exhaustible resources to the inputs of the production function of the basic neoclassical growth model of Section 2.1.1. Historically, the effects of the existence of exhaustible resources was the first to receive careful theoretical attention. Our central concerns are the conditions under which it is possible to maintain sustained growth by substituting out of the exhaustible resource into produced capital, and the impact of exogenous technological growth, and to re-assess the positive effects of exogenous population growth. We also return to the issue of optimal population growth in these models with results closely related to those of Section 2.1.2 and 2.1.3. Finite lives are treated in Section 2.3.3, and then in Section 2.3.4 we develop a more general model in which both exhaustible and renewable resources enter into production. Our model is general enough to encompass the issue of the effects of pollution on the growth path amongst other resource issues. We concentrate on renewable resource issues since these seem to be the most interesting and least understood area. We also allow for "amenity" affects of the resource to affect utility directly. Again we concentrate on the conditions necessary to ensure sustained growth in per capita income and the steady states that could plausibly arise.

2.1. Neoclassical growth: infinitely-lived agents

To fix ideas, we start with the one-good, discrete time, neoclassical growth model with infinitely-lived agents (henceforth, ILA), exogenous technical change, and exogenous population. With interaction between technical change and population absent,
their rates of change can be exogenously varied to analyze the positive comparative dynamic effects on steady-state income, etc. It seems natural to just consider physical capital in this section and leave human capital until we consider endogenous growth models in Section 3. Throughout the chapter we discuss models with a single produced good, where, in particular, the capital and the consumption good are not distinguished. A possible justification of this would be to place the discussion in the context of a small open economy where relative prices of goods are fixed by the world market. This allows aggregation of heterogeneous goods (by the Hicks theorem). However, for the purposes of the chapter it is easier to stick to a closed economy setting (for example, we want to determine the interest rate endogenously), and so we just make this an assumption.

2.1.1. Basic dynastic economy

In this section, we exposit the simplest model of economic growth based squarely on the accumulation of physical capital relative to labor and the consequent increase in the capital–labor ratio. Imagine a poor country with a low stock of capital relative to labor so that the marginal productivity of capital is high. In a perfectly competitive equilibrium this is equal to the interest rate which represents the return to saving. Thus the low capital stock generates a high incentive for individuals to save (as long as income effects are not strong) and this leads to a rapid growth of the capital stock. As the capital stock grows relative to labor its marginal product falls. As a consequence, the interest rate falls and thus the incentive to save. Eventually, under the standard assumptions, the marginal product falls so low that the return to future saving is exactly balanced by the costs and the growth of the capital–labor ratio stops. Such a situation is called a steady-state equilibrium. With exogenous technical progress of a labor augmenting type, the above story is still true except that the relevant variable which accumulates over time is “capital per effective worker” since workers are getting exogenously more productive. This is an unsatisfactory treatment of technological change. The treatment of population is equally unsatisfactory since it grows exogenously at a constant rate. In a steady state the endogenous variables are adapted to the exogenously growing rates of technology and population.

The demographic structure of the model conceives of the population as belonging to an altruistically linked dynasty with perfect foresight about the values of all relevant future variables and an infinite time horizon. This has the strong normative implication that allocations which arise in intertemporal competitive equilibria are Pareto optimal and, since all individuals are altruistically linked, the objective function of the dynasty is the only reasonable welfare function for society (since it is the same as the dynasty). It seems intuitively unreasonable to posit the existence of a social planner who weights the welfare of individuals differently from the dynasty.

Consider the representative agent neoclassical growth model. Time is discrete. There are two goods, a single produced good which can be consumed or used as
capital, and labor. We consider a real economy where the produced good is the numeraire with price normalized to unity in each period (hence we choose a different numeraire at each date as opposed to simply using the produced good at date one as the numeraire for all time). We assume that investment is irreversible and, once the consumption good is converted into capital, it cannot be consumed. The economy is inhabited by a single dynasty with an initial population of unity. All members of the dynasty born at any date live forever. There are two main assumptions about the demographic environment in this economy. The one we follow is to assume that the size of the dynasty grows at the constant exogenous rate of \((1 + n)\), so that the size of the dynasty at date \(t\) is \(L_t = (1 + n)^t\) (since \(L_0 = 1\)). In this model each agent reproduces by parthenogenesis (marriage is abstracted from and leads to severe complications, see Bernheim and Bagwell (1988), Cigno (1991), Laitymer (1991)) and has \(n\) children at the end of each period. The alternative is to assume that each “dynasty” is rather a single infinitely-lived individual and population growth occurs through the addition of new individuals. This model has implications closely related to the overlapping generations model (see Weil, 1989).

We assume that each agent has preferences defined over infinite sequences of consumption:

\[
\hat{c}_t(i) = \lim_{\tau \to \infty} c_t(i),
\]

where \(\hat{c}_t(i)\) represents the consumption of agent \(i\) in period \(\tau\), born in period \(\tau\), and that these can be represented by a time separable utility function with constant exponential discounting,

\[
V(i) = \sum_{t=\tau}^{\infty} \beta^{t-\tau} U(c_t(i)).
\]

(2.1)

\(\beta \in (0, 1]\) is interpreted as the rate of subjective time preference. We assume that \(U\) is strictly increasing, strictly concave, and twice continuously differentiable, with \(U: \mathbb{R}_+ \to \mathbb{R}\), and \(U' > 0, U'' < 0\). Note that this implies that \(V: \mathbb{R}^\infty_+ \to \mathbb{R}\), so that the commodity space is infinite dimensional (as in Bewley, 1972). Each member of the dynasty is endowed with one unit of labor time in each period. We assume that the instantaneous utility function is identical for each agent in every period of life. The dynasty also holds a stock of capital in each period, denoted \(K_t\). Since decision-making is at the level of the dynasty, we do not specifically keep track of intradynasty holdings of capital or other assets.

The dynasty treats all individuals alive at any date equally so \(\hat{c}_t(i) = C_t/L_t\), where \(C_t\) is total consumption and \(L_t\) the number of people alive. Since we want to consider environments with technical progress, we need to define variables in such a way as to be constant in steady state. Per capita consumption will not be constant, but
\( c_i(i) = C_i/A_iL_i \) (consumption per "effective person") will be. It is important to keep this in mind since below we write the budget constraint in terms of \( e_r \), but Eq. (2.1) is in terms of \( \bar{e}_r \).

There is a single competitive "representative firm" in the economy. The firm rents capital and labor on competitive factor markets, taking prices as given, to maximize profits. Given the nature of the technology, there are no intertemporal aspects to the firm's problem. Maximizing the present discounted value of profits (which will be unambiguously the firm's objective since we will specify a market structure which is isomorphic to complete markets) reduces to maximizing profits period by period. The firm's technology is represented by a production function, \( Y_t = F(K_t, A_tL_t) \), which we assume to be concave, strictly increasing and twice continuously differentiable, where \( F: \mathbb{R}_+^2 \rightarrow \mathbb{R}_+ \). Let \( F_i \) represent the partial derivative of \( F \) with respect to variable \( i = K, L \), and \( F_{ij} \) the partial derivative of \( F_i \) with respect to variable \( j = K, L \). Then we assume that \( F_K > 0, F_L > 0, F_{KK} < 0, F_{LL} < 0 \), so that marginal products are positive but strictly diminishing. \( A_t \) represents the level of labor augmenting technology in period \( t \), and \( K_t, L_t \) the stocks of capital and labor hired by a firm. There is no distinction between total population and the size of the labor force. Since we wish to examine steady states, the assumption of Harrod neutral (i.e., labor augmenting) technical change is necessary (Phelps, 1962). We assume that \( F \) is homogeneous of degree one so that by Euler's theorem we can re-write the production function in terms of per capita quantities. Denoting \( y_t = Y_t/A_tL_t, k_t = K_t/A_tL_t \), as the output-labor and capital-labor ratios (where labor means "effective labor") the production function can be written, \( y_t = f(k_t) \). It is immediate that \( f \) is strictly concave, strictly increasing and twice continuously differentiable, with \( f: \mathbb{R}_+ \rightarrow \mathbb{R} \), and \( f' > 0, f'' < 0 \) (where \( f' \) and \( f'' \) are the first and second partial derivatives respectively of \( f \) with respect to \( k_t \)). Denote the competitive wage per effective unit of labor, and the rental rate for capital in terms of the numeraire as \( w_t, r_t \), respectively. The level of technology increases exogenously over time at rate \( (1 + g) \), so that \( A_{t+1} = (1 + g)A_t \).

The equilibrium concept we use is a standard competitive one with sequentially complete markets and perfect foresight. This is equivalent to a model with complete markets where all trading is undertaken in the initial period. Since the economy is deterministic, and individuals have perfect foresight about all future prices, the single asset available in each period is sufficient to span the state space (the model is a degenerate multi-period version of Arrow's (1963–1964) model (see also Radner, 1972) and is thus equivalent — in terms of allocations — to a complete markets Arrow–Debreu economy).

At the start of each period a competitive capital and labor market opens. The dynasty rents its labor services and capital to firms who minimize unit costs of production. This generates factor demands per unit of output. Minimum cost is equal to the price of output which is equal to unity by the choice of numeraire. The assumption of inelastically supplied and fully utilized supplies of capital and labor then determines the scale of output. From unit cost equals price (equals unity) and cost minimization
we have, $A_t L_t [w_t + r_t k_t] = 1$, $A_t f(k_t) = 1$, and $f'(k_t) = r_t$. Both labor and capital are supplied inelastically and market equilibrium requires, $L_t^t = L_t$, and $K_t^t = K_t$.

Each dynasty maximizes utility subject to the sequential budget constraint,

$$K_{t+1}^t + C_t \leq w_t A_t L_t + r_t K_t + (1-\delta)K_t, \quad (2.2)$$

where for simplicity, we have assumed that capital depreciates at the constant rate of $\delta \in (0, 1)$ per period. Since utilities are strictly increasing, Eq. (2.2) holds with equality. We ignore the issue of the irreversibility since we shall not consider situations where the dynasty desires negative net investment and so it is impossible to distinguish between the cases of irreversible investment and of potentially reversible investment. We now re-write Eq. (2.2) in per effective person terms:

$$\frac{K_{t+1}}{A_{t+1} L_{t+1}} + \frac{C_t}{A_t L_t} = \frac{w_t A_t L_t}{A_t L_t} + \frac{r_t K_t}{A_t L_t} + (1-\delta) \frac{K_t}{A_t L_t} \quad (2.3)$$

or

$$k_{t+1} (1+g)(1+n) = w_t + r_t k_t - c_t + (1-\delta)k_t, \quad (2.4)$$

Euler's theorem for linearly homogeneous functions implies that Eq. (2.4) can be simplified by noticing that $f(k_t) = w_t + f'(k_t) k_t = w_t + r_t k_t$. Intuitively, since the dynasty owns all the factors of production, the whole of output must be distributed to it in various forms. Hence in effective per capita terms,

$$k_{t+1} (1+n)(1+g) = f(k_t) - c_t + (1-\delta)k_t. \quad (2.5)$$

The dynasty is composed of individuals maximizing $V(i)$ defined in Eq. (2.1). We assume that the dynasty itself maximizes the per capita welfare of a particular member alive at each date ignoring the number of its members alive at any date. Hence the objective function for the dynasty is

$$\sum_{t=0}^{\infty} \beta^t U(c_t A_t)$$

starting from $t = 0$. This might not be thought the most natural specification. Unfortunately the objective function of the dynasty is not usually derived from an explicit aggregation in the infinitely-lived agent setting, and in order to keep our analysis close to that of the literature, we similarly finesse this issue at this stage. Note that, in particular, this form of the objective function is only sensitive to the per capita welfare of
descendants and not the number of descendants as such. It also discounts the welfare of future generations at the same rate that each individual discounts his/her own lifetime consumption. However, a dynasty which takes into account the number of descendants could be viewed as maximizing the objective function,

$$
\sum_{i=0}^{\infty} \beta^i (1+n)^i U(c_i, A_i) = \sum_{i=0}^{\infty} \beta^i U(c_i, A_i),
$$

where $\beta = \beta(1+n)$, and, as long as $0 < \beta < 1$, the formal analysis would be the same. We return to this issue in Section 2.2.3. In Section 3.1, we develop a model due to Becker and Barro (1986, 1988, 1989) where the dynastic utility function is derived from an explicit aggregation across altruistically linked generations. At this point it becomes clearer exactly what sort of assumptions are needed to generate the welfare function of the sort we adopt here.

Since labor and capital are supplied inelastically, the only decision is the consumption-saving choice. The Lagrangean for this problem is referred to as Problem 1:

$$
\Lambda = \sum_{i=0}^{\infty} \beta^i U(c_i, A_i) + \sum_{i=0}^{\infty} \lambda_i \{ w_i + r_i k_i - c_i + (1-\delta)k_i - (1+g)(1+n)k_{i+1} \}.
$$

Note that $c_i A_i = \hat{c}_i$. Problem 1 ignores the side constraints that $c_i \geq 0$, $k_i \geq 0$. We also assume that the problem is well defined in the sense that the objective function converges (we try to keep the discussion nontechnical in the chapter to the extent that we do not explicitly set out assumptions guaranteeing that the problems we analyze are mathematically well defined in all cases). Intuitively for this to be the case, the discount rate must be sufficiently high compared to the rate of technological progress. The initial condition on the capital–effective labor ratio is $k_0 = K_0/A_0 L_0 = k_0/A_0$. The standard necessary conditions for this problem are Eq. (2.5) and the following conditions, Eqs. (2.6) and (2.7):

$$
\beta^i \Lambda_i U'(c_i, A_i) = \lambda_i, 
$$

$$
\lambda_i = \lambda_{i+1} \left( \frac{1+r_{i+1}-\delta}{(1+n)(1+g)} \right),
$$

and the transversality condition, Eq. (2.8):

$$
\lim_{t \to \infty} (\lambda_t k_t) = 0.
$$
Leading Eq. (2.6) and using it in conjunction with Eq. (2.6) to substitute into Eq. (2.7) gives the standard form of the Euler equation:

\[ U'(c_t A_t) = \left( \frac{1 + r_{t+1} - \delta}{1 + n} \right) \beta U'(c_{t+1} A_{t+1}). \]  

(2.9)

Using the condition for factor market equilibrium, we derive

\[ U'(c_t A_t) = \left( \frac{1 + f'(k_{t+1}) - \delta}{1 + n} \right) \beta U'(c_{t+1} A_{t+1}). \]  

(2.10)

A perfect foresight competitive equilibrium of the economy is a set of sequences for the endogenous variables,

\[ \{c_t\}_{t=0}^{\infty}, \quad \{k_t\}_{t=0}^{\infty}, \quad \{w_t\}_{t=0}^{\infty}, \quad \{r_t\}_{t=0}^{\infty}, \]

such that at these prices, the dynamic objective function is maximized subject to Eq. (2.5) at the specified quantities, firm profit is maximized at these quantities, and all markets clear.

The aggregate dynamics of the economy are described by the two difference equations, Eqs. (2.5) and (2.10), in \( k_t \) and \( c_t \). Given two boundary conditions, the initial capital–effective labor ratio, \( k_0 \), and the transversality condition for the dynasty, Eqs. (2.5) and (2.10) determine the evolution of all the endogenous variables of the economy. Consider the steady state (or balanced growth path) for this economy where all per effective capita variables are constant, per capita variables grow at the constant rate of \( g \), and level variables grow at the constant rate of \( n + g \) (approximately). Note that this implies \( k_{i+1} - k_i = 0 \). Thus in steady state

\[ k^*(n + g + ng + \delta) = f(k^*) - c^*, \]  

(2.11)

\[ \frac{U'(c^* A_t)}{U'(c^* A_{t+1})} = \frac{\beta(1 + f'(k^*) - \delta)}{1 + n}. \]  

(2.12)

For a steady state the marginal rate of substitution on the left-hand side of Eq. (2.12) must be a constant. Note that the right-hand side is independent of time. This implies, given \( A_t = (1 + g)^i A_0 \), with \( g \neq 0 \), that the elasticity of marginal utility is constant or that the utility function is of the form \( ye^\theta + \omega \).

Consider initially the case of logarithmic utility, \( U(\tilde{c}_t) = \log \tilde{c}_t \). Eq. (2.12) now reduces to an intuitive form. The left-hand side of Eq. (2.12) now is \( 1 + g \). Notice that defining \( \beta = 1/(1 + \rho) \), and then multiplying both sides of Eq. (2.12) by \( 1 + \rho \) and \( 1 + n \), the left-hand side of Eq. (2.12) is \( (1 + n)(1 + g)(1 + \rho) \), which reduces to
1 + n + ρ + g if we neglect all the product terms, since n, g, ρ are assumed to be small. Under this assumption, Eq. (2.12) can be written as

\[ f'(k^*) = ρ + δ + n + g. \] (2.13)

Eq. (2.13) represents the steady-state capital stock in this economy. The left-hand side represents the marginal benefit to the dynasty of increasing the capital–effective labor ratio. The right-hand side is the marginal cost. Note that this is not the original Golden Rule proposed by Phelps (1966) (though it is often referred to as such). Phelps derived the Golden Rule by choosing the capital–labor ratio which maximized steady-state consumption per capita. In the current model, Eq. (2.13) includes a preference parameter which implies that, due to impatience (or imperfect altruism), the economy will not accumulate as much capital as would maximize steady-state consumption. Note that setting \( k^* = \bar{k} \) where \( f'(\bar{k}) = (1 + n)(1 + g)-(1 - δ) \) maximizes steady-state consumption. Since \( U \) must be of constant elasticity for a steady state to exist, we consider the constant elasticity of marginal utility (or of intertemporal substitution) utility function

\[ U(\bar{c}_t) = \frac{(\bar{c}_t)^{1-\sigma}}{1-\sigma} \]

(more generally the steady-state capital–effective labor ratio also depends on the preference parameter \( \sigma \) (which is simply the inverse of the elasticity of intertemporal substitution)). Now from Eq. (2.12), it follows that

\[ f''(k^*) = (1+ρ)(1+n)(1+g)^\sigma-(1-δ) \]

and so

\[ f'(\bar{k}) - f'(k^*) = (1+n)(1+g)[1-(1+g)^{\sigma-1}(1+ρ)]. \]

Thus with \((1+n) > 0, g > 0, ρ ≥ 0, \) then if \( σ > 1, f'(\bar{k}) - f'(k^*) < 0 \) so that \( \bar{k} > k^* \). With logarithmic utility \( σ = 1, k^* \to \bar{k} \) as \( ρ \to 0 \). With \( σ ∈ (0, 1), (1+ρ)(1+g)^{σ-1} \geq 1 \) implies \( k^* < \bar{k} \). If in this case, \((1+ρ)(1+g)^{σ-1} < 1, \) then \( g > ρ, \) in which case the objective function does not converge and an optimal path does not exist. Then, regardless of parameters, if the optimal path exists and converges to a steady state, we have that \( k^* < \bar{k} \).

We can now investigate the effects of an increase in the population growth rate on the steady state. Now

\[ c^* = f(k^*) - k^*[(1+n)(1+g)-(1-δ)] \]
so that

\[ \frac{dc^*}{dn} = [f'(k^*) - ((1+n)(1+g) - (1-\delta))] \frac{dk^*}{dn} = [f'(k^*) - f'(\hat{k})] \frac{dk^*}{dn} \]

Since

\[ f''(k^*) \frac{dk^*}{dn} = (1+\rho)(1+g)^\delta \]

by concavity we have \( \frac{dk^*}{dn} < 0 \). Hence as long as \( k^* < \hat{k} \), we have \( \frac{dc^*}{dn} < 0 \).

It is straightforward to derive the sufficient conditions that guarantee the existence of a unique \( k^* \) satisfying Eq. (2.13). All one requires is that for low capital-labor ratios the marginal product is relatively large. Then by concavity the left-hand side of Eq. (2.13) is monotonically decreasing in \( k^* \) and, if it falls to the constant \( \rho + \delta + n + g \), then a steady state exists. The conventional (though strong) sufficient conditions for this are the Inada conditions (e.g. \( \lim_{k \to 0} f''(k) = +\infty \) and \( \lim_{k \to \infty} f''(k) = 0 \)). Under these it is clear that such a steady state exists and that it is unique since \( f''(k) < 0 \).

The costate equation, Eq. (2.7), can be used to give a more intuitive content to the transversality condition Eq. (2.8). Eq. (2.7) is a difference equation in \( \lambda_n \), solving this forward (and for simplicity letting \( (1+g)(1+n) = 1+n+g \)) gives

\[ \lambda_t = \lambda_0 \prod_{s=1}^{t} \left( \frac{1+n+g}{1+r_s - \delta} \right) \]  

(2.14)

Now substitute Eq. (2.14) into the transversality condition Eq. (2.8),

\[ \lim_{t \to \infty} \left[ k_t \lambda_t \prod_{s=1}^{t} \left( \frac{1+n+g}{1+r_s - \delta} \right) \right] = 0. \]  

(2.15)

Eq. (2.15) represents a necessary condition for optimality. For the limit to go to zero, it must be the case that the product goes to zero (note that \( \lambda_0 > 0 \)) which will be true if \( n + g < r_s - \delta \). This says that the (geometric) average net interest rate must be greater than the sum of the rate of population growth and the rate of technical progress. Notice that this condition is satisfied in a steady state (this follows from Eq. (2.13)).

The welfare implications of steady-state allocations in this model are well known. Consider a social planner maximizing a social welfare function, \( W \). Since the economy consists of a single unified decision-making entity, the standard assumption is that the social planner respects the preferences of this dynasty. It should be clear that it is a
restrictive assumption. For instance, as we mentioned, a utility function such as the one maximized by the dynasty is not immediately derived from aggregating the preferences of successive altruistically linked generations. In particular, one must rule out specifications of preferences which induce time-inconsistencies. As Bernheim (1989) has argued, this is not obviously reasonable. Firstly, it is not derived from any deep axiomatic basis, and secondly, it rules out within-dynasty conflicts which seem to be important phenomena in reality. When it is derived from such an aggregation process, then $\rho$ reflects not simply impatience but also the degree of altruism between generations. Does a planner have to respect this?

The planner chooses resource allocations directly, and suppose he or she solves the following optimization problem (ignoring nonnegativity), Problem 2:

$$\max_{\{c_t\}_{t=0}^\infty \{k_t\}_{t=0}^\infty} \sum_{t=0}^\infty \beta^t U(c_t, k_t)$$

subject to the resource constraint

$$k_{t+1}(1+n)(1+g) = f(k_t) - c_t + (1-\delta)k_t.$$

As we have mentioned, the model is isomorphic to a convex, complete markets, Arrow-Debreu economy. It follows that competitive equilibria are Pareto optimal in the sense that the consumption of any individual living at any date $t$ cannot be increased relative to its value in a competitive equilibrium without reducing the consumption of some individual living at some date, again relative to its value at the same competitive equilibrium. Since Problem 2 is a concave problem, there is in fact a unique such optimal allocation. Thus, associating the preferences of the dynasty with the social welfare function has a strong implication. The standard argument to show this in the present context is to directly compare the necessary conditions for Problems 1 and 2.

The messages of the neoclassical growth model for the present chapter are simple. Population growth is bad for development, since it induces capital widening at the expense of capital deepening. Along the transition path to the steady state, an increase in the population growth rate reduces the growth rate in per capita income, and in the steady state it reduces the capital-effective labor ratio and hence per capita income. What about resources? The model assumes constant returns to scale to the accumulation of capital and labor, and hence the scale of the economy is not constrained by the presence of any resource constraints. Many have argued that the model flagrantly assumes away resource issues. We return to this.

2.1.2. Optimal population: issues and static analysis

We first consider static models. In optimizing population size two factors are critical, the form of the objective function and the nature of returns to labor in the production
technology. An immediate problem is that maximization of per capita utility in conjunction with diminishing marginal productivity of labor implies a zero optimal population size. The most obvious solution to this "problem" is to change the objective function to give explicit value to the number of people. With diminishing marginal productivity, this induces a trade-off between per capita consumption and the number of people enjoying any level of consumption. This can lead to an interior solution for the optimal level of population. The other solution to this problem is to relax the assumption of a monotonically diminishing marginal product of labor. This solution is less attractive, since in its usual form it involves a nonconvex technology.

The literature has concentrated on the "Genesis" problem. This, in the spirit of Rawls, considers the optimal population from behind the "veil of ignorance". In the Genesis problem, a social welfare function is posited, and the whole path of population is solved for. Such problems do not lead to fruitful analysis or much empirical content. In particular, they frequently invoke notions of "potential people" who weigh off the benefits from living against the costs of doing so. The more interesting agenda is to examine "actual" problems in situations where parents explicitly choose the number of their children and the resources to be allocated to them. The questions of optimal population can then be examined using standard tools of welfare economics, although it should be noted that the Pareto criterion is not well adapted to compare allocations when there are different numbers of people alive. In this case, the family utility functions have embedded within them exactly the issues which the philosophers have agonized over. With this framework, we argue that the crucial empirical issue is the nature of intergenerational preferences.

The standard models treat population growth and technical progress as given. In his original work, Solow (1956) suggested that one might endogenize the rate of population growth by making it a function of the capital-labor ratio (see Nerlove and Raut's chapter where they analyze various early models of this type). Another literature (the modern formal analysis which started with Dasgupta (1969)), continued to treat \((1 + n)\) as exogenous to private agents but subject to the control of the government (or planner). This literature attempts to discover the welfare effects of various population growth rates on the agents of a neoclassical growth model and to broach the issue of the "optimal" population. We now examine these issues. Before doing so, we need to clarify whether we are considering optimal population growth or optimal population size. Static analyses do not allow a meaningful discussion of this, so consider a dynamic model. Assume, as we shall, that a steady-state equilibrium exists. When population is exogenously controlled by a central planner or when we are examining normative issues in an economy where the population growth rate is endogenous, there will be some constant growth rate of population in this steady state. If this growth rate is zero, then it makes sense to talk of the optimal size of the population. In this case the optimal growth rate of population is zero. On the other hand, if this rate is positive (or for that matter negative), it only makes sense to talk of the optimal growth rate of population. There is no optimal size.
Ch. 21: Long-Term Consequences of Population Growth

To see what are the important forces at work, we first consider the question of the optimal population in a static model. This clarifies the nature of the mapping from welfare functions to optimal allocations. It also shows the importance of various assumptions about returns to scale. This approach to the problem is associated with the founders of the modern literature: Cannan, Wicksell and Robbins (see Dalton, 1928; Gottlieb, 1945). Having clarified this, we move to a more satisfactory dynamic treatment. This is obviously required for our study, since many of the supposed effects of increased population which we shall consider later are concerned with dynamical phenomena such as capital accumulation, innovation, division of labor, and learning of various forms. The static analysis typically suppresses all of this by assuming that the available technology is independent of the level of population.

Assume that there are initially no people in existence but that the total number of people, $L$, has to be chosen in the "original position" to maximize some social welfare criterion (this is what Dasgupta (1987) calls the "Genesis problem"). As we shall see, while this perspective immensely simplifies the issues (for example, even if we can convincingly formulate and characterize a concept of optimal population, we may never be able to converge to it from an arbitrary starting population), it is probably a bad place to start philosophically. The use of this original position perspective (Rawls, 1971) also involves some implicit account of the utility of a "potential person" (Ng (1986) suggests the alternative term "prospective individuals") who may be brought into existence, but in fact ends up not being so. This is because the kernel of "Genesis problems" is the trade-off between the absolute size of the population and the average level of welfare of those alive. This trade-off is evaluated using different social welfare functions and different technological assumptions. The optimal population is found at the point where the value society attaches to creating another person is matched by the loss in value experienced by the reduced consumption and therefore utility that existing individuals have to incur to allow the new person to live.

A logically consistent approach to determining optimal population size can be derived from the contractual approach to social welfare. This would be to start with the complete pool of potential people and determine optimal population size by maximizing their expected utility. In this set-up, the population in equilibrium will represent the probability of being brought into existence (on the assumption that a random selection is made from the pool of potential people). This also forces us to make an assumption about the utility of not being born. While these contractual theories, following Harsanyi (1955), Vickrey (1960) and Rawls (1971) have been influential we do not consider this is a fruitful approach to thinking about optimal population. Rawls himself was worried about whether his theory applied to intergenerational issues, and its application to population policy is more troublesome still. It is not clear that the notion of a social contract between potential people is very useful, and in fact Rawls' construction with a variable population is confusing, since it is unclear exactly who is doing the choosing (there are clear logical problems in thinking of the original position as concerning only actual people, see Pasek (1993)). Dasgupta (1987) argues in
this vein that we should resist thinking of the original position as a "congress of souls". Nozick (1974) comments, "Utilitarianism is notoriously inept with decisions where the number of persons is at issue."

There is a technology for converting labor into a produced good which can be consumed. This is represented by a twice continuously differentiable, strictly increasing, and strictly concave production function, \( F: \mathbb{R}_+ \rightarrow \mathbb{R}_+ \), where \( Y = F(L) \). This implies that the derivatives of the function have the following signs: \( F' > 0 \), \( F'' < 0 \). Each individual is identical and is endowed with a continuously differentiable, strictly increasing and strictly concave utility function defined over consumption, \( U: \mathbb{R}_+ \rightarrow \mathbb{R} \). We assume that the utility function is twice continuously differentiable with derivatives \( U' > 0 \), \( U'' < 0 \). The utility of consumption, \( c \), is denoted \( u(c) \).

The social planner wishes to choose \( L \) to maximize the welfare of society (in fact the early writers on the subject chose consumption or output per capita as the objective function rather than working with a utility function as we shall). We start with the reasonable criterion that society wishes to maximize utility of consumption per capita (under the assumption that output is divided equally amongst all individuals in existence). This is referred to as "average utilitarianism". In this case, the optimal level of population, \( L^* \), solves the problem, \( \max L \ U(C/L) \) subject to \( C = F(L) \) and \( L \geq 0 \). Substituting the first constraint into the objective function and letting \( \lambda \) be the Lagrange multiplier on the nonnegativity constraint, the first-order condition for this problem is

\[
U' \left( \frac{F(L)}{L} \right) \left[ \frac{F'(L)L - F(L)}{L^2} \right] + \lambda = 0.
\]

An interior solution implies \( LF' = F \). But by diminishing marginal productivity \( F/L > F' \) for all \( L \). This immediately implies that \( \lambda > 0 \) and the optimum is \( L^* = 0 \)! It is apparent that this result depends on diminishing returns to labor. Because of diminishing marginal productivity extra people always produce less than they consume (since output is distributed evenly), per capita output must fall when population expands. If \( F'' = 0 \) then \( L^* \) is indeterminate, and if \( F'' > 0 \) then \( L^* = \infty \). Pitchford (1974b) deals with these cases by assuming that \( F \) is first convex and then concave (the standard Marshallian assumption) which generates a unique interior optimal population. This is the assumption appealed to by the early writers to make population size determinate. These ideas extend to a model with a fixed factor. Assume that the technology is now \( Y = F(L, T) \), where \( T \) is a fixed factor such as "land" or some sort of natural resource. In this case, diminishing marginal productivity of labor implies \( L^* = 0 \) (the argument is identical to that embodied in Eq. (2.16)).

A more utilitarian version of this formulation has been strongly advocated by Meade (1955) (building on the earlier work of Sidgwick (1907)). Indeed Sidgwick (1907) explicitly argued that "if the additional population enjoys on the whole positive happiness, we ought to weigh the amount of happiness gained by the extra number
against the amount lost by the remainder". In this, known as the "total" or "Classical" utilitarian model, the maximand is \( LU(F(L)/L) \), with first-order condition, where \( \tilde{c} = F(L)/L \).

\[
U(\tilde{c}) + U'(\tilde{c}) \left[ \frac{F'(L)L - F(L)}{L} \right] + \lambda = 0.
\]  

(2.17)

It is clear that Eq. (2.17) may admit a positive solution for population in the case where the production function exhibits diminishing marginal productivity of labor (since \( F'L - F < 0 \) by concavity). Meade’s argument for this formulation (versions of Eq. (2.17) are often referred to as the Meade-Sidgwick rule) centers on incorporating some notion that society may care about the size of the population directly and not just the effect it has on per capita consumption. Pitchford (1974b) considers other variants and extensions to multiple commodities. There are also other variants such as the "critical level utilitarianism" formulated by Blackorby and Donaldson (1984) (and recently defended by them in Blackorby et al. (1993)).

The intuition behind Eq. (2.17) is immediate. It balances the social costs and benefits of bringing another person into existence. The first term is the gain in social welfare from the utility of the new person. The second term is the loss in social welfare due to diminishing marginal productivity dragging down the average consumption level.

It seems plausible that individuals care not just about per capita consumption but also about total population so that the above welfare functions might be thought of as special cases of a more general form such as \( U(C/L, L) \). A main argument against this formulation is that it may lead to very large numbers of people all enjoying very low levels of consumption. This result has become known as the "repugnant conclusion" (see Dasgupta, 1987; Parfit, 1984).

The repugnant conclusion raises nicely the difficult issue of the extent to which the welfare of existing individuals is to be traded off against the welfare and existence of potential individuals. On one level, this is a philosophical problem with no definitive solution. Broome, in a series of thoughtful papers (e.g., Broome, 1992, 1993a,b), has argued strongly against the importance of this trade-off. Broome’s view is that unborn individuals have no rights on society which can force them to be brought into existence at the expense of the welfare of existing individuals. This perspective suggests that attempting to consider the welfare of "potential" people is otiose.

Average utilitarianism has also been extensively criticized. Broome (1993a) argues that adding a person with utility above average is justified under this criterion, whether or not the welfare of existing individuals is improved by the addition of this person. Narveson (1978) asks, should one refrain from having a child simply because it is known that it will enjoy below average welfare? Should one feel morally obliged to have a child if it is known that its welfare will be above average? Sumner (1978) argues against average utilitarianism on the grounds that it discriminates in favor of
existing individuals. On the other hand, Sikora (1978) has asserted that “it is prima facie wrong to prevent the existence of anyone with reasonable prospects for happiness”. But how is such a dictum to be implemented in population policy?

One influential view, called the “person affecting view” is that “duties must always be duties to someone or other; if no person is affected by an action, then that action (or inaction) cannot be a violation or fulfillment of a duty” (Narveson, 1978). In this view it cannot be the case that we owe anything to future generations, since “if there is no subject of obligation, then there is no obligation”. Of course we can leave assets to posterity, but this is not a debt we “owe”. As Parfit (1983) points out, if this view is accepted, and if different policies lead to differing sets of future people becoming actual, then as long as these lives are not miserable, which policy we choose is not morally constrained by consideration for future people. However, Parfit (1983) argues that “it is bad if those who live are worse off than those who might have lived”. This approach stresses that what matters is not identities (i.e. the fact that in different histories different potential people become actual) but rather the number of living happy people.

In the next section, we study “Genesis problems” in dynamic models. However, in the rest of the paper, we concentrate exclusively on actual problems. At any moment society is made up of a set of individuals with preferences over their own welfare and the welfare of their descendants and ancestors (and maybe over their friends or even enemies!). Intertemporal optimization of individual agents will generate a path for the evolution of population. The number of children an individual parent will have is determined by the costs and benefits facing the parent. To the extent these differ from the social costs and benefits, or to the extent that society weights the welfare of children differently from parents, there will be normative implications. From this perspective, the repugnant conclusion is an artifact of not formulating the problem of optimal population in terms of an explicit model of intergenerational preferences, constraints and set of social institutions where the rate of population growth is endogenous. In particular, when parents care about the welfare of their children, and this is part of the choice problem along with fertility, it seems unlikely that the repugnant conclusion could arise. It seems improbable that parents would want to bring impoverished children into the world. Of course, the fact that parents care about bringing happy people into the world is not the only motive for fertility. But whatever the case may be, the relevant questions can only be sensibly posed in an explicit model of population growth.

Of course, the moral obligations of parents to children and vice versa may not be adequately captured by such a specification. How much parents care about the welfare of children may not be the same as how much they should care. Unfortunately, while we can examine the positive and normative questions in models where preferences are given (determining how much parents do care and what will be equilibrium fertility and population growth), it is much harder to develop a convincing theory which deals with how much they should care which is separate from this, except to the extent that
their behavior generates externalities, is noncooperative, or induces obvious deviations from efficient behavior. We should perhaps pause to consider the ramifications of this, since in this case, Pareto optimal population growth can imply that it is efficient for parents to bring children into the world when they are treated like slaves. We stress again that this issue can only be resolved by empirical work on the nature of preferences and intra-family relationships.

Unlike philosophers, economists have more generally given up the attempt to propose first-best efficient allocations based on interpersonal comparisons of utility. Perhaps it is not surprising that this should also be the case with regard to population growth.

2.1.3. Optimal population: dynamic analysis

We now consider the implications of average and total utilitarianism for the optimal rate of population growth in a dynamic context where agents live forever. We again derive analogues of the Meade–Sidgwick rule. However, as in the static case, maximizing average utility leads to implausible results (at least with standard technological assumptions). It implies that starting from any level of population, it is optimal to reduce population as quickly as possible, and it also implies, if the initial level of population can be controlled, that it be set to zero. The problem with this model is that while there are costs to having a positive rate of population growth (or larger size of population), there are no benefits. More plausible results emerge under the total utility version. In this case, there is a trade-off between the welfare of existing agents and the social value of creating more people. When the production function exhibits constant returns to scale, there is no optimum level of population but an optimum rate of growth of population. When the production function exhibits decreasing returns, the optimum involves a constant level of population. Hence, if diminishing returns are caused by fixed factors, such as resources, this implies that optimal population growth comes to a halt.

Now return to the dynastic growth model. Instead of treating the rate of population growth as fixed, assume that whilst still exogenous to choices by private individuals, it can be varied by the social planner to maximize welfare. What rate of population growth would maximize the welfare function of the social planner? Notice that in the context of the dynastic model, the answer to this question simultaneously reveals the rate of population growth the dynasty would itself choose. Index the rate of population growth by time, \( n_t \). This rate must be nonnegative, so add to Problem 2 the side constraint that \( n_t \geq 0 \), this adds the term \( \sum_{t=0}^{\infty} \mu_t n_t \) to the Lagrangean.

We assume that the rate of population growth is costlessly controllable by the social planner. Pitchford (1974b) proposes various models where the costs of altering population are explicitly modeled. However, this is an exercise which seems more interesting in a model where population growth is modeled from the choice theoretic
perspective. This gives us a sound basis to assess the welfare implications of population growth, and moreover, it provides an explicit microeconomic foundation for policy. The necessary conditions are now Eqs. (2.5)-(2.8), the complementary slackness conditions and \( \mu, n_t = 0 \), along with the following:

\[-\lambda_t (1 + g) k_{t+1} + \mu_t = 0. \] (2.18)

Eq. (2.18) shows immediately that no positive rate of population growth can be optimal. If \( n_t > 0 \) then \( \mu_t = 0 \) and Eq. (2.18) cannot be satisfied unless \( \lambda_t = 0 \). But \( \lambda_t > 0 \) as long as marginal utility is positive (see Eq. (2.6)). Hence \( n_t = 0, \mu_t > 0 \). The fact that the shadow price on the nonnegativity constraint is positive indicates that the value of Problem 2 could be increased by making \( n_t \) negative! Starting from any initial level of population, \( L_0 \), Eq. (2.18) then suggests that the optimal plan is to set \( n_t = 0 \) and accumulate capital until the steady state is reached. The intuition for these results seems to have been very influential on early work by authors attempting to assess the benefits of population control in developing economies (see for example, Coale and Hoover, 1958; Enke, 1971). Can we then determine what the optimal level of population might be? Consider the problem of choosing the level of population instead of the growth rate. The solution to this is to set \( L_t = 0 \). The intuition for this is identical to the static model with the average utilitarian welfare function (see Lane, 1977).

The implications of the model are not very plausible. One does not have to go as far as Julian Simon to disagree with the proposition that the optimal level of population is zero. This result seems to suggest, in the spirit of Koopmans' desiderata, that the model is badly formulated. There are two possibilities. The first is that the model fails to incorporate important relationships between population and productivity. We investigate this idea extensively in Section 3.3. The second, which we explore first, is that the objective function does not correctly capture the effects of population on social welfare.

In his seminal work on optimal population growth Dasgupta (1969) (see also Dasgupta, 1974) used not the average utilitarian but rather the Meade–Sidgwick total utilitarian formulation,

\[ \sum_{t=0}^{\infty} \beta^t L_t U(\zeta_t). \] (2.19)

Notice again that Eq. (2.19) is not the result of any obvious aggregation over individuals since future utilities are again being discounted from the point of view of the initial individual. The importance of Eq. (2.19) is, as we shall see later, that it can be derived from an aggregation over individual altruistically linked generations who choose the number of children to have endogenously (Becker and Barro, 1986, 1988, 1989). As we shall also see, the allocations which the Becker–Barro model generates
are closely related to those which maximize the utilitarian objective function Eq. (2.19).

This formulation has a nice property, as the following example (due to Arrow and Kurz, 1970; Lane, 1977) makes clear. Imagine a country split into two islands, one with population $L_1$ and one with $L_2$, where $L_1 > L_2$. The social planner has a fixed endowment of goods, $C$, to distribute between the two islands where all individuals have identical utility functions and all individuals within an island will get equal treatment. The social budget constraint is $C = L_1 c_1 + L_2 c_2$, where $c_1$, $c_2$ are the per capita consumption (not in effective units) of individuals on the two islands respectively. Assume that the planner allocates the resources to maximize $U(c_1) + U(c_2)$. The first-order condition for this problem is $U'(c_1)L_1 = U'(c_2)L_2$. Since $L_1 > L_2$, $U'(c_1) > U'(c_2)$, and hence by concavity, $c_2 > c_1$. Now consider the welfare function $L_1 U(c_1) + L_2 U(c_2)$. The first-order condition now implies $c_1 = c_2$. We see that the average utilitarian framework discriminates against people on the first island, simply because they are more populous. In an intertemporal framework with positive population growth, future generations are similarly discriminated against. This seems a strong argument in favor of the specification in Eq. (2.19).

The natural approach to Eq. (2.19) is to assume that this is now the welfare function of the dynasty. How does this change our previous analysis? Consider Problem 1 with the objective function replaced by Eq. (2.19). Call this Problem 3. Note that we continue to assume that the production function exhibits constant returns to scale. To see the implications of the reformulation for the existence of an optimal rate of population growth, Eq. (2.19) can be re-written

$$U(\hat{c}_0) + \sum_{t=1}^{\infty} \left( \prod_{s=1}^{t} (1 + n_s) \right) \beta^t U(\hat{c}_t).$$

More explicitly, this sum is

$$U(\hat{c}_0) + (1 + n_1) \beta U(\hat{c}_1) + (1 + n_1)(1 + n_2) \beta^2 U(\hat{c}_2) + \cdots.$$ 

If the production function exhibits constant returns to scale then this problem can be solved for an optimal constant steady-state equilibrium rate of population growth. The first-order conditions for this problem are:

$$\prod_{s=1}^{t} (1 + n_s) A_s \beta^t U'(c_s A_s) = \lambda_t,$$  

(2.20)

$$\frac{1}{1 + n_1} \sum_{t=r}^{\infty} \beta^t U(c_s A_s) - \lambda_t (1 + g) k_{r-1} + \mu_t = 0.$$  

(2.21)
If there is an interior solution then \( \mu_i = 0 \), and these equations can be combined to generate simultaneously a version of the Meade–Sidgwick rule as well as the standard Keynes–Ramsey rule (the consumption Euler equation). The intuition behind Eq. (2.21) is as follows. The sum represents the discounted total change in social welfare caused by a slight increase in the rate of population growth in period \( t \). Such an increase means that the level of population will be higher in all future periods, and given the way that Eq. (2.21) is constructed, this has to be taken into account in calculating the change in social welfare. The second term in Eq. (2.21) is the marginal social cost of increasing the rate of population growth. In this neoclassical environment, increasing \( n_i \) reduces the capital–labor ratio, and this change is evaluated at the marginal utility of consumption. This term, therefore, captures the adverse effect of an increase in population growth on per capita utility. Hence Eq. (2.21) is the dynamic extension of Eq. (2.17).

If the production function exhibits decreasing returns to scale, then we instead determine a constant optimal level of population and a constant capital stock in a steady state. Consider maximizing Eq. (2.19) subject to the constraints \( K_{t+1} = F(K_t, L_t) - c_tL_t + (1-\delta)K_t \) (with multiplier \( \lambda_i \)) and \( L_t \geq 0 \) (with multiplier \( \mu_i \)), where we set \( g = 0 \). The first-order conditions with respect to \( c_t \) and \( L_t \) are:

\[
\beta U'(c_t) = \lambda_i, \quad \beta U(c_t) = \lambda_i [F_L - c_t].
\]

From these two equations, along with the costate equation and the capital accumulation equation, we can determine the stationary values of \( K, L, \lambda \), and \( c \). Note that the Meade–Sidgwick rule follows immediately from the above two conditions.

Having obtained this characterization of the optimal steady-state growth rate of population, there are many other questions we could examine, for example, what dynamic paths converge to this steady state. Along an optimal path from an initial population and capital stock, is \( n \) equal to its optimal level from the start and does the economy accumulate to the steady state with this constant rate of population growth? This question was raised by Dasgupta (1969). Consider starting from a low level of capital. Dasgupta shows that in the case when the production function exhibits decreasing returns to scale, the optimal approach to the stationary state involves monotonically increasing both the capital stock and the level of population over time until they reach their constant stationary levels. Intuitively, even though population is costlessly controllable, it is not optimal to set it immediately to its stationary level, because this would imply a very low per capita consumption (given the low capital stock).

2.2. Neoclassical growth with finite lifetimes

In Section 2.1, we stressed that certain strong implications of the model depended on the assumed demographic structure. We now develop the main alternative to the dy-
nastic framework, the overlapping generations model. We focus on the simplest interesting case, where generations of two-period-lived individuals overlap forever, and where initially there are no intergenerational links. While the equation governing the dynamics of the model closely resembles that in Section 2.1.1, the current model allows, even when contingent markets are complete, intertemporally inefficient equilibria to exist. This was first discovered by Allais (1947) and independently by Samuelson (1958) and is due to the existence of equilibrium price systems which imply that the aggregate wealth of the economy is infinite. This implies that the first welfare theorem does not hold. Intertemporal transfer schemes can improve welfare above the decentralized equilibrium. The reason that such allocations cannot arise in the model of Section 2.1.1 is that the transversality condition rules them out. If aggregate wealth were unbounded, individual budget sets would not be well defined, and the dynastic problem would not have a solution. Therefore, inefficient allocations are ruled out by the necessary conditions for optimality. But with overlapping generations, although each generation has a well defined decision problem, the social allocation can imply infinite wealth (see Geanakoplos, 1987; Geanakoplos and Polemarchakis, 1992).

In this sub-section, we extend the analysis to simple discrete time overlapping generations models (henceforth, OLG). An alternative (which we do not pursue) would be to adopt the continuous time OLG framework due originally to Blanchard (1985). We do this initially by ignoring intergenerational links. The model follows closely the seminal work of Diamond (1965a) (who built on the work of Samuelson and Allais). Nowhere, however, is the consideration of intergenerational linkages more important than in the study of population growth. We, therefore, extend the model in later sections to consider the various forms this can take. This issue is also treated in depth by Nerlove and Raut in their chapter, and we make our exposition complementary with theirs. Results here turn critically on the exact form which relations take. We offer a discussion of altruism and bequests.

2.2.1. Overlapping generations and neoclassical growth without intergenerational links

As in the previous section, we assume that there is a single produced good (designated as numeraire) which can be consumed or used as capital and that investment is irreversible. Time is discrete. Each agent lives for two periods. In each period \(t = 0, 1, 2, \ldots\), a generation of \(L_t\) identical individuals is born. Generation \(t\) is "young" in period \(t\), "old" in period \(t+1\), and dead thereafter. Each agent has preferences defined over consumption when young, denoted \(C_t\), and old, \(C_{t+1}\) (note that superscripts refer to generations and subscripts to periods) represented by the separable utility function, \(U(C_t) + \beta U(C_{t+1})\). We assume that the instantaneous utility function has the same properties as that in the previous sub-section and that \(\beta \in (0, 1]\). Each individual is endowed with one unit of time in youth and none in old age. The structure of the
model is standard: when young agents supply their unit of time to a competitive labor market. All the capital stock is owned by old agents at the start of any period who rent it to firms in a competitive capital market. Old agents consume their rental income (their marginal propensity to consume is unity), and for simplicity we assume that there is 100% depreciation. Young agents make a consumption/saving decision out of their wage income. The structure of firms is identical to that of the previous subsection. For simplicity, we assume a single price-taking, competitive, representative firm with the same technology. As in Section 2.1.1, there are no intrinsic intertemporal considerations, and the firm hires capital and labor in each period so as to minimize the costs of production. A representative young agent chooses saving, $S_t$, to solve the following Problem 4:

$$S_t(r_{t+1}, w_t, \beta) = \arg \max_{S_t} \left\{ U(w_t - S_t) + \beta U[(1 + r_{t+1})S_t] \right\} .$$

The solution to the problem is a saving function, $S_t(r_{t+1}, w_t, \beta)$, where $S: \mathbb{R}_+ \times \mathbb{R}_+ \times [0, 1] \to \mathbb{R}_+$ (note that since the characteristics of agents are stationary over time, the function will be stationary, and so we drop the subscript on $S_t$ from now on) implicitly defined by the first-order condition

$$U'(w_t - S_t) = (1 + r_{t+1}) \beta U'[(1 + r_{t+1})S_t] .$$  \hspace{1cm} (2.22)

The aggregate stock of capital is just the new saving, hence, $K_{t+1} = L_t S_t$. In per capita terms, using profit maximization by firms and factor market clearing we can write this as

$$k_{t+1}(1+n)(1+g) = S_t f'(k_{t+1})/f'(k_t) - k_t f'(k_t)/\beta .$$  \hspace{1cm} (2.23)

Eq. (2.23) implicitly defines a difference equation in the capital–effective labor ratio. We denote this $k_{t+1} = \chi(k_t)$, where $\chi: \mathbb{R}_+ \to \mathbb{R}_+$. The dynamical system for the OLG model is thus one-dimensional. The behavior of this dynamical system has been intensively studied (see Azariadis, 1993).

We now consider the welfare properties of the above equilibrium allocation (Azariadis (1993) gives an extensive treatment). Capital–effective labor ratios which satisfy the model do not have to be efficient. There is also now a real problem of how to aggregate preferences. The usual approach is to adopt a Bergson–Samuelson type of social welfare function which is a weighted sum of welfare of all present and future individuals in the economy. It should immediately be apparent that difficulties arise as to the weighting of potential people. For the moment we take the rate of population growth as fixed, and so this gives a well defined set of individuals (present and future).
We assume that the economy begins at time zero and the social planner attaches a weight \( \theta_{-1} \) to the welfare of the initial old person \((L_{-1} = 1)\). The planner treats all agents within a particular generation equally and also discounts the welfare of future generations at a constant rate \( \gamma \in (0, 1) \). The welfare function is

\[
W = \theta_{-1} U(C_0^{-1}) + \sum_{i=0}^{\infty} \gamma^i \bar{L}_t \left( U(C_t^0) + \beta U(C_{t+1}^0) \right).
\]

(2.24)

Using the equal treatment embodied in Eq. (2.24) allows the aggregate feasibility constraint to be written

\[
K_{t+1} + L_t C_t^0 + L_{t-1} C_{t-1}^0 = F(K_t, A_t, L_t).
\]

(2.25)

To derive the constraint in per capita effective terms, divide Eq. (2.25) by \( A_t L_t \), which gives

\[
k_{t+1}(1+n)(1+g) + c_t^0 + \frac{c_{t-1}^0}{(1+n)(1+g)} = f(k_t).
\]

(2.26)

The form of social welfare function embodied in Eq. (2.24) is not that typically used in the literature, however. It is more usual (e.g. Blanchard and Fischer, 1989) to specify Eq. (2.24) in per capita terms, so, letting

\[
\tilde{c}_t^0 = \frac{C_t}{L_t} \quad \text{and} \quad \tilde{c}_{t+1}^0 = \frac{C_{t+1}}{L_{t+1}}
\]

be per capita consumption when young and old, respectively, Eq. (2.24) is written (allowing for technological change)

\[
W = \theta_{-1} U(c_0^{-1} A_0) + \sum_{i=0}^{\infty} \gamma^i \left( U(c_t A_t) + \beta U(c_{t+1} A_{t+1}) \right).
\]

(2.27)

Of course Eq. (2.27) brings the social welfare function as close as possible to the one we have initially used in examining the dynastic framework.

Problem 5 is to maximize Eq. (2.27) subject to Eq. (2.26). This problem has the Lagrangean

\[
L = \theta_{-1} U(c_0^{-1} A_0) + \sum_{i=0}^{\infty} \gamma^i \left( U(c_t A_t) + \beta U(c_{t+1} A_{t+1}) \right)
\]

\[
+ \sum_{i=0}^{\infty} \lambda_t \left\{ f(k_t) - c_t^0 - \frac{c_{t-1}^0}{(1+g)(1+n)} - (1+g)(1+n)k_{t+1} \right\}.
\]
The necessary conditions for this problem are:

\[ \theta_{-1}A_0 U'(c_0^{-1}A_0) = \frac{\lambda_0}{(1+g)(1+n)} \]  \hspace{1cm} (2.28)

\[ \gamma' A_t U'(c_t^i A_t) = \lambda_t \] \hspace{1cm} (2.29)

\[ \gamma' A_{t+1} \beta U'(c_{t+1}^i A_{t+1}) = \frac{\lambda_{t+1}}{(1+g)(1+n)} \] \hspace{1cm} (2.30)

\[ \lambda_t (1+g)(1+n) = \lambda_{t+1} (1+f' k_{t+1}) \]  \hspace{1cm} (2.31)

Combining Eqs. (2.29), (2.30) and (2.31) gives the standard condition for optimality within each individual's lifetime

\[ U'(c_t^i A_t) = \left( \frac{1+f'(k_{t+1})}{1+n} \right) \beta U'(c_{t+1}^i A_{t+1}) \] \hspace{1cm} (2.32)

Leading Eq. (2.32) by one period and combining it with Eq. (2.33) gives the condition showing the relationship between generations in the planning problem:

\[ \beta U'(c_{t+1}^i A_{t+1}) = \frac{\gamma U'(c_{t+1}^i A_{t+1})}{(1+g)(1+n)} \] \hspace{1cm} (2.33)

Here the welfare of future generations is "discounted" due to greater numbers, positive technological progress, and the fact that future welfare is weighted less in the specification of Eq. (2.27). Consider now steady-state allocations where

\[ c_{i+1}^i = c_{i+1}^{i+1}, \quad c_{i+1}^i = c_{i+2}^{i+1} \]

Leading Eq. (2.29) and using this and Eq. (2.29) to substitute into Eq. (2.31) gives

\[ U'(c_t^i A_t) = \left( \frac{1+f'(k)}{1+n} \right) \gamma U'(c_{t+1}^{i+1} A_{t+1}) \] \hspace{1cm} (2.34)

Now let \( \gamma = 1/(1+r) \), and consider the special case where the utility function is logarithmic. In this case Eq. (2.34) immediately gives the condition (neglecting terms involving products of \( r, g \) and \( n \))

\[ f'(k) = \tau + g + n. \] \hspace{1cm} (2.35)
Notice that in Eq. (2.35) the steady-state capital effective labor ratio depends on the social rate of discount \( \tau \). The larger is \( \tau \) the smaller is \( \gamma \) and the higher is the weight of present generations relative to future generations. From Eq. (2.35), this implies that a smaller capital–effective labor ratio is accumulated in steady state.

2.2.2. Optimal population with finite lives

We now consider the notion of optimal population growth in the OLG context. This was first explored by Samuelson (1975). Samuelson’s intuition was that the OLG structure was different from the standard neoclassical growth model and this might allow for a positive optimum rate of population growth. Recall that for a positive optimal rate of population growth to exist, it must be the case that there are benefits to having a rate of population growth larger than zero. These do not arise under standard technological assumptions without adopting an objective function which explicitly gives weight to larger numbers of people. However, unlike in previous models, in OLG models there is a new feature emerging from the constraint (2.26). Increasing the rate of population growth has the standard social cost of capital “dilution” through the first term on the left-hand side of Eq. (2.26). There is now another term in Eq. (2.26), however. This is the ratio \( \frac{\nu_t^{1/n}(1+n)(1+g)}{1} \). An increase in \( n \), since it increases the ratio of young workers to old dependents, decreases the dependency ratio, and this reduces the burden of feeding \( \nu_t^{1/n} \) to the old on the social planner.

Samuelson examined stationary allocations in the case with zero technological progress and chose \( n \geq 0 \) to maximize stationary welfare subject to Eq. (2.26). Samuelson’s objective function was \( U(c_t A_t, c_{t+1} A_{t+1}) \) (nonseparable), but this does not alter the characterization of the optimum.

Now consider Problem 5 again. If the population growth rate is chosen by the social planner in Problem 5, then this delivers the following condition:

\[(1+g)^2 k^* = \nu_t^{1/n}(1+n)^2. \]  

(2.36)

The interpretation of Eq. (2.36), sketched above, seems plausible. However, as Deardorff (1976) was quick to point out (and Samuelson (1976) to acknowledge), the second-order condition shows that Eq. (2.36) actually characterizes a minimum in the Cobb–Douglas example used by Samuelson. However, this just demonstrated, unsurprisingly, that restrictions on utility and production functions are required to establish the existence of a stationary optimum with \( n > 0 \) (this should have been evident from the earlier literature (see Lane, 1977)). Michel and Pestieau (1993) have recently established conditions under which Eq. (2.36) characterizes an interior solution (see also Jaeger, 1989).

The question of optimum population size in an OLG model with a Meade–Sidgwick objective function has been examined by Gigliotti (1983). He assumed that
the social planner discounted generations at the same rate that individuals discounted utility between periods and used the following objective function:

$$\sum_{t=0}^{\infty} \gamma^t (L_t U(c_t^t) + L_{t-1} U(c_{t-1}^{t-1})),$$

which is of course Eq. (2.27) when $\gamma = \beta$. The results of this model are very similar to those of Dasgupta (1969). Apart from inessential details, we again derive a version of the Meade–Sidgwick rule.

2.2.3. Intergenerational linkages

In this section, we consider the complex issue of the connection between generations. (Stark (1984) presents a useful conceptual discussion of this topic.) The OLG models developed in the previous sections assumed that there were neither interconnections between the preferences of distinct generations, nor did people belong to integrated family decision-making units. In two seminal papers, Barro (1974) and Becker (1974) argued that in fact one should extend individual preference relations to encompass some notion of the welfare of their descendants. The natural extension of this argument is that preferences might also encompass the welfare of predecessors. The theoretical importance of this innovation is that, to the extent that intergenerational linkages are operational, a sequence of overlapping generations generate equilibria which are identical to that produced by the dynastic model. Whether or not this occurs depends on how the intergenerational preferences are specified.

There are three basic models which consider how parents care about their children. Firstly, the “joy of giving model” where parents get utility directly from giving gifts to their children. Second is the model where parents care about the consumption levels of their children. This model is referred to as “paternalistic altruism”. Finally, there is the model where the parent derives utility directly from the utility of the offspring. This latter is typically referred to simply as the “altruism model”. These models are incomplete to the extent that it seems natural, having taken this step, to consider the utility that children might experience from the utility of their parents. Transfers from children to parents are referred to as “gifts” to distinguish them from “bequests”. Again, these models could have children deriving utility from the giving itself, from the consumption of parents, or from the utility of parents. What is crucial in making a sequence of generations perform like a dynasty is that parents care about the utility of children and simultaneously children care about the utility of parents (the so-called “two-sided altruism model”). It is only when utility is derived from utility itself that a recursive dynamic utility function is generated by overlapping generations. For example, parents care about the utility of their children, who in turn care about the utility of their children, and so indirectly parents care for the utility of their grandchildren
(allowing directly for this effect does not change the situation substantively). While dynastic utility functions can be generated by one-sided altruism (we will examine an important example of this later when we discuss the model of Becker and Barro (1988, 1989)), in general one-sided altruism is not sufficient to rule out dynamically inefficient paths or guarantee Ricardian equivalence (and in this sense make equilibria generated by a sequence of generations identical to that of the infinitely lived agent model), although it is sufficient in some examples (see Stark, 1995). This was originally pointed out by Weil (1987). Weil noted that, in the standard example of dynamically inefficient equilibria, Pareto improvements involve transferring resources from children to parents. A bequest motive cannot generate such a transfer in the case where there is a nonnegativity constraint on bequests. What is required is gifts from child to parent and hence two-sided altruism. In fact, it is not even sufficient to have two-sided altruism, since it is necessary for altruism to be strong enough (otherwise individuals can be at a zero gift or bequest corner solution). These issues are discussed in Abel (1987), Kimball (1987) and Stark (1995).

Models which assume paternalistic altruism are analytically the hardest, because they embed incentives for strategic behavior. For example, consider a parent who inherits a bequest and must decide how much to consume and bequeath herself. If the utility of the parent depends on the consumption of the offspring, then the optimal bequest will depend on the amount of savings of the child. If the child can commit itself to saving a lot for its own children, then this may induce the parent to make larger transfers. Such behavior would of course be rational for the child, if it has preferences of the same form as the parent. These problems cannot be resolved by allowing children to value the consumption of their parents, since this induces new strategic phenomena. For example, parents may now save little in order to credibly induce children to make transfers to them. These models have to be solved using game theoretic tools (see for example, Leininger, 1986; Bernheim and Ray, 1987; Bernheim, 1989) and the type of issues discussed above have been analyzed in Bernheim and Stark (1988).

These extensions to preferences are not necessary for the purposes of examining the endogenous choice of fertility. In many developing countries, children perform productive tasks for the family and thus generate a return to their parents. The demand for children can be modeled not just as a matter of parental utility of children or child’s welfare but because of the income stream children generate for the family (see our discussion in Section 3.1). These models typically assume that parents can enforce these income streams. Bernheim et al. (1985) show how bequests can be used as a “carrot” to enforce such income flows. Children provide services for parents in nonaltruistic models because they will receive a bequest. Here then bequests are driven by a pure exchange process. These models implicitly assume some sort of family structure which is missing from our exposition of the OLG model above.

Interestingly, there seems to be no model in the literature where siblings care for each other, apart from the analysis in Stark (1995), who shows how such considera-
tions may be crucial in spreading cooperative behavior between generations in a model where children mimic parental behavior. This might be important, given the evidence that the amount of resources that a family devotes to each child decreases in the number of children parents have. The first child, once born, might have an incentive to oppose further births. There also seem to be many issues in altruistic relations not captured by existing theories. For example, while parents may care for children's welfare, they tend to have specific ideas about what constitutes a "good" or "fruitful" life. Pollak (1988) observes that parents treat differently a request for financial help from their children depending on what the money is to be spent on (a sports car or a college education). He uses this to argue that it cannot be simply the utility of the children which is valued, unless a richer model is added (perhaps children's preferences are dynamically inconsistent).

2.3. Neoclassical growth with resources

Although historically the study of growth was closely connected to resources and particularly the issue of whether or not finiteness of natural resource stocks put bounds on the feasible paths an economy might follow, these issues were to a large extent ignored in the theoretical flowering of growth in the 1950s and 1960s. The discussion in the nineteenth century was initially focused on land as a fixed resource, but later in the century other exhaustible resources began to loom large. A famous example is Jevons's (1865) forecast that the British economy may be constrained by the running down of its coal stocks. Barbier (1989) contains a nice discussion of early views on the topic. The fact that such Cassandras seemed to have been refuted probably led to the neglect of these issues. The events of the 1970s resuscitated interest in resource constraints.

In this section, in the context of exogenous technical change and population growth, we introduce resources (both exhaustible and renewable). The distinction between the OLG and the ILA frameworks is important here because of the possibilities of intergenerational externalities without compensating altruism (individuals may deplete natural resources or deplete the environment and do not take into account the effects on the next generation (this phenomena has been explored by John et al. (1995)). This problem is particularly pressing for unowned and unpriced resources, since even if there is no altruism towards future generations, present generations may be induced to exploit resources efficiently, if they have the option of selling undepleted resources to future generations (though we shall see that this in itself does not ensure dynamic efficiency).

We start by introducing an exhaustible resource into the technology and review the well-known results due to Dasgupta and Heal, Koopmans, Stiglitz, and Solow. These clarified the extent to which finite resources could constrain growth. Many of the tools and intuitions developed in this literature proved to be useful later. In particular, the literature concentrated on the "essentiality" or "necessity" of resources to production
and the extent to which resource depletion would constrain growth. This clearly depends on the extent to which capital accumulation and technical change are able to compensate for falling stocks of resources. This stimulated a number of authors, notably Dasgupta et al. (1976), Davidson (1978) and Kamien and Schwartz (1978), to endogenize technical change.

We synthesize the results in the literature by modeling the interaction between population growth and resource depletion. We then discuss the wider context of economy-environmental interrelationships. This leads us to move the emphasis away from exhaustible to renewable resources and their implications for growth. We develop a prototype growth model capturing what we see as being the most important interactions and extend it to the important case where utility depends not simply on consumption but also environmental "amenity" services.

2.3.1. Neoclassical growth with exhaustible resources: infinitely lived agents

In this section, we add exhaustible resources to capital and labor as inputs in the production function of a neoclassical growth model. Although resources eventually are completely used up, the economy may be able to exhibit sustained growth in per capita consumption, as long as resources are not "too important" (in a sense we make precise) in the production of output. Even without technical progress, capital accumulation can offset the depletion of the resource. Technical progress makes it more likely that consumption can be sustained. Exogenous population growth makes it harder to sustain growth in per capita consumption. Whatever happens to the resource stock or per capita consumption, the dynamic path of the economy is optimal in a dynastic setting. Optimal population growth introduces issues identical to those in Section 2.1.3. With finite lives, we may have inefficient underexploitation of the resource.

In this section, we review the literature on exhaustible resources developed in the 1970s before moving to the more interesting issue of renewable resources.Treating a resource as exhaustible implicitly assumes that there are no substitutes for the resource and that the ability to recycle the resource is limited. These are quite restrictive assumptions. The major contributions to this literature include Anderson (1972), Vosden (1973) and Mäler (1974), and in particular, Koopmans (1973), Dasgupta and Heal (1974), Solow (1974a), and Stiglitz (1974a,b). The literature is authoritatively surveyed in Dasgupta and Heal (1979). The surveys by Kamien and Schwartz (1982), and Withagen (1991) are also useful.

Consider the ILA model of Section 2.1 with the posited dynastic utility function. The production technology of the economy is now represented by the linear homogeneous function, \( Y_t = F(K_t, A_t, L_t, D_t) \), with \( F: \mathbb{R}_+^3 \to \mathbb{R}_+ \). \( D_t \) is the amount of the resource used in a period, and \( R_t \) is the stock of the resource at any date. We assume that the production function is twice continuously differentiable and concave with (using the previous notation for partial derivatives), \( F_K > 0, F_{KK} < 0, F_L > 0, F_{LL} < 0, F_D > 0, F_{DD} < 0 \). Notice that the assumptions mean that the economy does not exhibit constant
returns with respect to the accumulation of capital and labor alone. The case which has received most attention is when $F$ is of the constant elasticity of substitution form,

$$Y_t = [\alpha_1 (K_t)^\nu + \alpha_2 (A_t L_t)^\nu + \alpha_3 (D_t)^\nu]^{1/\nu},$$

where

$$\sum_{i=1}^{3} \alpha_i = 1$$ and $$-\infty \leq \nu \leq 1.$$ 

When $\nu = 0$ this reduces to the Cobb-Douglas function, where $Y_t = K_t^{\alpha}(A_t L_t)^{\alpha}; D_t^{1-\alpha}$. The elasticity of substitution, which we denote by $s$ (where $s = 1/(1-\nu)$), turns out to be critical in determining the extent to which it is possible for society to substitute out of finite resources and into other factors of production in order to sustain growth. First we give some important definitions (which stem from Dasgupta and Heal (1979)).

**Definition 1:** The resource is necessary if $D_t = 0$ implies $Y_t = 0$.

**Definition 2:** The resource is essential if the only sustainable rate of per capita consumption for the economy is zero.

If $s > 1$ then no input is necessary in the production process and the resource is both unnecessary and inessential (as we shall see this condition, and others, have been rediscovered in the endogenous growth literature). In this case it is possible for the economy to substitute out of the resource. If $s < 1$ then substitution possibilities are restricted. Each input is necessary for production and the resource is essential.

The stock of the resource again evolves according to $R_{t+1} = 1 = R_t - D_t$. There are no extraction costs. Assume that the dynasty owns the resource and that the price of a unit of the resource is $q_t$ (notice that since we are assuming zero extraction costs the price of a unit of the stock of the resource in the ground is equal to the price of a unit of the flow). As in the previous section there is a competitive market where firms buy the resource in each period to maximize profits. Now the dynasty has the nontrivial problem of deciding on the dynamic supply of the resource.

The firm chooses $K_t^d, L_t^d, D_t^d$ in each period to minimize costs. Homogeneity of the production function implies, $y_t = f(k_t, d_t)$, where $d_t = D_t/A_t L_t$ is the resource extracted per effective unit of labor. As in previous sections we model the firm in a way as to let the dynasty make all the dynamic decisions. Similar results would follow from allowing the firm to own the resource and repatriate profits to the dynasty (what is important for the present characterization is not who owns the resource but rather that someone does – it is important to stress that this is not in general true, a vital point to which we return later). Note that in the present case Euler's theorem states, $F = F_K K_t + F_L A_t L_t + F_D D_t$.

The dynasty now faces the following constraints. The first is the period-by-period
budget constraint, the second limits the flows of the resource over time to the total available stock.

\[ K_{t+1} - (1 - \delta) K_t + C_t = w_t A_t L_t + r_t K_t + q_t D_t. \quad (2.37) \]

\[ \sum_{t=0}^\infty D_t \leq R_0. \quad (2.38) \]

We abstract from the further constraint that investment is irreversible, i.e.,

\[ C_t \leq w_t A_t L_t + r_t K_t + q_t D_t, \]

since this is slack along paths with positive net investment. Dividing the above constraints by \( A_t L_t \) and denoting \( R_t / A_t L_t \) by \( \Delta_t \), we can write them in per effective person terms as

\[ (1 + g)(1 + n)k_{t+1} = w_t + r_t k_t + q_t d_t - c_t + (1 - \delta) k_t, \quad (2.39) \]

\[ \sum_{t=0}^\infty (1 + g)^t (1 + n)^t d_t \leq \Delta_0. \quad (2.40) \]

Note that the stock constraint for the resource is

\[ \frac{R_0}{A_0 L_0} \geq \frac{D_0}{A_0 L_0} + \frac{D_1}{A_1 L_1} + \ldots. \]

Now form the Lagrangean for the dynastic optimization problem. Call this Problem 6.

\[ L = \sum_{t=0}^{\infty} \beta^t U(c_t A_t) + \sum_{t=0}^{\infty} \lambda_t [w_t + r_t k_t + q_t d_t - c_t + (1 - \delta) k_t - (1 + g)(1 + n)k_{t+1}] \]

\[ + \omega \left[ \Delta_0 - \sum_{t=0}^{\infty} (1 + g)^t (1 + n)^t d_t \right]. \]

The necessary conditions are:

\[ \beta^t A_t U'(c_t A_t) = \lambda_t, \quad (2.41) \]

\[ \lambda_t q_t - \omega (1 + g)^t (1 + n)^t = 0, \quad (2.42) \]

\[ -\lambda_t (1 + g)(1 + n) + \lambda_{t+1} (1 + r_{t+1} - \delta) = 0. \quad (2.43) \]

Using Eqs. (2.41) and (2.42) and the fact that in a competitive equilibrium the price, \( q_t \), is equal to the marginal product of the resource, denoted \( f_{A_d} \), implies
\[ \beta'^t A_t U' (A_t c_t) f_d = \omega (1 + g)^i (1 + n)^i. \] (2.44)

The left-hand side of Eq. (2.44) is the marginal benefit of using up an extra unit of the resource per effective labor unit at date \( t \) discounted back to time zero. The right-hand side is the marginal cost of using up this increment of resource at date \( t \), i.e., the present value of the resource \( \omega \), times the unit resource increment per effective unit of labor, times the number of effective labor units at date \( t \).

We can derive another fundamental result by leading Eq. (2.42) and eliminating \( \omega \):

\[ \lambda_{t+1} q_{t+1} = (1 + g) (1 + n) \lambda_t q_t. \] (2.45)

Now use Eq. (2.43) to substitute \( \lambda_{t+1} \) out of Eq. (2.45); this gives

\[ 0 = \lambda_t \left[ \frac{q_{t+1}}{1 + r_{t+1} - \delta} - q_t \right]. \] (2.46)

Hence the term in brackets in Eq. (2.46) must be zero, rearranging this formula gives

\[ \frac{q_{t+1} - q_t}{q_t} = r_{t+1} - \delta. \] (2.47)

This result, first derived by Hotelling (1931) and hence called the Hotelling rule, says that the price of the resource rises over time at the net interest rate. The intuition for this is immediate: by arbitrage, the return to holding the resource in the ground must be equal to the return to holding capital.

We now consider the social planning problem for this economy, denoted Problem 7. Since the resource is privately owned and markets are complete, intuition suggests that the allocations characterized above are efficient. This intuition is correct. However, we are also interested in determining whether the presence of an exhaustible resource alters the characterization of optimal population policy. Problem 7 is almost identical to Problem 6, except that the budget constraint is removed and replaced by the social feasibility constraint. This constraint is written

\[ k_{t+1} (1 + g) (1 + n) = f(k_t, d_t) - c_t + (1 - \delta) k_t. \] (2.48)

Note, \( f_k > 0, f_{kk} < 0, f_d > 0, f_{dd} < 0 \). The intensive form of the production function, \( f_i \), inherits the properties of \( F \) in the natural way. The necessary conditions for Problem 7 are now Eqs. (2.48) and (2.41) and the following two conditions:
\[
\lambda_t f_d(k_t, d_t) - \omega (1 + g)^t (1 + n)^t = 0 ,
\]
(2.49)

\[
\lambda_t (1 + g)(1 + n) - \lambda_{t+1} [1 + f_d(k_{t+1}, d_t) - \delta] = 0 .
\]
(2.50)

The Hotelling rule now becomes

\[
\frac{f_d(k_{t+1}, d_{t+1}) - f_d(k_t, d_t)}{f_d(k_t, d_t)} = f_h(k_{t+1}, d_{t+1}) - \delta .
\]
(2.51)

An optimal plan must satisfy the further necessary (transversality) condition for optimality that the resource be completely exhausted asymptotically.

From the above models, we can deduce the behavior of both the decentralized and the "planned" economy over time and in steady state. We first discuss the main results that one can derive from this framework. As in the literature we state these results in terms of the definitions of "necessity" and "essentiality". Notice that these definitions concern feasibility and not optimality. For example, it might be possible to sustain a positive level of consumption eternally, but yet this might not be the optimal thing to do.

Firstly, if \( g + n = 0 \) then in the Cobb–Douglas case the necessary conditions for the resource not being essential are a zero depreciation rate (\( \delta = 0 \)) and a greater share of capital than the resource in output, \( \alpha_1 > \alpha_3 \). These conditions are also sufficient. To see why this is so, we show by construction, the existence of an infinite horizon extraction path with constant per capita consumption if and only if this inequality holds. Consider a dynamic path where output and consumption are constant over time. Consider, for simplicity the case where population is normalized to unity, in this case we have that \( K_{t+1} - K_t = \kappa > 0 \). From this it follows that

\[
\frac{Y_{t+1}}{Y_t} = \frac{K_t^{\alpha_2} D_t^{\alpha_3}}{K_t^{\alpha_2} D_t^{\alpha_3}} .
\]
(2.52)

Using the fact that \( r_{t+1} = r_t \), Eq. (2.52) is a difference equation determining the extraction path for the resource in this case. This is

\[
D_{t+1} = D_t (x_t)^{-\alpha_2/\alpha_1} ,
\]

where \( x_t = [(\kappa + K_0)/(t + 1)x + K_0] \). Note that \( x_t < 1 \). The key issue now becomes the feasibility of this path. It is feasible if the sum \( \sum_{t=0}^{\infty} D_t \) converges to less than or equal to \( R_0 \). This will be the case, if and only if \( \alpha_1 > \alpha_3 \). The sustainable level of consumption is then deduced from the initial size of the stock, since this will determine \( D_0 \) and hence output. In this case, even with zero technological change the economy can
maintain sustained consumption. Over time the input of the resource must fall, however, if \( \alpha_1 > \alpha_3 \) this can be offset by capital accumulation. If the inequality is not satisfied, then consumption must decline to zero asymptotically. This result was first derived by Solow (1974a). The fact that zero depreciation is required is a special feature of the type of depreciation we have assumed and is not general (Dasgupta and Heal, 1979: Chapter 7).

If \( g + n > 0 \) then a necessary condition (still in the Cobb–Douglas case) for the resource to be inessential is \( g > n \alpha_3 \). Again, this turns out to be sufficient (see Stiglitz, 1974a: Proposition 4). The ratio \( g/\alpha_3 \) can be interpreted as the rate of resource augmenting technical change. This last condition has immediate implications for population growth. The higher is the rate of population growth, the harder it is for this situation to be satisfied. The basic intuition for this is identical to the standard neoclassical model. Higher population growth implies higher capital deepening, and this makes it harder for the economy to generate sustained consumption. For the resource not to be essential, it must not be “too important” for production. Notice that this inequality can never be satisfied if population growth is positive and there is zero technical progress. On the other hand, if population is constant, then the resource is always inessential if there is positive technical change.

These results tell us something about the feasibility of certain paths, but they are uninformative about what society actually wants to do. Whether or not it is optimal for the dynasty or society to have continued consumption growth depends on whether the return to accumulating is high enough. This depends, when \( g = 0 \), on whether the asymptotic marginal productivity of capital is greater than or less than the sum of the social rate of discount and the population growth rate (Dasgupta and Heal (1974: Proposition 8) for the case where \( n = 0 \)). This condition has been extensively studied in the recent literature on endogenous growth (see Section 3.3). Notice that in the Cobb–Douglas case the asymptotic marginal product of capital is zero so that even if \( \alpha_1 > \alpha_3 \) so that sustained growth is feasible, it is not optimal.

Alternatively, Stiglitz (1974a) showed in the case where \( g > 0 \) that if the rate of technological progress is larger than the rate of discount then the optimal path is characterized by increasing consumption. If the rate of technical progress is sufficiently high, then sustained growth of consumption is feasible independently of the elasticity of substitution. As many authors have pointed out (e.g. Kolstad and Krautkraemer, 1993) for capital-resource substitution to generate continual consumption increases, it is necessary that the average and marginal productivity of the resource goes to infinity. It is not clear that this assumption is realistic empirically, or even consistent with basic physical principles.

Dasgupta and Heal (1979) give a sharp characterization of the optimal program when population is constant, technical change is zero and the production function is Cobb–Douglas (see Ingham and Simmons (1975) for growing population). If there is zero discounting, then per capita consumption rises monotonically over time. In this case, the economy accumulates a large capital stock and more than compensates for
the declining resource. If, on the other hand, there is positive discounting, then consumption asymptotes to zero. It does so monotonically if discounting is high, but if the discount rate is low the path of consumption per capita first rises and then falls towards zero.

Are the types of restrictions on parametric production functions discussed above at all realistic? Slade (1987) provides a useful discussion of the empirical status of these conditions. There seems to be no consensus about even the sign, let alone the magnitude, of the elasticity of substitution between capital and resources. There are difficult aggregation problems and estimates run from −3.2 (Berndt and Wood, 1975) to 1.43 (Pindyck, 1979). Berndt and Wood also find that, for US data, the shares of capital and resources (for which they use energy) in output are almost identical. There is evidence of resource saving technical progress, but this tends to be different in different sectors of the economy. Some technical progress is resource saving, and some is resource using (e.g. Jorgenson and Fraumeni, 1981). This makes it difficult to say much at an aggregate level.

2.3.2. Optimal population

The implications for the optimal path of population in the models of Section 2.3.1 differ little from the basic neoclassical models of Section 2.1. We observe here that the assumption of exponential population growth is certainly odd. As Dasgupta and Heal (1979) put it, “our concern is in the main part with the implications of a finite earth for the growth possibilities open to an economy. In this context the assumption of an exponentially rising population size is an absurdity, if only for reasons of space”. Now increases in population have both capital and resource diluting costs and, with an average utilitarian formulation of the social objective function, no benefits. With a total utilitarian maximand, the issues are again identical. The most complete treatment of this problem appears in Dasgupta and Mitra (1982) (see also Lane, 1977). Dasgupta and Mitra show that the optimum path for population is characterized by the Keynes–Ramsey rule, the Meade–Sidgwick rule, the Hotelling rule, and transversality conditions for the capital and resource stocks. As in Dasgupta (1969), they show that there is no optimal program, if utilities are not discounted. They then show that, if future utilities are discounted, the optimal path for population implies that the population converges to zero. Intuitively, this follows from the results discussed above. With discounting, consumption goes to zero in this case, and when population becomes controllable the optimum reduces the population as consumption falls. The introduction of exhaustible resources, therefore increases the costs of population size in the social welfare function. This result extends that of Koopmans (1973) to a model where capital accumulation can potentially substitute for the depleted resource. While it is feasible to have equilibria with a constant population experiencing positive consumption for ever, such paths are not optimal.
2.3.3. Finite lives

The majority of the resource literature has been in the (implicit) context of dynastic models. We wish to make one point about finite lives. The main difference here is the possibility that the resource will not be extracted efficiently in a competitive equilibrium. OLG models with resources can generate the same type of dynamic inefficiency which can occur in simple OLG models of capital accumulation. The intuition for this is the same. Dynamic paths can be inefficient because the economy as a whole does not satisfy the transversality condition. Similarly, with resources, a dynamic path which satisfies the Keynes–Ramsey rule and the Hotelling rule may imply asymptotically inefficient underuse of the resource (the resource is “overaccumulated”). This result is proved formally in Homburg (1992).

2.3.4. Renewable resources

We now propose a simple formal framework for thinking about renewable resources. To keep the analysis tractable, we ignore exhaustible resources in this section. Renewable resources come in many forms from land, forests, aquifers, and complete local ecosystems, to global resources such as the climate and atmosphere. These clearly have widely differing implications concerning the extent to which one might be able to define property rights over them. The ownership structure is of course vital for our formalization and the welfare properties of decentralized equilibria.

Renewable resources are hard to include formally into growth models in convincing ways. The dynamics of environmental resources, for example, seem to be nonlinear, and we have little information which allows us to model them simply in aggregate models. We sketch the issues involved. One can write down optimal growth models which have steady-state growth paths where resources are conserved over time and per capita income grows due to capital accumulation and/or technical change. The real issue with environmental and renewable resources is the decentralization of such a path. Resources, particularly global ones, do not lend themselves to well-defined property rights. For local renewable resources, we also caution that the standard property rights solution must be applied with care. In this case, one cannot expect the laissez faire extraction path to mimic the optimal path, and one can construct models in which equilibria imply inefficient extraction and ultimate exhaustion of a renewable resource. The effects of population growth are closely related to those in previous models, a higher rate of population growth tends to reduce both physical capital per person and the level of the environmental stock per person, both along a transition path and in a steady-state equilibrium. Optimal population raises the previous issues and is again characterized by the Meade–Sidgwick rule, if society cares about the number of people alive rather than just per capita welfare.

Many aspects of economy–environmental interaction have received partial treatment. For example, the question of the effect of pollution on the economy over time
has received treatment under a variety of various assumptions. The first model of this type was suggested by Keeler et al. (1971), and developed by Brock (1977) and Gruver (1976). Mäler’s (1974) book also develops models which encompass this issue.

In the 1980s, however, the scope of these models has been widened. Pezzey (1989) provides an excellent overview of the “capital theoretic” approach to economy-environment interaction. Barbier (1989) develops a similar model, see also Mäler (1991). We begin by assuming that the aggregate production function of the economy for the produced good depends not only on produced capital and effective labor, but also on both the stock of a renewable resource, denoted \( E_t \) (the “environment”), and the flow of this resource over a period, \( S_t \). The formalization does not distinguish between the quantity and quality of environmental resources (for example, pollution/waste reduces the stock but clearly in some cases pollution may affect the quality rather than the quantity or vice versa). A good example is soil degradation (Dasgupta (1982) discusses many of the issues in modeling natural resources). In general, it would be desirable to distinguish between a fall in soil nutrients and humus on the one hand, and erosion of the soil altogether (by wind or water). To highlight the special nature of renewable resources we think of the stock as being a public nonrivalrous good. The flows, since we shall treat them as inputs into production processes are private goods. Now

\[
Y_t = F(K_t^r, A_t, L_t^r, S_t, E_t)
\]  

(2.53)

where \( F: \mathbb{R}_+ \rightarrow \mathbb{R}_+ \). We assume that \( F \) is concave and twice continuously differentiable with partial derivatives, \( F_S > 0, F_{SS} < 0, F_E > 0, F_{EE} < 0 \). \( K_t^r \) and \( L_t^r \) denote the amount of capital and labor, respectively, allocated to the production of the consumption good. Allowing for both flow and stock effects encompasses all of the models in the literature (which typically concentrate on one or the other). For example, a forest can be harvested, and this harvest (timber) is a flow which increases production. However, the stock also matters. The total size of the forest affects greenhouse gas accumulation and maybe soil erosion and affects species diversity. Thus, one wants to allow for both effects in general.

The resource has a natural rate of recovery but is degraded as the result of production (we can think of this as “pollution” or the general result of waste products being deposited in the environment). We denote the quantity of capital allocated to abatement (or regeneration) activities (which we describe shortly) \( K_t^r \), where \( K_t^r + K_t^H = K_t \). We can also think of this as any activity which improves the quality of environmental resources. With \( L_t^r \) being the amount of labor devoted to current production, \( L_t - L_t^r = L_t^e \) is devoted to abatement or environmental improvement. Denote the level of abatement activities by \( B_t \). The resource stock evolves in the following way:

\[
E_{t+1} = H(E_t, S_t, Y_t, B_t)
\]  

(2.54)
where $H: \mathbb{R}_+ \to \mathbb{R}_+$, concave and twice continuously differentiable. Here we might assume the following signs for the partial derivatives: $H_E > 0$, $H_{EE} < 0$, $H_S < 0$, $H_Y < 0$, $H_{YY} > 0$, $H_B > 0$, $H_{BB} < 0$. The specification of Eq. (2.54) simplifies, since it does not allow for a separate stock of pollution (as in Kamien and Schwartz (1982), for example). Instead we concentrate on the "net environmental quality", inclusive of pollution activities. Notice that we have also ruled out a direct negative effect of population on the evolution of the environment. If we were assuming that the economy was also constrained by exhaustible resources, then we would also be simplifying by assuming that the dynamics of environmental quality are not directly dependent on the extraction path of depletion of the exhaustible resource (though, there would be an indirect effect which works through the output of the consumption good and waste/pollution degrading the environment). To simplify the analysis, we make use of various plausible restrictions of Eq. (2.54) below. Abatement activities may take capital and labor resources so that there is an allocational problem in the economy. In any period, the total labor force (population) must be allocated between producing current output and abatement. The technology for abatement is denoted $B_t = G(K_t^s, L_t^f)$, where $G: \mathbb{R}_+^2 \to \mathbb{R}_+$. For simplicity, we assume that neither the stock of environment nor the exhaustible resource directly affect the abatement technology. We assume that this function is twice continuously differentiable and concave and has the following signs for the partial derivatives with respect to capital and labor inputs: $G_K > 0$, $G_{KK} < 0$, $G_L > 0$, $G_{LL} < 0$.

It is also important to consider the possibility that the state of the environment can directly affect welfare. To take this possibility into account, we respecify the objective function of the dynasty to be

$$\sum_{t=0}^\infty \beta^t U \left[ \frac{C_t}{L_t}, E_t \right].$$

(2.55)

We assume that the utility function, $U: \mathbb{R}_+^2 \to \mathbb{R}$, is again twice continuously differentiable, strictly increasing and strictly concave, with the following signs for the partial derivatives: $U_C > 0$, $U_{CC} < 0$, $U_E > 0$, $U_{EE} < 0$. It is also intuitive to assume that $U_{CE} \geq 0$. We exclude flow effects from utility since most of the plausible examples of amenity effects concern stocks rather than flows. We make no attempt here to discuss the conceptual problems involved in measuring these amenity services (which is clearly important for cost–benefit analysis), however, there is a lot of serious work on this. For example, Graves (1991) discusses fascinating attempts to value long-range visibility in the western USA which is considered to be important for viewing the scenery.

The most critical assumptions concern the structure of property rights in the economy. In particular: is the environment "owned" by anybody? Who, if anybody, is responsible for waste activities, and thus who would be the likely demander of abate-
ment services? The most straightforward assumption is that there is a price for abatement services, $m$, and that these firms hire capital and labor from the dynasty in order to provide abatement services which are demanded by goods producing firms. To understand the nature of this problem, however, we concentrate on the characterization of optimal allocations. We then use this to discuss the welfare implications of alternative institutional arrangements and consequent distributions of property rights and the types of issues that surround the desirability of laissez faire paths.

The issue of property rights is of course critical in understanding the differences between the type of exhaustible resources we examined in the previous section and the renewable resources of this section. The type of environmental resources captured by our variable $E$, tend to be goods over which it is logically and logistically very difficult to define property rights. There is a clear presumption that such resources will be inefficiently exploited in equilibrium. It is much easier to define property rights over a coal or oil deposit. This does not imply that the intertemporal extraction path will be efficient since, as is well known, such efficiency requires a complete set of contingent Arrow–Debreu markets. However, such resources do not generate the type of external effects which typically are associated with $E$, so potentially inefficiency seems to be of a differing order of magnitude.

Externalities and incomplete markets are intimately linked. The existence of widespread environmental externalities can be seen as stemming from the inability to define property rights which would allow the commodity to be traded (Mäler (1985a) provides a rigorous treatment of environmental resources from the perspective of Lindahl equilibrium and the Coase theorem). The role of institutions is especially important here. In the next section, we examine a typical local commons problem which arises in many situations in developing economies. An immediate response to this would be to think that the problem can be resolved by property defining property rights. While we agree with this statement in general, one has to be very careful with the way such a scheme is implemented. Systems of property rights have important implications for income distribution. This point, stressed by Starrett (1972), has recently been raised in the context of developing nations by Dasgupta and Mäler (1995) and Van Arkadie (1989). As Van Arkadie puts it, "Thus while there has been a widespread presumption that a movement toward securely held registered title is economically desirable, recognition of the problems involved has been slower to emerge. For example, conferring land tenure rights on sedentary agriculturalists (already apparent occupants) may disrupt a system of pastoral seminomadism, based on rights of passage and of dry season grazing, which represented a sophisticated response to a particular ecological problem. Likewise, the allocation of land rights to an individual may misinterpret and disrupt arrangements within the family (displacing the rights of women, for example)". Many societies, while lacking the type of extensive formal system of property rights which characterizes much of the developed world, may nevertheless have developed highly sophisticated institutional solutions to allocational problems (see the discussions in Dasgupta (1993a) and Ostrom (1990)). Without an
understanding of these, simple policy prescriptions are flawed. This perhaps explains some of the evidence that the types of productivity gains that we might expect to arise from defining private property rights do not always seem to occur (e.g., Migot-Adholla et al., 1991). One reason for this may be a connection between distribution and efficiency. Such a connection is common in models of incomplete contracts and markets and situations where there is asymmetric information. For example, in a general equilibrium model with incomplete markets, Roemer (1993) has studied the connection between distribution and efficiency in the context of pollution and other “public goods”.

Simple “opening markets” solutions have other potential caveats. Starrett (1972) also pointed out that such situations naturally give rise to nonconvexities in production sets so that an equilibrium may not exist. In fact, there are robust situations where, while an equilibrium with markets does not exist, government designed tax equilibria may exist (see Dasgupta and Heal, 1979: Chapter 3).

We take the objective function of the social planner to be our amended dynastic welfare function, Eq. (2.55), and we start by ignoring the amenity value. We also make some restrictions on Eqs. (2.54) and (2.53). We assume that output of the consumption good does not directly affect the evolution of the environment and that abatement or regeneration expenditures can be captured by allocating capital to the task. This implies that Eq. (2.54) is now

\[ E_{t+1} = H(E_t, K_t^e) - S_t. \]

We additionally assume that \( H \) is homogeneous of degree one. We also assume that there are no stock effects in the production function for the produced good and initially ignore technical progress. What now are the social feasibility constraints? The first is for the consumption–capital good, Eq. (2.56) below, and the second for the stock of environmental quality, Eq. (2.57). We write these in per capita effective form. To do this, we make several more simplifications. We assume that labor is only used to produce the consumption good,

\[ k_{t+1} (1+n) - (1-\delta) k_t + c_t = f(k_t^e, s_t), \quad (2.56) \]

\[ e_{t+1} (1+n) = h(e_t, k_t^e) - s_t. \quad (2.57) \]

This problem is obviously very complicated to analyze, so we begin by considering a much simplified version. We assume that population is constant (normalized to one), and for convenience we drop it from the production function. Output is produced using capital and a flow of resources, and resources regenerate in a way which is a strictly concave function of the current stock. We also start by ignoring amenity effects. Thus we have the constraints
\[ K_{t+1} = F(K_t, S_t) - C_t + (1 - \delta)K_t, \]  
(2.58)

\[ E_{t+1} = H(E_t) - S_t. \]  
(2.59)

We assume that in this form \( H \) is still twice continuously differentiable, strictly increasing and strictly concave with derivatives, \( H' > 0, H'' < 0 \). To simplify the analysis, we take a recursive point of view (see Stokey et al., 1989) and formulate the Bellman equation for the social planner. Denote the value function for the planner \( V(K_t, E_t) \). This function satisfies

\[ V(K_t, E_t) = \max_{K_{t+1}, E_{t+1}} \{ U(F(K_t, H(E_t) - E_{t+1}) + (1 - \delta)K_t - K_{t+1}) + \beta V(K_{t+1}, E_{t+1}) \}. \]

The necessary conditions are

\[ U'(C_t)F_S = \beta V_E(K_{t+1}, E_{t+1}), \]  
(2.60)

\[ U'(C_t) = \beta V_K(K_{t+1}, E_{t+1}), \]  
(2.61)

and the envelope conditions

\[ V_K(K_t, E_t) = U'(C_t)[F_K + 1 - \delta], \]  
(2.62)

\[ V_E(K_t, E_t) = U'(C_t)F_S H'. \]  
(2.63)

From these we derive the arbitrage relationship

\[ H'(E_t) \frac{F_S(K_t, H(E_t) - E_{t+1})}{F_S(K_{t-1}, H(E_{t-1}) - E_t)} = F_K(K_t, H(E_t) - E_{t+1}) + 1 - \delta. \]  
(2.64)

Since society can save for the future either by producing more of the consumption good today and storing it or by reducing the current exploitation of the environment so that the environment is more bountiful in the future, Eq. (2.64) says that at an interior optimum the marginal return to these two methods of saving must be equal.

A steady-state equilibrium in this economy will involve a set of constants \( E, K \) and \( C \) which satisfy the equations, \( \delta K = F(K, H(E) - E) - C, F_K(K, H(E) - E) = \rho + \delta \), and the steady-state version of Eq. (2.64), \( H'(E) = F_K(K, H(E) - E) + 1 - \delta \) (in a steady state \( V(K_t, E_t) = V(K_{t+1}, E_{t+1}) \)), and these equations characterizing the steady state follow immediately from Eqs. (2.60)–(2.63)). Notice that these last two equations imply that \( H'(E) = 1 + \rho \). Now standard (Inada type) assumptions on the renewal function
guarantee the existence of an interior steady-state equilibrium. Denote this \( E(\rho) \) where \( E' < 0 \) by the concavity of \( H \). The equilibrium capital stock, denoted \( K(\rho, \delta) \) satisfies \( F_k(K, H(E(\rho)) - E(\rho)) = \rho + \delta \). Notice that across steady-state equilibria, as \( \rho \) changes, we have

\[
\frac{dE}{dK} = \frac{F_{kk}}{H'' - F_{ks}(H' - 1)} > 0. \tag{2.65}
\]

Both the numerator and the denominator are negative. The sign of the denominator follows from the fact that \( H \) is concave, \( H' > 1 \), and since \( F \) is linear homogeneous and satisfies diminishing marginal productivity, \( F_{ks} > 0 \).

The two first-order conditions, Eqs. (2.60) and (2.61), implicitly define the policy functions \( K_{t+1} = \Gamma(K_t, E_t) \) and \( E_{t+1} = \Omega(K_t, E_t) \) and a two-dimensional dynamic system. Unfortunately, it is impossible to say much about the global or local behavior of these equations without putting a lot of special structure on the problem. There has been some work on the conditions under which models of this type may exhibit local saddlepoint behavior in the case where the environmental stock is interpreted as pollution. On this see Brock (1977), Becker (1982), van der Ploeg and Withagen (1991) and Tahvenen and Kuuluvainen (1991, 1993). Here one must remember that in reality we know very little about the form of the function \( H \). In some cases, this may have discontinuities, in the sense that once the stock falls below a certain level, it cannot recover naturally. Clearly, aggregate dynamics are going to depend a lot on the form of this function, and so it would be surprising, if we could say anything very general.

If the economy converges to the above steady state, then it experiences a constant capital stock, constant environmental quality and constant per capita income.

To introduce population growth, we return to the assumption that \( H(E_t) = H(E_n, K_t^e) \) where \( H \) is a linear homogeneous function. Population now grows at rate \( n \). This implies that the environment can regenerate either because the stock is higher or because capital is allocated to regeneration activities. In this case, the constraints can be written in per capita terms as in Eqs. (2.56) and (2.57) above. Now we can solve the problem by directly substituting these constraints into the objective function

\[
\sum_{r=0}^{\infty} \beta^r U(f(k_t - k_t^e, h(e_t, k_t^e) - e_{t+1}(1+n)) + (1-\delta)k_t - k_{t+1}(1+n)).
\]

The necessary conditions are:

\[
f_k(k_t - k_t^e, s_t) = f_k(k_t - k_t^e, s_t) h_k(e_t, k_t^e), \tag{2.66}
\]

\[
U'(c_t)(1+n) = \beta U'(c_{t+1})[f_k(k_{t+1} - k_{t+1}^e, s_{t+1}) + 1-\delta]. \tag{2.67}
\]
\[ U'(c_i)f_z(k_i - k^e_i, s_i)(1 + n) = \beta U'(c_{i+1})f_z(k_{i+1} - k^e_{i+1}, s_{i+1})h_z(e_{i+1}, k^e_{i+1}). \]  

(2.68)

The analogue of Eq. (2.65) is

\[ h_z(e_i, k^e_i) \frac{f_z(k_i - k^e_i, s_i)}{f_z(k_{i-1} - k^e_{i-1}, s_{i-1})} = f_z(k_i - k^e_i, s_i) + 1 - \delta. \]  

(2.69)

A steady-state equilibrium for this economy is a set of constants, \( k, k^e, c \) and \( \epsilon \) which satisfy the following equations: first, a standard condition for the marginal product of capital, \( f_z(k^e, \epsilon) = \delta + \beta + n \), next the steady-state version of Eq. (2.69), \( h_z(e, k^e) = f_z(k - k^e, h(e, k^e) - \epsilon(1 + n)) + 1 - \delta \). From these two equations, it follows that \( h_z(e, k^e) = 1 + \beta + n \). There is also the steady-state form of the feasibility constraint, \( k(n + \delta) = f(k - k^e, h(e, k^e) - \epsilon(1 + n)) - c \). The final equation is the condition that the capital stock be allocated efficiently. This equation follows from Eq. (2.66):

\[ f_z(k - k^e, h(e, k^e) - \epsilon(1 + n)) = f_z(k - k^e, h(e, k^e) - \epsilon(1 + n))h_z(e, k^e). \]

Notice that we are here making use of the approximations discussed in Section 2.1.

To see the effects in this type of model of allowing for the amenity value of the environment, let the momentary utility function take the separable form \( U(c) = W(c) \), where \( U \) and \( W \) are both continuously differentiable, strictly increasing and strictly concave. In letting utility depend on the per capita resource stock in this way we are using the property that the resource is a pure public good. In this case, if the total stock is \( E \), then this is also the stock per capita. In this case Eq. (2.68) has an extra term \( \beta W'(e_{i+1}) \), on the right-hand side. The effects of this is seen by re-deriving Eq. (2.69). In steady state, this now becomes \( U'[f_z + 1 - \delta] = U'h_z + W \). The equilibrium arbitrage relationship between capital and resource is altered because the resource has intrinsic value. In equilibrium, since \( W > 0 \) we will have \( f_z + 1 - \delta > h_z \). Now in the previous model, this would have unambiguously implied that the resource stock would have been higher in steady state. This is not necessarily the case here since the allocation of capital has to be determined endogenously. It could be the case that general equilibrium effects reduce the resource, though this seems a pathological case.

Now consider the effect of varying the rate of population growth. In a steady-state equilibrium, a higher rate of population growth increases the marginal products of both the resource and the capital stock. It seems plausible, modulo general equilibrium effects, that an increase in \( n \) would reduce the steady-state stocks of both capital and the resource. Hence, an increase in the rate of population growth has “capital widening effects” not just with respect to physical capital, but also with respect to natural capital. A higher rate of population growth, therefore, tends to lead to a lower quality of environment in steady state.
It is important to consider the nature of this equilibrium. With population growing exogenously at rate \( n \), the equilibrium implies that the environmental stock is constant. This stems from the public goods assumption. However, a constant \( k_e \) implies that \( k_e \) is growing at the rate of population growth. In this equilibrium, as the economy accumulates capital, more of it is allocated to maintaining the resource stock so that a larger flow can be extracted from it to produce the consumption good. One could develop this model by adding exogenous technical progress. A major problem, however, in constructing steady-state equilibria is the behavior of the stock of natural capital. Does it make sense that the level of the environment can increase forever? The addition of technical change can allow the existence of growth paths along which per capita income grows and the quality of the environment continually improves. Even though increased per capita income may imply a higher degeneration of the environment, the stock is increased by allocating a larger and larger amount of resources (physical capital and in a more general model labor) to abatement and maintenance (such a model is constructed in van Marrewijk et al. (1993)). While constructing such a model is feasible, the extent to which it represents a realistic dynamic is not clear. A vital topic for future research is to understand more about the function \( H \) and attempt to develop better measures of renewable resources, which allow more convincing modeling.

Notice that Eq. (2.65) does not embody cross-sectional properties that are easily associated with the environmental Kuznets curve (i.e., that there is a nonmonotonic relationship between per capita income and capital–labor ratios and the quality of the environment). For example, think of countries as having converged to their steady states and as being distinguished by each having a different value for \( \rho \). Eq. (2.65) shows that “impatient” countries with a low capital–labor ratio and low per capita income also have a low environmental quality. Similarly, “patient” countries have high steady-state stocks of both types of capital. In this model, Kuznets curve type behavior must be generated by the dynamics of the transition path. On the other hand, as the discussion on the previous page makes clear, once capital allocation between sectors is introduced, there is no logical reason why physical and environmental capital should move together, though perhaps this is the most plausible case in models, like the one considered, where environmental resources are used in producing the consumption good.

The types of necessary conditions studied above, taking into account not just the positive gain in future utility which comes from expanded technological possibilities, but also incorporating the negative side effect of increased environmental degradation, have recently been explored by Weitzman (1993a). He uses this to stress the fundamental point, that in the presence of environmental effects, the social rate of return to a project will typically be less than the private rate of return.

We now return to finite lives and optimal population. Finite lives have the usual implications. As in simpler models (without resources), it is possible to have paths where there is over-accumulation of resources, if there is not sufficient altruism be-
tween generations. The extra feature here, mentioned at the beginning of Section 2.3, is that when considering problems of decentralizing optimal allocations we have an inter-generational externality as well as an intra-generational externality (on which see John et al., 1995). Optimal population issues are standard. With no direct social benefit from the numbers of people, adding in renewable resources alters nothing. The optimal rate of population growth is negative. Adopting an objective function, such as Eq. (2.19), generates a version of the Meade–Sidgwick rule and generally an interior optimal rate of population growth under constant returns to scale.

3. Endogenizing population and technical change

In this section, we bring the analysis of the previous sections into closer contact with the data, and moreover make it more useful for normative and policy purposes. In particular, we bring fertility and mortality within the scope of behavior (Section 3.1), and develop their implications for the exploitation of resources (Section 3.2). This is an important step. The first two sections consider models either with no technical progress or with a constant exogenous rate of technical progress and concentrate on the types of conditions necessary to generate a “demographic transition”. Imagine a world with no technical progress and resources. If population growth is exogenous and positive, such an economy is doomed if resources are nonrenewable (Section 2.3.1), if resources are renewable then there may be steady states where consumption per capita stabilizes at a positive level (Section 2.3.4). Endogenizing population forces us to specify the reasons that parents have children. If altruism is a plausible one of these then we might expect the prospect of bringing impoverished children into the world (something which happens on the transition to “doomsday”) to put a break on fertility. Even without altruism, this may occur if children are normal goods so that as income falls fertility falls along with consumption. Our concern in this paper is to articulate the nature of the relationships between population, resources and development. Endogenizing fertility in plausible ways suggests that population growth may well adapt both to development (the “demographic” transition) but also to resource constraints and the onset of the doomsday. We aim to clarify these issues.

Section 3.2 moves away from the general development to stress situations in which there is no trade-off between protecting the environment and population growth. Section 3.3 introduces the central issues involved in the endogenization of technical progress. We then (in Section 3.4) examine the interaction between population growth and endogenous technical change. This area has deep roots both in economic history (exemplified by the work of Boserup, Habakkuk and McNeill) and also in the more recent formal literature (e.g. the existence of “scale effects” in endogenous growth models). Allowing for the joint endogeneity of technical progress and technical change can radically alter the tenor of the results of the previous sections. We examine mechanisms through which population growth in itself may foster increased technical
change, and through which technical change influences individual decisions on fertility and mortality. We bring together some of the threads of the discussion in the final two sections to understand the feasibility of growth when the use of natural resources in a dynamic economy and the interactions between resource usage and demographic behavior are explicitly taken into account.

3.1: Models of endogenous fertility and mortality with exogenous technical change

In this sub-section, we build on the analysis of Section 2.2 by endogenizing fertility and mortality. Much of the impetus for this work stems from the research of Gary Becker, in particular his (1960) article and more recent book (1981) (although Leibenstein (1957) also made an important early contribution). Becker has not only extended decision theory to examine fertility and other aspects of family behavior, but has also examined, and has indeed stressed, the aggregate implications of these models (which is primarily our concern). The main aggregate implication of interest to our concerns is how fertility responds to development and the conditions under which a demographic transition will take place. This has motivated much of the literature.

Although population growth is simultaneously determined by fertility and mortality, the largest part of the literature focuses on endogenizing fertility rather than mortality since the latter has seemed more sensibly treated as exogenous. However, this consensus seems to be changing. The evidence in fact suggests that the stylized facts about trends in mortality in relation to modern industrial growth and the demographic transition are just as systematic and startling as those about fertility (Mokyr, 1993). As such, there seems little rationale for not endogenizing mortality (see Ray and Streufert, 1993). To keep the analysis within bounds, we do not treat these issues formally.

It is traditional, therefore, to start by endogenizing fertility. A good discussion of many of the different models in the literature is contained in the books by Nerlove et al. (1987) and Razin and Sadka (1995). There are two basic types of models: Altruistic models assume that the main reason for having children stems from some form of interdependence between the preferences of adults and children. If parents care about the utility of children, for example, then children must exist for children to experience utility. Parents then transfer resources to them to influence their utility. Such transfers go under the rubric of affecting “child quality” (the notions of child “quality” and “quantity” go back to Darwin (1871)). This can imply either transfers of a consumption good or subsidies aimed at human capital accumulation. This type of model, studied by Becker and Lewis (1973), is used by Razin and Sadka (1995) to study how increases in parental income (perhaps as part of the process of economic development) affects the choice between the quantity and quality of children. Nonaltruistic models assume people have children either because they like having children, or because of the resources they can extract from them, or the beneficial exchanges they can make.
with them. Stark (1995) shows that people may also want to have grandchildren in
models where children learn how to behave by watching their parents. Grandparents
want their children to look after them, but they will only do so if forced to do so by
having to show a good example to their children (so they in turn will be looked after
in old age).

Models where adults get utility from having children assume that the number of
children is an argument in the utility function, and that it is a choice variable (we will
henceforth treat the number of children as a continuous variable; not necessarily an
innocuous assumption (Sah, 1991)).

Parents may be able to make exchanges with children which they cannot make with
nonfamily members because the ties of kinship can be important in enforcing incom-
plete contracts. We partition these latter models into two: the “old-age security mo-
tive” and the “children as producer or capital goods” models. The first model develops
the idea that capital and insurance markets are typically incomplete in underdeveloped
countries, and having children is often the only way of providing for old-age needs.
Cassen (1976) remarks, “it seems likely that high fertility is a characteristic of socie-
ties in which the family is the only source of social and economic security” (see
Nugent, 1985). Important formalizations of this idea are due to Neher (1971) and
Willis (1980) (see Razin and Sadka (1995: Chapter 4) and Nerlove and Raut in this
Handbook). The “children as producer goods” model is based on the fact that, in poor
economies, much production goes on within the household unit or family farm. Chil-
dren play important roles in production and are needed to produce for the family.

All of these models can be used to explain the demographic transition. In models
where parents are altruistic towards children, the opportunity cost of time devoted to
child raising rises with development (since real wages rise), and this tends to reduce
fertility. On the other hand, higher income may increase fertility if children are normal
goods. These models tend to argue that development raises the return to child quality
relative to quantity, and thus leads to substitution away from high fertility. In terms
of old-age security models, the use of children as financial insurance rests on the un-
availability of alternative assets. As the economy develops, these become available
and, as Neher (1971) puts it, “the good asset (bonds) drives out the bad asset (chil-
dren)” (though the introduction of new assets can also have positive income ef-
fects). Finally, models which stress the productive role of child labor in home produc-
tion can also address the demographic transition. Azariadis and Drazen (1993) de-
velop a model where children work on the family farm and bargain with their parents
over the output. They then show how urbanization increases the outside option of the
children and lowers the return to parents from having children (see also David and
Sundstrom, 1988). There is debate as to the plausibility of this model. While Caldwell
(1990) has calculated that the net wealth flows from children to adults can become
positive by the middle of adolescence, Cassen (1976) argues that the evidence is not
conclusive on whether or not having a child is really a good investment. In fact, Fogel
and Engerman (1971) calculated that a slave raised from infancy brought a positive
return to his owners after 27 years. Moreover, Stark (1991) has argued that the opening up of the formal economy may in fact generate an increased demand for children, since we do in fact observe remittances from children, and formal wages are both higher than and imperfectly correlated with agricultural productivity.

In developed economies, it is typical to think of the main motivation for child-bearing as being altruistic in nature, and it is assumed that parents care directly for the utility of their children. However, even here it seems plausible that parents derive direct utility from having children. In developing economies, however, it is widely agreed that this misses some of the key motives for childbearing we have mentioned. In reality, all of these motives must be present. People in developing countries do not care less for their children than people in developed countries, it is just that the institutions and constraints in which they operate are different so that we suppress other motives when modeling what we perceive to be the critical aspects of behavior. A complicating feature is that, in reality, preferences are endogenous. For example, cooperative models of the family are often motivated by intra-family altruism, but such altruism must develop after marriage, and, thus, preferences in this literature are implicitly endogenous.

There are then a plethora of different assumptions about the motivations behind fertility. This is problematic since different models have different implications for social welfare and, in particular, whether or not there is a "population problem". In one extreme case, imagine that adults care about the utility of their parents and the utility of their children in a way which is sufficient to generate the dynastic utility function. In this case, population growth may be first-best efficient since the dynasty (society) solves the same optimization problem that a social planner would solve. Once we deviate from this case, however, the situation becomes considerably more complex. Consider a model where children were brought into the world just to work on the family farm and where parents do not care about their welfare. In this case, the rate of population growth might still be Pareto optimal, it might not be possible to reduce the number of children without harming the welfare of parents, but if society weighted the welfare of children explicitly, the rate of population growth might well be socially inefficient.

Inefficiency may also stem from more direct external effects; for example, rapid population growth rates may directly crowd the environment or per capita levels of natural resources, or it may congest infrastructure and public goods (though here the effects are ambiguous since new people add both to government expenditures and revenues). There is also the nature of decision-making within the family to consider. Even though such interaction is intrinsically noncompetitive, the models in the literature assume that the family acts as a unified decision-making unit. This seems a very strong assumption and has been criticized on empirical grounds by Alderman et al. (1995). It has typically been assumed that a corollary of the "unified household" axiom is that outcomes of family decision-making would be efficient, in particular, given the ability of family members to negotiate with each other. This assumption has
recently been challenged in an important paper by Udny (1994), and if his view is correct, then noncooperative behavior within the household may be a potential source of inefficiency in fertility decisions. For example, if husbands and wives bargain non-cooperatively, over the number of children to conceive, or if fertility is determined cooperatively, but other aspects of household decision-making are noncooperative (for example, the allocation of time to existing children), then the equilibrium fertility rate will not be efficient and, in general, will be too high (see Baland and Robinson, 1996a,b). Social norms of various sorts may also generate inefficient population growth if they become dysfunctional. Dasgupta (1993a,b) stresses that social norms may have a self-fulfilling character leading to multiple equilibria. A nice example of this is provided in Crook (1978). Individuals’ preferences may be a function of family size relative to the average since this determines a family’s influence in local political and social institutions (for example, the village council). It is clear that there may be many Nash equilibria in a game where individuals choose family size to maximize relative family sizes. There also seems to be strong evidence that some poor people lack information and knowledge about family planning. This is witnessed by the continual finding that there is an unmet demand for fertility limitation (see, for example, Birdsall, 1988).

We now consider the one-sided altruistic (parents care for children but not vice versa) model of Becker and Barro (1986, 1988, 1989) (these papers build on the work initiated by the seminal paper of Razin and Ben Zion (1975)). This model is a nonoverlapping generations model where each person lives only for one period and cares about his/her own level of consumption, the number of children that he has, and the welfare of each child. This model generates a dynamic utility function of the form of Eq. (2.22) where the discount factor is explicitly related to the degree of intergenerational altruism. Our treatment is concise since this model is treated in great detail in Nerlove and Raut (1994). The utility function of a representative generation is

\[ U_r = v(c_r) + a(n_r) n_r U_{r+1}, \]  

(3.1)

where \( a(n_r) \) is the “altruism function”. This takes the form \( a(n_r) = \alpha (n_r)^{-\epsilon} \) where \( \alpha, \epsilon \in (0, 1) \). Here, the utility of a parent depends on own consumption and both the number and utility of children, with the latter two terms being weighted by the degree of altruism. Recursive substitutions yield

\[ U_0 = \sum_{r=0}^{\infty} \alpha^r (N_r)^{1-\epsilon} v(c_r), \]  

(3.2)

where

\[ N_r = \prod_{s=0}^{r-1} n_s. \]
If the altruism function is linear in \( n_t \) (i.e. \( \varepsilon = 0 \)), this objective function collapses to Eq. (2.22), the total utilitarian maximand where \( \beta = \alpha \). Note that Eq. (2.1) can also be derived in this framework by assuming that a parent cares not about the total utility of his/her offspring, but rather about the average level of welfare. Eq. (3.2) is maximized subject to a sequence of budget constraints of the form

\[
w_t + (1 + r_t)k_t = c_t + n_t(\theta + k_{t+1}).
\]  

(3.3)

In Eq. (3.3), the parent inherits an amount of capital, \( k_t \), earns wage income from a unit of time inelastically supplied and allocates this between own consumption, bequest per child, \( k_{t+1} \), and child rearing costs per child, \( \theta > 0 \). This problem has the first-order conditions

\[
v'(c_t)(n_t)^\varepsilon = \alpha(1 + r_{t+1})v'(c_{t+1}).
\]  

(3.4)

\[
v(c_t)(1 - \varepsilon - \sigma(c_t)) = v'(c_t)[\theta(1 + r_t) - w_t].
\]  

(3.5)

Becker and Barro primarily study the steady-state equilibria of this economy under the assumption that the production function exhibits constant returns to scale (particularly in their 1989 paper). In this case, the dynasty chooses a constant steady-state rate of population growth. It is immediate from the above necessary conditions, however, that the fertility rate at any date is positively related to the interest rate and the degree of altruism. The unsurprising feature of Eq. (3.5) is that it is a version of the Meade–Sidgwick rule.

From this point on in the paper, we abandon making causal statements about how population growth affects development and resource utilization, but rather concentrate on the properties of their joint dynamic behavior.

### 3.2. Natural resources in economies with endogenous population

How does the endogenization of fertility affect the dynamic paths of resource extraction and exploitation that we have studied? Start by considering the Barro–Becker model of the previous section with diminishing returns to scale. In this case, the steady state is characterized by a zero rate of population growth. A similar result is deduced by Eckstein et al. (1988) in a nonaltruistic model where the only motivation for having children is that parents get utility from having children. They show that, with an essential resource present, there are diminishing returns to capital and labor combined, so that when population grows exogenously, per capita consumption must converge to zero. However, once fertility is endogenized, the economy converges to an equilibrium with constant population, and constant and positive per capita income. Their
results essentially replicate, in a decentralized economy, the results of Dasgupta (1969) (discussed in Section 2.1.3) that when there are decreasing returns to scale, there is a finite optimal population. Eckstein et al. (1988) assume that the production function is a linear homogeneous function of capital, labor and the fixed resource (land). In a steady-state equilibrium, the ratio of land to labor must be a constant. Since the stock of land is a constant, population must be constant in such a steady state. The economy converges to this equilibrium because fertility and consumption move together. As adults get poorer, they reduce their fertility (children being normal goods) and eventually converge to a situation with constant fertility and consumption.

The situation is little different when an exhaustible resource is a necessary input in the production function. Under certain specifications of intergenerational preferences, population growth converges to zero (recall that without exogenous technical progress, such a model cannot sustain a positive consumption level with positive population growth). The key parameters determining steady-state equilibria are those describing altruism, the impatience of agents, the costs of rearing children, the amount of net resource flows between children and adults, and, in the OLG framework, the social welfare weights assigned to different generations. Parameter changes which lead to an increase in steady-state population typically reduce the steady-state resource stock (though this is not necessarily the case as we saw in Section 2.3). With renewable resources, one can define steady-state equilibria with positive population growth, constant per capita consumption, and a constant stock of environmental resources.

What about capital accumulation? In models where population is endogenous, higher rates of population growth will typically be associated with lower per capita income and lower rates of accumulation of capital per worker. For example, economies with higher degrees of altruism towards children would tend to have a lower capital-labor ratio in steady state. As we make clear in Section 3.3, however, the types of parameters which are exogenous in these models, and thus determine the steady-state values of endogenous variables, do not make for a convincing theory of development. It seems to us highly unlikely that strong altruism, for example, is a significant cause of either the lack of development or the high rate of population growth that we observe in many developing economies. Both are a joint product of other factors hampering development.

The only existing formal work on the interaction between renewable resources and fertility that we are aware of is due to Nerlove (1991, 1993) and Nerlove and Meyer (1993). These papers stress that population growth and resource extraction can be locked into a vicious circle in the context of a local commons phenomena (this interrelationship has also been stressed by Dasgupta (1993)). Higher population growth leads to more resource depletion which reduces the marginal productivity of the resource. In order to offset this, families have more children, further depleting the resource, and so on. Models of this sort, with severe externalities, often possess multiple Pareto ranked equilibria, some with high fertility and a low resource stock, and others
with low fertility and a high resource stock. Such models allow for a potential role for policy to coordinate individual behavior on the desirable equilibria. We now discuss two examples of how, when population is endogenous, there are examples where good policy would help resolve both environmental and population "problems". The first of these is a model of multiple equilibria closely related to the above discussion.

3.2.1. Local environmental-demographic complementarities

Our example is based on degradation of the rangeland of Botswana and is designed to illustrate what the World Bank (1992) calls "no trade-off" situations which contradict the widespread belief that preserving the environment implies sacrificing consumption or welfare. In Botswana, the primary form of livelihood is cattle ranching. The rangeland is common land. While cattle fulfill social roles (in terms of status), they are also the primary intertemporal store of value in the society. There is evidence (Barbier et al., 1989; Dasgupta and Mäler, 1994) that this interrelationship can have perverse effects. In particular, the evidence suggests the presence of self-fulfilling expectational effects. The quality of the range affects the productivity of cattle. Since each herder perceives himself or herself to be too small to affect the quality of the range, he or she makes decisions about how many cattle to hold treating the quality of the range as given. However, in equilibrium, the quality of the range is a function of the joint decisions of herders since the more cattle that the range has to support the lower its quality, and the less productive is each cow. Children are the primary method of looking after cattle, and, thus, children can be thought of as a producer good which is complementary to cattle. This induces an interesting dynamic interaction between population growth and environmental degradation.

In Robinson and Srinivasan (1995a), we model this phenomena by building a simple overlapping generations general equilibrium model. We show that the economy has Pareto ranked multiple equilibria each of which may be supported by self-fulfilling sets of beliefs. Herders at any date must decide how many cattle to breed in a period (given their inherited stock), and how many children to have to look after the cows. They do this in the light of the expected quality of the rangeland. The evidence suggests that there is a strong dominance of the income effect of changes in the quality of rangeland over the substitution effect. Consider that herders imagine that the quality of the rangeland will deteriorate in the next period (perhaps a drought is anticipated — beliefs can also be conditioned on "sunspots"). If the income effect dominates the substitution effect they respond to this by increasing their herd of cattle and having more children. The increased stock of cows which these conjectures induce has the effect, in equilibrium, of leading to the degradation of the range which confirms the beliefs. Thus, one may have Pareto ranked equilibria with inefficient equilibria characterized by low environmental quality and high population growth, and efficient equilibria having high environmental quality and low population growth.

What is the source of inefficiency in this model? The clear problem is the
"commons" nature of the environment. The rangeland is being overused because individual herders impose costs on others by increasing their herds which they do not take into account. This problem is intertwined with the fact that cattle are the only medium of saving, and so is exacerbated by the rudimentary nature of the financial infrastructure in the economy. One solution to this problem is to introduce an alternative store of value. Another is to internalize the "commons problem" by defining property rights over the rangeland (modulo the problems we discussed in Section 2.3.4).

The multiple equilibria in the above model give a nice example of "no trade-off" situations. If policy measures can change the nature of the equilibrium set and lead to the coordination of the economy on the Pareto preferred equilibria, then the rate of population growth will fall and the quality of the environment will improve.

3.2.2. Infrastructure, health, mortality and fertility

We now describe informally a simple theoretical model which stresses other types of complementarities which emerge between environmental issues and population growth rates which lead to "no trade-off" situations (the analysis is presented formally in Robinson and Srinivasan, 1995b). The aim of this model is to describe a key class of situations where policies to deal with inefficiencies will promote both an improved environment and the demographic transition.

In many less developed economies, there is a presumption that there is underinvestment in public goods and vital infrastructure. Socially efficient investment in infrastructure (such as the provision of potable water, refuse collection and sewerage) increases the health of individuals and is a form of investment in human capital. This makes individuals more productive (since productivity depends on their health as in the nutrition model of efficiency wages (see Dasgupta, 1993a)). If individuals wish to have children because of the "old age security" motive, the number of children that parents wish to have would depend on infant mortality (as in Sah (1991) or Ehrlich and Lieu (1991, 1993)). An improvement in infrastructure reduces child mortality implying that parents need to have less children to guarantee a surviving child to care for them in old age. Note that the improvement in the health of parents may also increase the opportunity cost of rearing children since market wages may increase. Both of these effects tend to reduce fertility (there is an effect which works in the opposite direction, which is that if parents are healthier, this increases the chance they will survive to old age and hence increases the expected return to having children). We show that increasing infrastructure expenditures raises welfare and reduces infant and adult mortality and parental fertility. Here, policies to improve the environment are complementary to the goals of reducing fertility and mortality.

3.3. Theories of endogenous technical change

In this section, we introduce the central issues surrounding the endogenization of
technical progress. This literature has been extensively surveyed in Grossman and Helpman (1989) and Barro and Sala-i-Martín (1995). Other valuable surveys are Romer (1989), Raut and Srinivasan (1993), Hammond and Rodriguez-Clare (1993), and Schmitz (1993).

We start with an observation due to Solow (1956) (and recently rediscovered by Jones and Manuelli (1990)). Remove the exogenous technical progress from the basic growth model of Section 2.1.1 (set \( g = 0, A_r = 1 \)). In this case, the economy converges to a steady state with a constant capital–labor ratio. Level variables grow at the rate \( n \). Why does this occur? The key reason is indefinitely diminishing marginal productivity of capital. Along a transition path to the steady state, capital accumulates relative to labor. As the capital-labor ratio rises, the marginal product falls. In essence the marginal product is the return to saving. Consider the consumption Euler equation. If the economy is to grow over time, then it must be the case that the dynasty wishes the path of consumption per capita is upward sloping, \( c_{t+1} > c_t \). This implies \( U'(c_{t+1}) < U'(c_t) \). For this to be desirable it must be the case that

\[
\frac{\beta[1 + f'(k_{t+1}) - \delta]}{1 + n} > 1.
\]

The left-hand side of this inequality is monotonically decreasing in \( k_{t+1} \). For small capital–labor ratios, the Inada condition implies that this inequality will be satisfied. However, the second Inada condition (used to guarantee the existence of a steady state) implies that, at some point, \( \beta(1 + f'(k_{t+1}) - \delta) = 1 + n \). At this point, the return to accumulation has fallen so low that the dynasty desires \( U'(c_{t+1}) = U'(c_t) \), and hence \( c_{t+1} = c_t \), and the economy stops growing. In order to guarantee sustained growth in such an economy, all that is necessary is to put a sufficiently large lower bound under the marginal product of capital. In this case inequality (3.6) will always be satisfied. There are various technologies which will do this, in one the aggregate production function has the form \( F(K, L) = AK + BL + K^aL^{1-a} \). In this case, the marginal product of capital goes to \( A \) as the capital–labor ratio goes to infinity, and if \( A \) is sufficiently large, then inequality (3.6) is satisfied. Alternatively, a CES production function with an elasticity of substitution greater than one will suffice (as Solow (1956) noted in his original paper).

From this perspective, it is easy to understand the results in the literature. The different mechanisms which authors have proposed to generate endogenous growth are just different methods for stopping diminishing marginal productivity bringing accumulation to a halt. Consider the seminal paper by Romer (1986). Consider the production function of a particular firm \( j \), \( Y_i(j) = A_i(j)F(K_i(j), L_i(j)) \), where \( A_i(j) \) represents the “state of technology” at date \( t \). Romer argued that new technology of “knowledge” was generated by the process of aggregate capital accumulation itself and that this process was external to the firm (in the spirit of a “Marshallian external-
ity"). If technology evolves as a function of aggregate investment, then the level of
technology at any time is a function of past cumulative investment, or in the absence
of discounting the aggregate capital stock. Assume that there are a continuum of identi-
cical firms distributed uniformly on the unit interval with a representative firm being
indexed, \( j \in [0, 1] \). Hence, \( A_y(j) = A(K_y, j) \), where \( K_y = \int_0^1 K_y(j) \, dj \). The ideas underlying
this model are closely related to Nicholas Kaldor's notion of a "technical progress
function", recently revived by Scott (1989). Romer also appealed to the idea of learn-
ing-by-doing, put in a growth theory context by Arrow (1962).

How might this model generate sustained growth? As a firm builds capital, it ex-
pipes its own production possibilities, but inadvertently it also generates new knowl-
edge and ideas, and, thus, shifts out the production possibility frontier for all firms.
One sees immediately that, if this effect is sufficiently strong, the effect of diminishing
marginal productivity for an individual firm, holding \( A_y \) constant, can be just offset
by the resulting increase in technology caused by the actions of all firms. To see what
"sufficiently strong" means consider the Cobb–Douglas case where, \( A(K, j) = K_y \), and
\( Y_y(j) = K_y \phi K_y^\alpha(j)L_y^{1-\alpha}(j) \). Each firm treats \( K_y \) parametrically. The private marginal
product of capital is, therefore, \( \alpha K_y \phi K_y^{\alpha-1}(j)L_y^{1-\alpha}(j) \). Now integrate over the set of
firms (recalling that they are all identical) to get the aggregate

\[
\int_0^1 \alpha K_y \phi K_y^{\alpha-1}(j)L_y^{1-\alpha}(j) \, dj = \alpha K_y^{\phi+\alpha-1} L_y^{1-\alpha}.
\]

If Eq. (3.6) holds, then the capital–labor ratio will be increasing over time. Note that
\( f^* = \alpha k^{\phi+\alpha-1} L_y^\phi \). Under what conditions would the marginal product of capital be
bounded away from zero as the capital–labor ratio increased? Clearly as long as
\( \phi + \alpha - 1 \geq 0 \). In the case where \( \phi + \alpha = 1 \) then the marginal product of capital is a
constant equal to \( \alpha L_y^{-\alpha} \), and it becomes easy to state a condition such that inequality
(3.6) will hold for all time.

To see the implications of this technology for the growth rate of the economy over
time, we need to embed it in a general equilibrium model. For simplicity, we remain
in the single firm framework. Assume that preferences are represented by the constant
elasticity of intertemporal substitution utility function, \( U(c_t) = c_t^{-\sigma} \). Following
standard methods, we can derive the Euler equation for the dynasty:

\[
c_t^{-\sigma} = \beta \left[ \frac{1+r_{t+1} - \delta}{1+r_t} \right] c_{t+1}^{-\sigma}.
\]

With a competitive capital market, the interest rate will be equal to the marginal
product of capital, hence

\[
r_{t+1} = \alpha K_{t+1}^{\phi} K_{t+1}^{\alpha-1} L_{t+1}^{1-\alpha}.
\]
The production function in per capita terms is

\[ y_t = K_t^\phi k_t^\alpha, \]

and hence,

\[ r_{t+1} = \alpha K_t^\phi k_t^{\alpha - 1} = \alpha L_t^\phi k_t^{\phi + \alpha - 1}. \]

Substituting into the Euler equation and re-arranging,

\[ \frac{c_{t+1}}{c_t} = \left[ \frac{\beta(1 + \alpha L_t^\phi k_t^{\phi + \alpha - 1} - \delta)}{1 + n} \right]^{1/\sigma}. \quad (3.8) \]

Romer (1986) considers \( n = 0 \) and \( \phi + \alpha = 1 \). In this case, the right-hand side is a constant.

Notice however that if \( \phi + \alpha > 1 \), then the economy exhibits increasing growth rates over time. The fact that the condition for a balanced growth path is balanced on a "knife-edge" has received criticism. While it is true that the condition for steady-state growth is not generic in the parameter space (formally, fix the Cobb–Douglas technology for the economy, then the set of economies which exhibit steady-state constant growth is a closed set of Lebesgue measure zero), the same could be said of constant returns to scale. However, an intuitively plausible "replication" argument can be offered in its favor. There seems to be no replication argument in favor of constant marginal productivity of capital. More generally, one might see this as a problem stemming from the restrictive nature of steady-state analysis. While focusing on steady states is attractive analytically, it is not clear that it is very useful as a description of actual growth experiences. Historically, growth has been rather spasmodic and cyclical (see Mokyr (1990) or Jones (1989) for many examples). Romer himself argues that the idea of increasing growth rates over time may not be so unreasonable as it sounds. He argues that the growth rate of the "leading nation" has historically been increasing (from the Netherlands to Britain, to the United States, to Japan, to Korea and Taiwan, and now perhaps to China).

Eq. (3.8) reveals something interesting about population growth. It shows immediately that the growth rate over time is an increasing function of the constant population under the conditions assumed by Romer. This has been called a "scale effect" in the literature. Such a state of affairs is not necessary however. In fact, examining Eq. (3.8) reveals that the presence of positive population growth rates now allows the condition for endogenous growth to be satisfied even in the case where \( \phi + \alpha < 1 \). The scale effect can be removed by simply defining the external effect to be in terms of the aggregate capital–labor ratio instead of the capital stock. The question is: which speci-
fication seems more in the spirit of the motivation for the specification? To see how this works, simply re-write the production function as \( Y_t = k_t^{\phi} K_t^{\alpha} L_t^{1-\alpha} \) and re-work the calculations.

These results show that in a one-sector economy, what is required for endogenous growth is constant returns to capital alone, or more generally, to a factor which can be accumulated. In Romer’s model, it is external increasing returns to scale which generates the sustained growth. The above discussion suggests that this is not necessary since there are other ways of putting a bound under the marginal product of capital. Unfortunately, these other methods have drawbacks in a one-sector model. Firstly, as observed by Raut and Srinivasan (1993), the technology must be such that output can be produced without any factors other than capital. Second, as pointed out by Jones and Manuelli (1992) and Boldrin (1992), such a technology is not sufficient to generate growth in standard two-period OLG models where capital accumulation is generated only by saving from wage income. In the one-sector case, in order to get away from these implications, one is forced to assume that there are increasing returns to scale.

The external increasing returns also generates inefficient growth paths. Since individuals do not take into account the effect of capital accumulation on the level of technology, the private return to investment is less than the social return, and growth and accumulation is inefficiently low in the decentralized economy. In contrast, if the growth is generated by constant returns to scale but with a lower bound on the marginal productivity of capital, then, in the decentralized economy, the growth path is efficient. The empirical relevance of external economies is hotly disputed. Recently, at industry level, Caballero and Lyons (1993) have found evidence supporting the existence of external economies. Interestingly, Backus et al. (1992) also find some evidence in favor of pure scale effects across countries.

A primary attraction of external increasing returns is that it allows a competitive equilibrium to exist. There is an issue of substance here. An obvious approach to generating sustained growth would be to introduce a technology for improving \( A_t \). We could think of firms in the economy dedicated to developing new technology and selling this to firms producing consumption goods. Unfortunately, with competitive factor markets and constant returns to capital and labor alone, there cannot be any revenues left over to pay for technology. This suggests that a more plausible aggregate production function would be \( Y_t = F(K_t, L_t, A_t) \) with constant returns to all three factors together. Romer has argued strongly for such a specification. An alternative to external increasing returns would simply be to set the increasing returns be internal to the firm but introduce imperfect competition. The study of dynamic general equilibrium models of imperfect competition is far more complex technically.

We are sympathetic to the arguments of Grossman and Helpman (1994) and Solow (1994) that putting a bound under the marginal product of capital, while it “works” in a formal sense, does not seem to capture the essence of the growth process. The one-sector growth model has always been regarded as a “parable”, in that it is clear that
growth does not occur simply as the result of accumulating more and more of a homogeneous capital good. Historically growth has been connected to the introduction of entirely new goods and production techniques, and the continual improvement of existing ones. Recent research has provided a more promising line of research with tractable models which treat these features (albeit in a very rudimentary way). Romer (1987, 1990), Aghion and Howitt (1992) and Grossman and Helpman (1989) show how growth can be sustained by either the continual improvement in the quality of existing goods or the expansion of the set of available goods (either consumption or intermediate goods). In these models, growth is sustained because, plausibly, there are no diminishing returns to improving goods or introducing new goods.

There are various other models which achieve endogenous growth in a similar way. For example, Barro (1990) generates an aggregate technology which is linear in the capital stock by introducing public capital into the technology. Another approach is that of Lucas (1988). Lucas essentially reinterpreted the labor augmenting technical change as human capital. The aggregate production function is \( Y_t = F(K_t, H_t, L_t) \). \( L_t \) is now "raw workers" and \( H_t \) is the stock of human capital possessed by each individual. Lucas presented two models of human capital accumulation. The first was one of learning-by-doing where human capital accumulates passively as a linear function of current employment:

\[
H_{t+1} = [\beta_H + \eta L_t] H_t. \tag{3.9}
\]

In the second model, a separate sector for the accumulation of human capital (following Uzawa, 1965) is introduced. In each period, workers are allocated between producing for current consumption and producing more human capital. This is thus a two-sector model. Consider the learning-by-doing model. It is easy to see that the formulation of learning embodied in Eq. (3.9) will generate a scale effect in exactly the same way as the Romer model (again this can be removed by specifying things in per capita terms).

Assume that population is constant, and, for convenience, set \( L_t = L \). The aggregate technology is \( Y_t = F(K_t, H_t, L) \), by homogeneity of degree one, we can write this as \( y_t = f(k_t) \), where \( y_t = Y_t / H_t L \), \( k_t = K_t / H_t L \). In either of these human capital models, the key to the generation of growth is that there is no diminishing marginal productivity to the accumulation of human capital. This process can therefore drive increases in per capita income forever.

The recent literature has provided us with simple analytical methods to verify the conditions under which an economy will exhibit sustained growth. However, it is not clear that in themselves they add much to our understanding of the process of development. In reality, much of this process stems not simply from factor accumulation (which in the broad sense is at the heart of this literature), but from changes and innovations in political and social institutions which govern and condition the process of factor accumulation (see Rosenberg and Birdzell (1986) for an emphasis on institu-
tional innovation and change). For example, North (1981) stresses that the key to whether or not a society grows or stagnates is in understanding the incentives of agents and rulers to create property rights and, in general, implement efficient policies. This view rejects the notion that cross-country experiences can be explained on the basis of different rates of time preference or the elasticity of intertemporal substitution, or, for that matter, simply on the basis of differences in technology. While it is true that the difference in per capita income between the US and Haiti can be described in terms of different technology or human capital, this does not explain why these differences are what they are. Such examples suggest that, in order to explain the distinction between a “miracle” and a “disaster”, we need a much more ambitious political economy framework with a much broader scope than any present in existing growth models.

This message in fact emerges from the empirical work on growth (see particularly the discussion in Barro and Sala-i-Martin (1995) and Sala-i-Martin (1994)), though when considering this literature one must be very careful making causal inferences since there are severe identification and simultaneity problems. How does the growth model explain cross-country growth differences? If all countries have the same parameters, then they all converge to the same steady-state growth path and eventually have identical growth rates (so called “absolute convergence”). In this model, countries which have a lower level of per capita income must have a higher growth rate if there is any aspect of diminishing marginal productivity. This implication is false empirically. If, more realistically, we assume that countries have different parameters, then there is no unambiguous connection between the level of per capita income and its growth rates. The models imply that countries converge to different steady states determined by their different parameters (“conditional convergence”). Therefore, differences between countries are explained by these parameters. These are typically parameters describing preferences (such as impatience and the willingness of individuals to substitute consumption intertemporally), technology and government policy (such as taxes and expenditure). It seems improbable that a convincing theory of comparative development could be constructed on differences in preference parameters (unless one had some way of endogenizing these). What about technology? While it is clear that Zaire, for example, has a worse technology than the United States, to use this as an explanation for why their growth experiences have been different, does not advance us above simply assuming that growth rates are exogenous. To build a convincing theory here, we need a model of the incentives to adopt and transfer technology, and this has not been provided by the literature thus far. Most attention then has concentrated on the latter set of parameters, those describing government policy parameters, augmented by other variables describing social and political institutions. The implication of this is “bad growth” is caused by “bad policy” (high taxation of capital income for example) and “bad” institutions (such as ill-defined property rights or ineffective procedures for enforcing contracts). But in reality, policy variables and institutions are not exogenous. To argue that policy is at fault forces us to articulate a model
where both political decision-making and the incentives to create institutions are endogenized. In short, we need a theory of bad policy and bad institutions. This, the growth literature has not provided, though it has been implicitly discussed in the more policy orientated literature on development (see Srinivasan, 1985; Findlay, 1990; Krueger, 1993).

Mokyr (1990) has described one fully fledged political economy model of growth and stagnation. His theory rests on the idea that in a world where compensating transfers cannot be made, innovations and new technologies take rents away from agents with sunk investments (exactly this phenomena occurs in the model of Aghion and Howitt (1992) for example). Technical progress in reality is rarely Pareto improving and has large effects on the distribution of income and of political power in society (witness the nineteenth century battle over the repeal of the Corn Laws in England). Agents with vested interests in the status quo have an incentive to suppress innovations through political mechanisms. Mokyr argues that the key to growth is in setting up institutions which allow innovators to succeed and prosper. One interpretation of Mokyr’s ideas have been formalized in an interesting paper by Krusell and Rios-Rull (1992). Other recent research by Acemoglu (1994) and Tornell (1993) have begun to think about private incentives to create socially efficient institutions. This is an area where the returns to future research seem particularly large.

3.4. Population and endogenous growth

We now consider the effects of population size and growth on economies with endogenous technology. We also discuss normative issues in this section and we review the arguments that population growth may be beneficial rather than inimical to economic growth. These arguments are important because many of them allow population growth in itself to generate technical progress. The basic neoclassical models assume that population growth is bad because it increases the burden of raising the capital–labor ratio. In considering optimal population, this effect can be offset by giving value to people as such. This represents one approach. Another is to question the technological assumptions underpinning the neoclassical model. In particular, many scholars have argued that population growth is a key part of social and technological progress, and that these effects are completely missing from the basic neoclassical model. It seems important to take this seriously given the empirical evidence discussed in Section 1. There we noted the overwhelming failure to find negative effects of population growth on economic growth. This suggests that there may well be positive effects to balance the negative effects of the neoclassical model.

3.4.1. Population and economic development: the pros and cons

As we have mentioned, the relationship and causal interactions between population
growth and development have given rise to much speculation. The Malthusian view is well known. This relates to a pre-industrial society where technology is fixed or exogenously changing and population growth is determined by a series of positive or preventative checks (or as Heckscher (1949) referred to the former, times when "nature audited her accounts with a red pencil"). There is much evidence that both checks were at work historically (Habakkuk, 1971). Population growth was limited by delayed marriage and rudimentary contraceptive techniques, and mortality was a severe disciplining force. These forces established an equilibrium for many centuries. For instance, it has been estimated (see Habakkuk, 1971) that the population of the Mediterranean countries and France was about the same in 1700 as it had been in the first century AD. This homeostatic equilibrium was changed during the eighteenth century (from about the 1740s onward). There seem to have been two main factors. The first (recently stressed by Razzell (1993)) was a fall in mortality due to improvements in domestic hygiene and improved medical practices (such as the widespread vaccination against smallpox (Razzell, 1978). Why did not population growth equilibrate to this situation through reduced fertility? The answer seems to be that the process of industrialization was causing structural changes in the fertility process. The movement from the countryside to the towns broke up social norms of delayed marriages. Industrialization also allowed children to be sources of income earlier and allowed women to work and earn income (thus also accelerating marriage). This latter phenomena is interesting since the European historical evidence suggests that marriage was often delayed until a high enough standard of living could be guaranteed. On the other hand, employment opportunities for women raise the opportunity cost of having children for women and thus reduce births. While it is necessary to have income to raise children, it also takes time. However, the evidence seems consistent with both views since it suggests that opportunities for employment in cottage and domestic industries were more favorable to fertility than factory work (Tucker, 1963).

The main question raised by Habakkuk is the relationship between the growth in population and the beginnings of the industrial revolution. While the Malthusian channels are well known, Habakkuk concentrates on five channels through which population may stimulate growth. Firstly, there may be pure economies of scale to a large population due to the division of labor and the creation of social overhead capital. Second, inspired by Lewis (1954), a large population may keep the wage rate low and thus encourage investment by capitalists. While this might be bad for per capita incomes initially, it may allow the economy to develop over a threshold from which sustained growth would be feasible. Thirdly, the pressure of population on finite natural resources may stimulate investment and induce capital substitution which induce a cumulative process of industrialization. Fourthly, population growth may have beneficial effects on effective demand, particularly by stimulating urbanization, and lastly, population pressures may induce people to work hard. As Habakkuk puts it, "I am not arguing that the effects of population growth were simple or straightforward or that they were invariably favorable. But I find it difficult to interpret the eighteenth cen-
tury without supposing that, on balance, population increase was a stimulus to the development of the economy. Thus population growth and economic growth continuously interacted and this interaction is perhaps the principal reason why the population increase was sustained". (Habakkuk, 1971: p. 48.)

Habakkuk's theme finds many echoes in the literature. North and Thomas (1972) argued that population growth was a stimulant to industrialization. Their thesis is the broad one that population growth, by changing the factor price ratio, induced the institutional changes which led to the industrial revolution (expansion of trade, property rights). The notion that population fluctuations are a cause of institutional change is widespread. It occurs in Lal's (1988) theory that the Indian caste system was a response to labor shortage, and also in many accounts of the adoption of the "hacienda system" in Latin America following the precipitous drop in the native population due to imported diseases (Halperin, 1993). Echoing this, Hayami and Kikuchi (1982) state: "the basic force inducing agrarian change in Asia is the rise in the return to land resulting from strong population pressure". While the positive effects of these pressures have been stressed particularly by Boserup, there seems to be no presumption that in fact such institutional innovations will be conducive to economic growth.

The anti-Malthusian camp suggests that diminishing returns do not set in. There are various reasons for this. An early one emerged in the heyday of the Keynesian revolution. Hansen (1939), echoing earlier work, hypothesized that slow or stagnant population growth had a bad effect on demand and the economy. Hicks (1939) suggested "one cannot repress the thought that perhaps the whole Industrial Revolution of the last two hundred years has been nothing but a vast secular boom, largely induced by the unparalleled rise in population". Both Kuznets (1966) and Hirschman (1958) argued that population growth could stimulate growth through scale effects and innovation.

Another central reason stems from the observation that "the division of labor is limited by the size of the market". Larger populations may expand the size of the market and thus allow more productive techniques to be adopted through a finer division of labor. This may not hold useful policy advice for developing economies, however. As the World Bank (1984) points out, countries like Singapore and Hong Kong have successfully reaped the division of labor by exploiting international trade, thus giving their industries access to a much larger set of potential customers than domestic residents. Another argument is that larger populations have more geniuses, and that, presumably, there are increasing returns to geniuses (this argument is presented in Simon (1981) and has been recently formalized by Kremer (1993)). Another stems from the adage that "necessity is the mother of invention". In a series of works, Boserup (1965, 1981) has argued that population growth, by putting pressure on land, resources and wages, induces innovation. Her ideas have found support in several pieces of careful empirical work (see for example, Hayami and Ruttan, 1987; Pingali andBinswanger, 1987). While this is undoubtedly the best documented positive effect of population growth, it is not without prominent counterexamples. Birdsall (1989) co-
gently argues that the history of Bangladesh, for example, cannot be understood in this way. The National Research Council (1986) argue that the evidence suggests that the rate of return to agricultural innovation is already high and does not need to be stimulated by population growth. On the other hand, Kelley (1988) argues that the population density may have been important in inducing the adoption of "green revolution" technologies in Asia. The anthropologist Geertz (1963) argued that population pressure was closely linked to the extension of irrigated rice agriculture in Java. On balance, Kelley (1988) concludes, "A critical component in untangling the relationships between technology and demographic change is the impact of population pressures on institutions (land tenure arrangements, government policies, and the like), especially because the new technologies flourish mainly where institutional conditions are favorable. Regrettably, no generalization is possible here." Srinivasan (1987) reaches a similar assessment.

One problem with this argument is that there is not a clear theoretical model of how population density induces innovation (see Darby (1980), Pryor and Maurer (1982), Robinson and Schutjer (1984) and Lee (1986, 1988) for attempts at (in our view, not wholly satisfactory) formalization). If innovation is profitable why does it not occur at low population densities? It could be that a high population density allows for greater social learning, a phenomena which it has recently been argued was important in the adoption of "green revolution" technologies. Hence there is a positive externality to population density which reduces the adoption cost of new technology. Yet much of the literature has stressed that population growth stimulates institutional change though the precise mechanism is unclear. Preston (1984) has argued that population growth could be good for development because development necessitates change which is often opposed by people with sunk investments or vested interests in the existing institutional or economic structure. This argument is of course reminiscent of that of Mokyr (1990) discussed in Section 3.

Simon, perhaps the most vociferous advocate of the positive effects of population, has explored various causal channels in a series of works (see Simon, 1977, 1981, 1986). He has stressed the ideas that there may be increasing returns to scale and that a larger population may allow for a greater division of labor and specialization in society. While he has developed simple models of this, traditional aggregative models of homogeneous capital accumulation and labor force growth with a neoclassical technology are not a good representation of the process of transformation and change which we call development. Economies of scale at this level do not seem the key issue. Simon and his co-authors (reported in Simon, 1986) have found evidence supporting the idea that population density has a positive effect on growth (see also our discussion of Kelley and Schmidt (1994) in Section 1). Supportive of this is the finding of James (1987) that, in a cross-section of 45 developing countries, the rate of growth of labor productivity in agriculture between 1960 and 1970 was positively related to population density, whereas that in manufacturing was not. However, Evenson's (1984) evidence does not support this.
On the negative side, apart from capital deepening issues enshrined in the neoclassical growth model, there is the problem of the crowding and overuse of public services and fixed costs. Rapid population growth often leads social services such as schools to become overstretched. As the World Bank (1984) puts it, "in the short run, ideas may be lost and Einsteins go undiscovered if many children receive little schooling".

Population growth has also been much discussed in relation to income distribution. Population growth may raise the share of capital relative to wages. The empirical effect of population on income distribution has been estimated to be significant and negative. Ahsuwallia (1976) finds a positive relationship between the rate of population growth and the income share of the richest quintile, while the evidence summarized in McNicholl (1984) and Jha et al. (1984) suggests that "the negative effect of population growth on the income shares of the poorest 30 or 40 percent of households is usually pronounced". Given the serious problems with data on income distribution these results have to be treated with extreme caution. Lam (1987), for example, examines the causal channels from population growth to income distribution and concludes that there is little evidence supporting any of them. Of course, even if population growth did induce greater inequality, this is not necessarily bad for growth. Some authors in the dual economy tradition (who typically adopt a "Classical" savings hypothesis) see a rise in inequality as necessary for capital accumulation. For example, Kelley and Williamson (1974) found that considerably higher rates of population growth would have made little difference to Japan's development. This is due to the classical saving hypothesis offsetting capital shallowing effects. On the other hand, more recent evidence (Alesina and Rodrik, 1995; Persson and Tabellini, 1994) suggests that income inequality may be harmful for growth.

Increases in population which reduce the wage rate may also affect the direction of technical change. David (1975), for example, argued that relative scarcity of labor in the US in the nineteenth century affected the nature of technology that it was profitable to adopt and the path of technical progress ever since.

Population growth caused by poverty also tends to transmit poverty between generations. If richer people in society start to have fewer children and, thus, each child will be wealthier on average, this may have the effect of widening the distribution of income. In fact, this suggests that endogenous population growth and intergenerational wealth transmission effects may in themselves provide an explanation for the Kuznets inverted U hypothesis of income distribution.

Population growth has also been related to saving (see Hammer, 1985). Faster population growth rates give a higher dependency ratio (this is the opposite of the Samuelson (1975) model discussed in Section 2.2.2, where a greater number of children helps in making transfers to the old since children are not dependent), and this can reduce saving since more resources are channeled to rearing children. On the other hand, poor people save little, and most saving in underdeveloped economies is by relatively rich people. In fact one aspect of the problem of rapid population growth
is often thought to be the lack of saving media. Mason (1987) found that the net effect of population growth on saving was positive when per capita income growth was zero and negative when it was 4%. Kelley (1988) concludes, "the hypothesis of an adverse impact of age dependency on saving rates has not been generally supported in empirical studies", and McNicholl (1984) states, "what then can be said about the net savings or investment impact of rapid population growth? The answer appears to be very little". We note also that, in terms of the process of growth and development, recent research has downplayed the role of aggregate saving. The efficiency with which it is allocated seems to be at least, if not more, important.

One serious issue is timing. Rapid population growth may have long-run benefits (in Simon (1981), it takes 80 years in his simulation model for population to have a positive effect), but it certainly has short-run problems. We have not discussed urbanization in this paper, but this is closely related to population growth and causes large problems of adjustment in the development process.

3.4.2. Population and social welfare: the pros and cons

We have treated the normative issues of population level and growth in both intuitive and formal ways. The message of the neoclassical model is simple. Population growth is bad for per capita income, but can be socially optimal if society places weight on the number of people existing. Over time, as capital accumulates, it can be optimal to bring more people into society and optimal population growth is positive. The arguments of the last section suggest that population growth may have a positive effect on growth. Introducing these effects implies that population growth is all benefits and no costs! There is, however, a large literature that suggests that the adverse effects of population growth are not simply in reducing the capital–labor ratio. We now consider these. Taken seriously, they add extra costs to balance the extra benefits. Willis (1987), Lee (1990) and Lee and Miller (1991) are excellent sources for this as are the surveys by Kelley (1988), Birdsall (1989) and McNicholl (1984).

There have been many claims that population growth is detrimental for social welfare (if not directly for economic growth) because population growth induces externalities. Perhaps the most famous example of this is the idea that when individual parents decide on the number of children to have, they take the future wage rate that their child will earn as given (this may be important because it determines the child’s standard of living which the parent cares about, or because it determines the ability of the child to make transfers to parents later in life). However, if all parents have more children, this will increase the labor supply and push down the wage. As Willis (1987) shows, this is a pecuniary externality and as such does not represent a true market failure.

Another important problem is the potential crowding of public goods which may be subject to congestion. Schultz (1987) shows that, although school enrollment rates are not affected by population growth, the quality of education is reduced. National Re-
search Council (1986) finds that resources per child within the family and in educational system fall with population growth. One might, however, regard the latter phenomena as a policy failure.

Another possibly adverse effect of rapid population growth stems from human capital externalities. These have been stressed in the recent theoretical growth literature (see Lucas, 1988, 1990; Shleifer, 1990). This literature argues that individual productivity may depend not just on the amount of human capital possessed by the individual, but also on the average level of human capital of co-workers, or some other reference group. If it is the case that what matters is average human capital and, as is the case empirically, resources given to an individual child are negatively related to family size, and this results in lower human capital in a wide sense (especially lower health and educational attainment (see Jha et al., 1994), then parents may not be taking into account the true social benefits and costs of having children. Human capital externalities suggests that the rate of population growth will be too high relative to the efficient rate and, moreover, that this will have an adverse effect on the growth rate of the economy.

As mentioned in Section 3.1, Baland and Robinson (1996a,b) also show that if the family behaves noncooperatively, then fertility will also be inefficient, and the presumption is that it will be too high.

One the other hand, Nerlove et al. (1987) show that a larger population implies that the cost of public goods per capita falls, and they argue that this is a positive externality. There is also the possibility that population growth may lead to crowding of resources in fixed supply. For example, the amenity value of resources may be reduced by crowding, or population pressures may disrupt the regeneration of environmental resources.

In the most careful and comprehensive empirical investigation of this issue, Lee and Miller (1991) identify possible population externalities as coming from a variety of sources, "dilution of the per capita value of collective wealth, dilution of costs of collective projects with public good aspects, incentive reductions due to proportional tax rates and the effects of the age distribution on the tax rate necessary to support public sector activities such as health, education, pensions, social infrastructure and other service". They find little empirical evidence that any of these are significant for developing nations.

In sum, what is surprising is that there are really remarkably few conceptually sound and empirically relevant externalities stemming from population growth.

3.4.3. A model of endogenous fertility and endogenous technical change

The first integration of endogenous fertility and endogenous growth is due to Becker et al. (1990). They take the Becker–Barro dynastic model and replace physical capital with human capital which is passed between generations. Since human capital accu-
mulates in a way which does not involve diminishing marginal productivity (as in Lucas, 1988), this induces a simple model of endogenous, unbounded growth.

A main motivation for a model of this type is to study the demographic transition. As we discussed in Section 3.1, a central achievement of choice theoretic fertility models has been to provide a simple framework for this. However, these models have been unsatisfactory in that they have treated the process of growth as exogenous to the fertility and mortality transitions (Ehrlich and Lui, 1990, 1994) study how mortality can interact with fertility in a model where infant and adult mortality (treated as exogenous) affect the incentives to have children). Indeed the analysis of Becker et al. (1990) shows that this feature can be significant. This paper also links with an older theoretical tradition which had considered how the dynamics of endogenous population and income growth could lead to multiple equilibria and “development traps” (see Nelson, 1956; Leibenstein, 1957). The ideas behind the model are simple. Becker et al. take the dynastic model of one-period lived agents and let parents allocate their time between producing a consumption good and teaching children. Children are born with some endowment of human capital and parental teaching adds to this. In the simplest version of the model, the consumption good is produced using just human capital (though the authors also extend the results to show that they extend to physical capital accumulation modeled in the same way as in Becker and Barro (1989)). The key assumption is that there are increasing returns to human capital accumulation. Hence when the stock of human capital is low, the return to accumulating more is low. This means that an economy with an initial low stock of human capital may not find it worthwhile accumulating more and gets stuck in a low level equilibrium with a stagnant level of human capital and therefore per capita output. This has the implication that the population growth rate will be high since the opportunity cost of having children is small. If on the other hand, the economy starts with a high enough initial stock of human capital, it can converge to an equilibrium with a higher level of human capital and low birth rates. Becker et al. (1990) argue that to understand the demographic transition, we need to understand how society moves from one equilibrium to another.

In a sense, this model incorporates both the demographic transition and a type of doomsday. This is because both steady-state equilibria are stable. If the initial stock of human capital is low, the economy converges to the equilibria with high fertility and stagnant growth. On the other hand, the assumptions about the technology of production ignore any resource constraint issues. In the low level equilibrium, there is nothing preventing population growth continuing forever.

3.4.4. Simple analytical mechanisms

We now discuss two simple analytical models where the rate of population growth can be important in driving technological progress and yet be consistent with a steady-state equilibria (unlike the scale effects studied in Section 3.3). One approach to for-
alizing existing notions about the relationship between population growth and technical change is to develop an alternative model of learning-by-doing. In Section 3.3, the rate of human capital accumulation depends on current employment, hence the level of human capital at any date is a function of cumulative past employment (Becker et al. (1990) assume that the rate of human capital accumulation depends only on the allocation of time of parents between teaching children and producing consumption so there is no scale effect in the model). An alternative specification for this learning technology is to relate the growth of human capital between two periods to the growth of employment between those periods:

\[
\frac{H_{t+1}}{H_t} = \varphi \left( \frac{L_{t+1}}{L_t} \right). \tag{3.10}
\]

In Eq. (3.10), we assume that \( \varphi \) is continuously differentiable with derivatives \( \varphi' > 0 \), \( \varphi'' \leq 0 \), and \( \varphi(1) = 1 \).

To see the implications of such a model, consider an overlapping generations model with logarithmic utility, \( \log C_i + \beta \log C_{i+1} \). The aggregate technology takes physical capital, human capital and "raw labor" and transforms it into a single produced good (which is the same good as physical capital). The production function is \( Y_t = F(K_t, H_t, L_t) = K_t^{\alpha}(H_t, L_t)^{1-\alpha} \). Individual agents supply one unit of labor to a competitive labor market when young and, due to logarithmic utility, save a constant proportion of this income which becomes the physical capital stock at the next date. For simplicity we assume that capital can be "eaten" after production. The dynamics of the economy are governed by Eq. (3.10) and the equation,

\[
K_{t+1} = \theta L_t w_t = \theta(1 - \alpha) L_t H_t K_t^{\alpha} (H_t L_t)^{-\alpha}
\]

(where \( \theta = \beta/(1 + \beta) \)). Assume that Eq. (3.10) is linear so that the equation for the accumulation of human capital is, \( H_{t+1}/H_t = \sigma(L_{t+1}/L_t) \), where \( \sigma > 0 \) is a constant (this allows us to describe the dynamics as an autonomous difference equation). For simplicity, set \( \sigma = 1 \). In effective per capita terms (where \( k_t = K_t/H_t L_t \)),

\[
k_{t+1}(1+n)^2 = \theta(1-\alpha) k_t^\alpha. \tag{3.11}
\]

This model converges to a steady state with interior capital–effective labor ratio of

\[
k = \left( \frac{(1+n)^2}{\theta(1-\alpha)} \right)^{1/(\alpha-1)}.
\]

At such a steady state \( K_t/H_t L_t \) is equal to a constant. This implies that \( g_K = g_H + g_L = 2(1+n) \). Output per capita, \( y_t = Y_t/L_t \), is
\[ y_t = \frac{K_t^a H_t^{1-a} L_t^{-a}}{L_t}. \]

The growth rate of output per capita is, thus,

\[ g_y = \alpha g_K + (1 - \alpha) g_H - \alpha g_L = \alpha(1+n) + (1 - \alpha)(1+n) - \alpha(1+n) = 1 + n. \]

Thus, in steady state, the economy exhibits a constant rate of growth in per capita income. This rate of growth is increasing in the rate of population growth since this directly feeds through into the way that human capital is accumulated in the economy.

This model can be seen in another light as one without human capital accumulation but where there are increasing returns to scale. Instead of the technology proposed by Romer (1986) consider Raut and Srinivasan (1994). Motivated by the work of Simon and others, Raut and Srinivasan consider the case where the external economies stem not from capital accumulation but rather from population expansion. They develop an aggregate technology of the following form: \( Y_t = A(L_t)F(K_t, L_t) \), where \( A(L_t) \) formalizes the notion that the level of technology depends on the level of population and employment. This model is interesting since fertility is also endogenous. In their paper, Raut and Srinivasan examine a logistic specification for this function and analyze the type of dynamics that the economy may exhibit. They show the existence of multiple steady-state equilibria (which should not be surprising given the external effects) with constant levels of population and constant per capita income. However, the model may also (depending on the exact nature of the external effects) exhibit sustained growth in population and per capita income or even chaotic dynamics, depending on the form the externality takes.

### 3.5. Resources and endogenous growth

We now discuss models of natural resources with endogenous technology, but assuming that population is exogenous. This is a field which has received very little attention with, to our knowledge, only the work of John and Peccenino (1994), van Marrewijk et al. (1993), Smulders (1995), and Bovenberg and Smulders (1995) in existence. None of these papers concentrate on the central interaction between population growth and technical change.

A convenient place to start our discussion is Rebelo (1991). From the above analysis, it should be clear that the formal requirement to generate endogenous growth in a one-sector model is the presence of a bound under the marginal product of capital. To stay with a convex technology in a one-sector model we need to assume that any finite resource is not necessary in the sense of Section 2.3.1. This is not an attractive assumption. In the one-sector framework, to adopt a technology which does not have this implication, one is forced to move to a model with increasing returns to scale es-
sentially because the capital and the consumption good are the same good. However, it is important to realize that one does not need constant returns to scale in the production of the consumption good even if all factors can be accumulated. What Rebelo showed was that once one moved beyond the one-sector set-up, all that was required for endogenous growth in consumption per capita (assuming that there is only one consumption good) was that there be some sector of the economy producing an input used to produce the consumption good in which it was not necessary to use resources. This result shows the sense in which convexity of the technology and endogenous growth are consistent with the use of resources. To the extent that one does not believe that there exists any such sector, then some form of increasing returns seems necessary to generate sustained growth.

This result really just extends those discussed in Section 2.3. In those models, we assumed the existence of exogenous technical progress, but many of the above models, such as the learning-by-doing model, have a similar analytical structure. Endogenous growth will be consistent with the finiteness of nonrenewable resources if there is sufficient scope for substitution of man-made, for natural capital, and it will occur in equilibrium (or in an optimal program) if the return to accumulating capital or technology remains high as the stock rises (marginal productivity does not diminish to zero). With respect to renewable resources, similar considerations apply. One can construct steady-state equilibria where human and physical capital accumulate, per capita income rises, and resource stocks are constant because, as the economy grows, even if rising income levels use or pollute resources, it is possible to allocate more resources to sustaining the environment (or perhaps because technological change reduces the reliance on or utilization of resources). For example, the dynamic (or social planning) model we developed in Section 2.3.4 can easily be extended to allow for a steady state of this form by allowing the production function for the consumption good to include a factor of production that can be accumulated linearly (for example, the human capital in Lucas (1988)). If the production function is a linear homogeneous function of physical capital, human capital and the resource flow, and human capital accumulates according to Eq. (3.9) (normalized to remove the scale effect), then we can describe a balanced growth path similar to that in Section 2.3.4 with the exception that per capita income now rises for ever. The difficulty is not in describing such a model, but knowing whether it is realistic empirically. The effects of exogenous population growth on such a model are as in Section 2.3.4.

In an interesting paper, John and Peccenino (1994) build a simple OLG model of the interaction between capital accumulation and environmental degradation. In their model, consumption degrades the environment and the level of the environment affects utility and not production possibilities. Individuals allocate their resources between accumulating capital and maintaining the environment. The model is simple enough to explicitly analyze the dynamics which they show may produce transition paths which resemble the environmental Kuznets curve.
3.6. Endogenous population and growth in the presence of natural resources

In this chapter, we have used the capital theoretic approach of growth theory to discuss what one might call the "dynamics of nations". We have also cautioned that specific predictions about policies or interpretations of empirical relationships between endogenous variables are fraught with difficulties. Consider as an example the relationship between the demographic transition and "convergence" (as described in Section 3.3). If the absolute convergence hypothesis were true, then richer countries have lower growth rates of per capita income. If the population growth rate falls as the level of income rises, then countries with fast growth rates in per capita incomes will also have fast rates of population growth. This prediction is the opposite of the one which takes population growth as exogenous and relates it to per capita income growth. If, on the other hand, the conditional convergence hypothesis is correct, there is no general relationship between population growth rates and the growth rates of per capita income, although if there is some absolute level of income which must be attained for the demographic transition to occur (a debatable notion), one can imagine situations where a country could converge to a steady state without the transition to low population growth having occurred.

It is impossible here to write down a model which is tractable enough to treat simultaneously the dynamics of technical change, capital accumulation (in a broad sense), population growth and resource depletion. Indeed, to our knowledge, no such model has been analyzed. However, we now try to draw the general implications of the models we have discussed.

On the normative side, one central implication is that, in lieu of specific market failures or absences, the laissez-faire equilibrium is likely to be Pareto optimal. Policy concerning intertemporal resource usage, capital accumulation or population must then be based on issues of intergenerational equity on which economists do not have unambiguous things to say. With respect to deviations from this position, there is a presumption that natural resources, particularly global ones such as the climate, will not be utilized efficiently. One cannot be confident, therefore, that the actual dynamics of the economy will represent an optimal path.

On the positive side, there are some robust lessons about the characteristics of steady-state equilibria. In equilibrium, different types of capital, be they physical, human or natural, will be accumulated or maintained up until the point where the marginal benefits of having more capital balance the marginal costs. One salient distinction between the different types of capital is that plausible initial conditions for most societies suggest that they will be well endowed with natural capital and lack physical and human capital and technology. In this situation, the marginal benefit to having more physical and human capital may be very high, whereas the marginal product of natural capital (and thus the marginal benefit) could be expected to be low. Along a transition path to a steady state, we would therefore expect to see natural resource stocks fall and physical and human capital accumulate, though this will of course be
tempered to the extent that societies place intrinsic valuation on natural capital or resources. Given what theoretical and empirical knowledge we have, it seems plausible that such a steady state can be consistent with growing per capita income and the preservation of environmental resources.

At low levels of income, a variety of models also predict that parents will rationally decide to have large families. The human capital of poor countries tends to be in "quantity" rather than "quality". As income rises, however, a large body of evidence supports the notion of a demographic transition. The process and structural transformation of development changes the costs and benefits to parents of family size in such a way as to favor smaller families. Similarly, mortality falls in the face of rising per capita incomes.

This sketch of development is subject to many caveats. We have seen examples of where forms of increasing returns or externalities can lead to multiple equilibria. Here, there is not a unique attracting steady state to which economies converge, and where along a dynamic path economies allocate resources in a socially rational way to trade-off accumulating more of one capital stock against another. In such a model, maintaining a larger stock of natural capital in equilibrium seems to imply having lower stocks of other assets and probably lower per capita consumption. However, in models of multiple equilibria, countries may become stuck in a "development trap" with low income and high population growth (as in Becker et al., 1990). The interaction of poverty and missing institutions and markets may similarly result in inefficient over-exploitation of natural capital in such a trap. Here there are potentially enormous welfare gains to be made if society can coordinate on preferred outcomes and these outcomes can feature not only a lower rate of population growth but also an improved environment or larger natural capital stock.

As we made clear in Section 3.3, we also have severe reservations about the extent to which growth models, as presently constituted, provide a "theory of development".

Note also that, as the evidence of the environmental Kuznets curve suggests, convergence need not be monotone. Preferences need not be homothetic and at higher levels of per capita income, relative tastes may well change in favor of consuming the amenity services of natural capital.

4. Assessment

We collect here some comments, framed by the discussion of this paper, on some related and important topics which up until now we have not explicitly addressed.

4.1. Sustainable development

It is appropriate, given the wide currency attached to the phrase in the context of the
issues studied in our survey, that we address the issue of "sustainable development" (our thoughts here echo those recently expressed by Hammond (1993), Nordhaus (1994b), Parikh (1991) and Dasgupta and Mäler (1995)). In our opinion, to the extent that it is coherent, the concept of sustainable development fits rather nicely into Koopman’s (1967) conceptual framework. The roots of this literature lie with Georgescu-Roegen’s (1971) claim that economic growth was inconsistent with the second law of thermodynamics. The main interesting implication of the second law is that the quantity of usefully concentrated energy and matter in an isolated system must decline. The earth is not, however, an isolated system since it receives solar energy. The question becomes an empirical one about the uses to which solar energy can be put, and the extent to which wastes can be re-cycled, and the material and energy content of goods reduced by technical progress. Some regard the end result as inevitable stagnation (e.g. Daly, 1991). But as Pezzer (1992) puts it, "on their own, thermodynamic laws tell us frustratingly little about sustainability (they do not tell us) how long material stocks will last, how much solar energy can be usefully captured by humans, what stock of material goods can be maintained in circulation, or what values these goods will have". As we have discussed, even if resources are essential for production, consumption can be sustained indefinitely if some form of resource economizing technical change is sufficiently high. Of course, this implies that there is no minimum physical resource content per unit of output value, and this may be regarded as implausible (Pezzey, 1992). For the path to be actually sustainable in the sense that consumption is maintained, discounting must be small in relation to the rate of technical progress.

Pezzey (1989) lists 19 different definitions of what sustainability might be about, and as Toman et al. (1993) put it, "there is not a "textbook" definition of sustainability that commands widespread agreement". However, they go on to add, "it is clear that the central issue is concern for the well-being of future generations in the face of growing pressure on the natural environment to provide a range of valued services (extractable materials, waste absorption, ecological system resilience, aesthetics)". Solow (1993) accepts that sustainable development is about obligations to future generations, but adds that "you can’t be morally obliged to do something which is not feasible". He suggests the definition that sustainability is "an obligation to conduct ourselves so that we leave to the future the option or capacity to be as well off as we are": "You have to take into account in thinking about sustainability, the resources that we use up and the resources that we leave behind, but also the sort of environment we leave behind including the built environment, including productive capacity (plant and equipment) and including technical knowledge. What we are obliged to leave behind is a generalized capacity to create well-being, not any particular thing or any particular natural resource".

There seem to be two key issues in sustainability. First, it is about the ability of the economy to generate growth paths which sustain welfare in some sense, and, at the same time, do not decimate the environment. Second, it is about the intertemporal
distribution of welfare. Writers in the sustainability literature see preservation of environmental resources as intimately connected to human welfare and worry that present generations are over-utilizing such resources to the detriment of future generations. When considering the nature of intergenerational welfare, it is worthwhile pondering the experience of the last two hundred years in the developed countries. Solow (1993) argues that our ancestors were probably excessively generous in providing for future generations given the extraordinary increase in living standards that has occurred.

In practice, most authors (see Pezzey, 1989; Toman et al., 1993) argue that the sustainability of an intertemporal program is best assessed in practice by examining whether or not per capita utility falls over time. If it does not, then the program is sustainable. This approach frees the concept from demanding preservation of any particular resource or environmental asset except in the case where it is uniquely irreplaceable or essential to production (the idea that natural capital stocks should be preserved results implicitly from a very strong assumption about substitutability).

What might determine sustainability? First consider the issue of feasibility. Consider a simple model of an exhaustible resource which can be consumed or left in the ground to be consumed in the future (Heal (1993) for a nice exposition). The objective function is the discounted sum of utilities,

\[ \sum_{t=0}^{\infty} \beta^t U(c_t), \]

and the constraints are

\[ S_T = S_0 - \sum_{t=0}^{T} c_t, \quad S_{t+1} - S_t = c_t. \]

In such a model, all consumption paths inevitably converge to zero. Krautkraemer (1985) shows that allowing amenity services to enter the utility function from the stock of the resource can imply that it is not optimal to exhaust the resource. Whether or not the resource is depleted depends in a natural way on boundary conditions on the marginal utility of consumption (Vousden (1973) provided an early discussion), and also on how productive the resource is. If sustainability means that a positive level of consumption is maintained forever or that utility is nondecreasing, then it is clear that no paths can be sustainable.

What about the more general models which allow for substitution and technical change? Consider the steady-state equilibria of the first model we developed in Section 2.3.4. If \( H'(0) < 1 + \rho \), then the steady-state equilibria implies that the environmental resource will be exhausted in the optimal program. Could such an equilibrium represent part of a sustainable development program? It would seem not. Moumouras
(1991, 1993) offers a discussion of sustainability in these terms. But how should we respond to this? In the dynastic model, this is not at all clear. \( \rho \) represents here the altruism of the dynasty, or some mixture of altruism and time preference. The question becomes whether or not society discounts the welfare of future individuals at a lower rate than that implied by a laissez-faire equilibrium. If it does (as in the example we discuss in the next section), then the fact that the path implied by a particular discount rate implied the exhaustion of certain renewable resources might lead us to revise our welfare weights.

This type of reasoning suggests that sustainability is a criterion which can be applied to rule out the sort of accumulation paths which we described at the end of Section 2.3.2, and which Dasgupta and Heal (1979: p. 257) describe as "intertemporally efficient but perfectly ghastly". This seems best understood as a question of intergenerational distribution.

From this point of view, sustainability may appear as an extra welfare criterion in assessing development programs. Having derived the implications of a particular welfare function, we ask ourselves if this represents an acceptable path for the economy to develop along. In making this assessment we might want to ask does utility decline over time. If it does, then we may want to rethink the nature of our objective function.

Here, "sustainability" appears as a sort of litmus test that an allocation must pass to be ethically acceptable. This seems a useful device (and is what we take to be the spirit of Dorfman (1993)). As we have explained, in our opinion, it is impossible to sustain an interesting abstract discussion of optimal growth paths without taking a particular criterion and putting it to work to see its implications in action. In a similar spirit, Dasgupta and Mäler (1990) argue that the time path of future changes in natural resource stocks have to be deduced "from considerations of population change, intergenerational well-being, technological possibilities, environmental regeneration rates, and the existing resource base. The answer cannot be pulled out of a hat". In assessing the implications of an optimality criterion, we need some desiderata which determine whether the solution we compute is acceptable, which we can then use to re-assess our objective function. Sustainability seems to have a potentially useful role here.

4.2. Discounting

The theoretical example discussed in the last section exhibits the crucial role of discounting in a simple way. Imagine now a reformulation of that model in terms of an OLG economy where the social welfare function was as in Eq. (2.27). The condition which guarantees the existence of a positive stock of environmental assets in equilibrium would become \( H'(0) > 1 + \tau \). It is important to be clear about what one means by discounting. In project appraisal, cost and benefit streams are discounted to the present because of the supposition that the value of costs and benefits varies depending on the
time at which they accrue. Why is this? There are basically three aspects. One is that “waiting” is productive. The opportunity cost of investing in a project is what one loses by not adopting another project. Since capital investment is productive, “waiting” increases output over time. The second consideration is individual impatience. This is encapsulated in our parameter $\beta = u(1 + \rho)$. The third consideration is the intertemporal distribution of income which appears as the parameter $\tau$. This is the weight in a social welfare function which shows the relative weights of the welfare of different generations in total social welfare. The form this weighting takes is due to wishing to avoid problems of intertemporal inconsistency in the optimal allocation (Strotz, 1956). In the overlapping generations model without full altruism, there is a role for such a weighting between generations. The social optimum is relative to this set of weights, and given these, the planner can implement the social optimum through intergenerational transfers (i.e., a tax-transfer policy which determines the accumulation of capital). This logic is nothing other than the Second Fundamental Theorem of Welfare Economics in the overlapping generations model (see Bewley (1981) for a definitive treatment). While this should be clear, it has been re-discovered in a number of papers in the resource economics literature (e.g., Howarth and Norgaard, 1993).

The causality runs from society’s preferences over intertemporal income distribution, to appropriate policy that implements this distribution, hence to the capital stock (widely conceived to encompass human capital, technology etc.), and thus to the marginal product of capital, viz. the interest rate. Hence, according to welfare economics, the weighting of current versus future generations in a sense determines the interest rate. It is the welfare weights which are the exogenous variables.

Discounting has often been connected to the sustainability debate. To see why, if given a choice of $\tau$, we find that utility declines over time we might want to revise our value for this weight. What if $H'(0) < 1 + \tau$, but per capita utility was increasing? This suggests that declining utility per se is not all that sustainability is about. It also seems to be about the intrinsic value of natural and environmental resources. Hence the specification of the utility function is critical, and, in particular, the behavior of utility if resources go to zero. Common and Perrings (1992) provide a useful comparison of the distinctions between environmentalists and economists thinking on these issues. The main problem seems to be that, as yet, the languages are not commensurate enough for a productive dialogue to emerge.

The philosophical arguments about discounting, starting with Ramsey (1928), all without exception attack the moral justification for a positive rate of social time preference and proceed from this to state that costs and benefits should not be discounted since this discriminates against future generations (Parfit (1984) and Broome (1992) are eloquent statements of these positions). As Partridge (1981) puts it, “the concept of discounting the future is a point of fundamental contention between economists and moral philosophers. To economists the concept is virtually axiomatic and thus beyond dispute. To many philosophers, the notion is, at best, arbitrary and unproved and, at
worst, absurd.” The issue of a positive social rate of time preference is seen to be one of intergenerational equity. If one takes the dynastic model seriously, then this argument is redundant. The discount rate represents the intertemporal opportunity cost of resources, and this is determined by the degree of altruism of the dynasty. Even if this rate of “time preference” were zero, it may still be correct to discount because the productivity of capital implies that future individuals will be better off than we will be.

Discounting clearly has a big impact on resource models. Consider the example from Heal (1993) discussed in the last section. If $\beta \in (0, 1)$, then the results are as described above. However, if $\beta = 1$ then the model becomes the “cake eating” economy of Gale (1967) and the problem has no solution. Again, the results described at the end of Section 2.3.2 show that discounting makes the difference between consumption converging to zero and consumption monotonically increasing.

There are various other justifications for discounting in the literature. Dasgupta and Heal (1979) show that, if there is a probability that the world will end at any time and that this is governed by a Poisson process, then discounting can be justified by an “original position” type of argument (individuals put less weight on being born into a future that may cease to exist). Heal (1993) shows that introducing other sorts of uncertainty into the problem (such as about the existence of a backstop, or the date at which a substitute will become available) technology also induces discounting like phenomena. Koopmans (1972) and Diamond (1965b) have also provided an axiomatic basis for discounting.

There is also the problem that, while it is commonly assumed that reducing the discount rate would help preserve the environment since environmental benefits are seen as long lived, this is clearly not always so. Many authors have noted (e.g. Krautkraemer, 1988) that reducing the discount rate would also stimulate capital investment and, if this investment was resource intensive, then the net result might be a deterioration in the environment. It is easy to see how this sort of thing might happen in the context of steady-state equilibria of the model we developed in Section 2.4. There we noted that general equilibrium effects stemming from the allocation of capital between the production of the consumption good and the preservation of the environment could easily lead to perverse comparative steady-state results.

The perspective of the dynastic model is different from this since it then becomes problematical as to how the preferences of society can differ from those of the dynasty. In this case, it is rather the impatience of the dynasty which determines the characteristics of the growth path. If this implies that the resource stock is driven to zero, what do we conclude (recall that we are considering a world here with no externalities, market failures etc.)? In our view, this issue is not crucially damning to sustainability. The dynastic model is highly restrictive and perhaps not the most useful way of considering the issues.

It is well known that undiscounted problems raise difficult conceptual and mathematical issues. A conceptual problem is that no finite sequence of costs and benefits
matters. A mathematical one concerns the convergence of the objective function. The obvious response to this difficulty is to use some partial ordering over paths such as the “overtaking criterion”. Another response in this situation might be to forego the benefits of a fully computed optimum, and again resort to the methodology we propose. In this case again, sustainability may have a role: as a guide as to what policies are admissible when we cannot compute a full optimum over all feasible paths. However, in its present state of articulation, the concept of sustainability is clearly of only limited practical use.

4.3. Uncertainty

Thus far, and in the rest of the paper, we abstract from uncertainty in our analysis. This is a severe restriction. An important ingredient in environmental issues is uncertainty surrounding the form of environmental dynamics and the possible existence of threshold effects which have serious implications for economic activity and social welfare. Another source of uncertainty is about the value of many environmental assets. Environmentalists argue that biodiversity and the existence of species have potential value which we cannot assess (perhaps in the form of new drugs etc.). Weitzman (1993b) develops an interesting attempt to put a metric on “diversity”. Uncertainty is important in these matters since much environmental change is irreversible. The important early work of Arrow and Fisher (1974) and Henry (1974) showed that, in such a situation, there was an imputed “option value” on the non-use of resources. With irreversibility and uncertainty, it is prudent to “wait and see what happens”. Beltratti et al. (1992) show that if there is a possibility that future preferences will change in the direction of a greater value for the environment, then this leads to the optimal plan preserving a larger amount now than without such uncertainty.

Heal (1984, 1990, 1991) develops a model where the climate affects production possibilities and takes on one of two states (“good” and “bad”). The climate starts in the good state and may make a transition to the bad state (which is absorbing) as a function of the cumulative extraction of a resource (“fossil fuels”). Such a possibility leads to reduced resource extraction. The rate of extraction depends in intuitive ways on risk aversion and the properties of the function governing the transition probability. These papers also provide an interesting discussion on the approaches we could take to climate change (see also Chichilnisky and Heal, 1993). This is an obvious idea to provide insurance and is feasible as long as there is some global variation in the effects (agricultural production is relocated rather than devastated globally) at least as long as such contracts could be enforced. Heal argues however that, given the uncertainty, such attempts at insurance may have the adverse effect of reducing attempts to mitigate climate change (the standard moral hazard problem with insurance contracts).
4.4. International issues

International issues are critical in thinking about the global environment since possibly the most intractable problems relate to externalities across countries (international law being a notoriously unreliable enforcement mechanism). Mäler (1990) provides a discussion of many of the issues. Here the question of distributional issues between countries is of utmost importance. Reducing global environmental degradation requires a large amount of coordination between nations and agreements on how much each country may contribute to degradation. For example, imagine that it was agreed that it would be desirable to halt global warming. Even if a good estimate of the output by which greenhouse gas emission would have to be reduced to stabilize global warming could be made, it would then have to be decided exactly how this reduction was to be distributed across countries. If this reduction is a cost, then it is not clear that countries who already dominate greenhouse gas emission should automatically be given future rights to dominate such emission (purely on the basis that they managed to industrialize first).

There are other interesting international issues connected to environmental resources. Chichilnisky (1993a,b) has shown that, in a world where less-developed economies are relatively better endowed with natural resources, standard Heckscher–Ohlin considerations suggest that they specialize in the export of commodities which use environmental resources intensively. There are no implications concerning efficiency about this. However, she argues that it is plausible that resources are less well managed and, in particular, property rights are less well defined in underdeveloped nations. This then leads to trade and international specialization based purely on the imperfections of property rights in underdeveloped nations. Even two nations which have identical fundamental specifications of endowments, technology and preferences (and therefore identical autarkic price vectors) can specialize and trade on the basis of differing property rights. While the failure to properly define property rights is the key source of inefficiency, trade may exacerbate the tendency for underdeveloped economies to over-exploit their natural resources.

5. Conclusions

We now recapitulate on our fundamental themes. The interaction between economic growth, population dynamics and resource use is complex and the jointly endogenous outcome of the whole process of evolution and development of the economy and social system. As such, correlations do not imply causation. Unfortunately, our empirical knowledge is very poor. Little is understood about the dynamics of growth or demography and even less about the relationships governing environmental resources. A key implication then is that we must bear in mind our uncertainty about how the economy will evolve. The most plausible view is that while population growth may impede de-
velopment, it does so by exacerbating more fundamental unsolved issues. These revolve around the causes of underdevelopment and poverty themselves. One of the key things that population growth can directly exacerbate is inefficient exploitation of resources. It is clear that in reality markets are incomplete, and there may be many deviations from the conditions ensuring a first-best allocation of resources, especially in an intertemporal context under uncertainty. This may generate a role for population policy as a second-best instrument. However, as in all second-best situations, it is hard to say anything general here without detailed empirical knowledge. While these basic theoretical considerations suggest that the economy is unlikely to achieve the first-best intertemporal allocation of resources, the pertinent question is what set of feasible policies and institutions are likely to increase welfare.

Both the World Bank's influential World Development Report of 1984 and the 1986 report of the National Academy of Sciences Working Group on Population Growth and Economic Development conclude that, on balance, lower population growth rates would be beneficial for underdeveloped economies, and we accept this finding. Weir (1989) notes that "population has gone from being overlooked to the single dynamic element in European history" and this approach has been pushed in the influential work of North and Thomas (1972) and McNeil (1990). While it may be true that population growth has some positive effects, it is hard to imagine that population growth in itself has much to offer the developing nations in the solution to their economic and social problems. The real issues seem to lie in the adoption of technology and institutional changes which seem unlikely to be able to benefit from crude scale economies or the like. Birdsall (1989) argues that "mainstream debate now centers on the quantitative importance of rapid population growth - whether its negative effects are minimal, and in any event so interlinked with more central problems such as poor macroeconomic policies, weak political and social institutions and so on, as to hardly merit direct attention; or greater than minimal, and in effect contributory to other problems".

It also seems likely that, while in the long run, population size and growth may not be a key issue in the process of development, it may be an important issue in the short run. This is so since most of the costs are in short run while the benefits are enjoyed over longer time scales. As such, population policy may be useful in allowing any benefits to accrue. In practice, what matters is not just the total integral of the costs and benefits. The intertemporal distribution may be important from the point of view of social and political possibilities.

An important empirical issue we have concentrated on is the nature of intergenerational preferences. Even if there are no externalities to population growth (positive or negative), the rate of population growth might well not be socially optimal. Outside the dynastic context, it seems reasonable to posit a social welfare function encapsulating the preferences for society over the distribution of intergenerational welfare. Such a social welfare function would induce a particular rate of population growth. It seems improbable that this would be identical to the rate of population growth under
laissez faire. On the other hand, if preferences were such that the dynastic model were the correct benchmark, then it is not clear how society could care about the intertemporal distribution of welfare in a different way than the dynasty. Of course, with heterogeneity, society would care about the distribution of welfare across dynasties, and this would have implications for population growth (unless of course one took the ideas in Bernheim and Bagwell (1988) seriously that marriage means that all individuals are linked altruistically together in one big "family"). The crucial issue is not the presence or absence of altruism, since even in lieu of altruism, the rate of population growth may well be Pareto optimal. What is key is whether or not altruism is sufficient to induce dynastic preferences, and whether or not one can then argue that society should weigh different generations differently from this. Note that the dynamic consistency of these preferences is also important. If the dynastic preferences are dynamically inconsistent, then future rates of population growth will not be the same ones that would be chosen by the current cohort of the dynasty.

Unfortunately, the nature of altruistic preferences has received little attention empirically. As Altonji et al. (1992) put it, "in recent years the infinite-horizon altruism model has played an important role in theoretical analysis and policy debate. This is surprising given the lack of direct empirical support for the model." Altonji et al. (1992) test, and strongly reject, the implication of the altruism model that the distribution of consumption is independent of the distribution of resources (see also the findings of Goldin and Parsons (1989)). Given our present knowledge, it seems unlikely that we could formulate an operationally convincing population or resource policy on basis of our evidence about these. This makes the case for concentrating, in terms of policy, on issues that we have more chance of conclusively analyzing and quantifying, in particular the issues we have repeatedly stressed of externalities and property rights.

While we understand these issues much better, they are also complex since we have come to realize that the relationship between property rights and incentives is less obvious than was perhaps once thought. It is ironic that the fundamental work of Coase (1960), in a sense, belittles the importance of property rights for incentives. In the Coasian world of zero transactions costs, efficiency is guaranteed as long as property rights are well defined. Who actually possesses the rights only matters for the distribution of income. Recent advances in economic theory stress that the assumption of zero transactions costs is very strong, and outside of this theoretical ideal, it can matter a great deal for efficiency who actually owns the rights. For example, Hart and Moore (1990) argue that the ownership structure of firms is an efficient response to the inability of individuals to write complete contracts. This is an example of the more general recognition of the inseparability of efficiency and distribution. This implies that how property rights are allocated is very important.

The theoretical literature on fertility and population growth also needs to be extended to allow for more disaggregated models of household decision-making and for a better integration with the social environment. A key feature determining the health
of a society seems to be the social institutions it creates to aid the intergenerational transmission of culture, norms and human capital in a wide sense (see Coleman, 1988). In most existing societies, this institution is primarily the family (though aided by formal educational institutions). The evidence suggests that when the family breaks down or becomes "dysfunctional", then this can have severe implications for society. As yet, we hardly have a good language for discussing these issues. There seem to be many social phenomena concerning the family and fertility which are outside of the scope of existing models. As an extreme example, consider the discussion by Levi-Strauss (1957) of the relationship between the social structure of the Nambikwara tribe in central Brazil and their fertility rate. According to Levi-Strauss, the tribe became so obsessed by issues of relative social status that they practiced complete infanticide because of the destabilizing effects children born to different clans might have on the social equilibrium. To allow the tribe to persist, they instead kidnapped babies from other tribes.

What then of the population and environmental problems? We agree with Cassen (1976) that "the study of the factors which influence fertility decline suggest that it is socio-economic progress in general that brings about the demographic transition. If this is correct, the resolution of population problems may well lie in fundamental changes in society, removing the obstacles to what we nowadays name by the word development - the provision of a decent life not for some but for all". Our view is that to the extent that there are population and environmental problems, these will be best resolved by the process of development itself. To succeed, this process requires institutional, political and structural changes in society which are undoubtedly difficult to achieve. Most environmental disasters are due to the same types of problems which themselves impede development - inefficient policies, the failure to enforce property rights or inefficient structures of incentives. It is the interaction of population growth with these that causes it to have its worst effects.

In understanding why inefficient institutional structures and policies persist in equilibrium, we need theoretical advances well beyond those embodied in the current growth models. In this vein, Bardhan (1995) concludes his survey on the recent growth literature by stating, "notwithstanding popular impression to the contrary, the advances made so far in the new literature on growth theory have barely scratched the surface. The new emphasis on fixed costs and nonconvexities in the process of introducing new goods and technologies is important. But these fixed costs actually go much beyond the ordinary set-up costs in starting new activities: particularly in a developing country they encompass massive costs of collective action in building new economic institutions and political coalitions and in breaking the deadlock of incumbent interests threatened by new technologies. While the new interest in model-building will be helpful in sharpening our analytical tools and in critically examining our implicit assumptions, let us hope that it will not divert our attention from the organizational-institutional issues and distributive conflicts in the development process which are less amenable to neat formalization." Perhaps in thinking about these topics
we also need to bear in mind the maxim of the great social anthropologist Levi-Strauss who cautioned that "to say that society works is a truism, but to say that all parts of society work is an absurdity" (Levi-Strauss, 1963).

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