

Article

How “Green Knowledge” Influences Sustainability through Behavior Change: Theory and Policy Implications

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Abstract: The urgent and critical challenges of transforming patterns of behavior from current unsustainable ones are encapsulated in the 2015 UN Sustainable Development Goals (SDGs). Central to these goals and targets are systems of sustainable consumption and production. This crucial goal depends on consumers and producers making choices that depend on knowledge available to them and on other factors influencing their preferences in accordance with norms and culture. This paper investigates how “green knowledge” (i.e., knowledge of ecologically and socially sound products and practices) influences sustainability in the intersections of knowledge, preferences, behavior, and economic and environmental performance. By employing a general equilibrium economic model, we show that consumers, producers, and industry regulators with different degrees of knowledge and concern about the health and environmental benefits of products and production would lead to different economic and environmental consequences. As “green knowledge” influences consumption patterns and government policy-making, our model shows that, in principle, there will be a shift in the content of the economy to that which supports the achievement of long-term sustainability.

Keywords: sustainable consumption and production; green knowledge; economic consequences of knowledge and preferences; general equilibrium economic model

1. Introduction

Humanity faces the urgent and critical challenge of transforming patterns of behavior from the current unsustainable patterns and practices to sustainable ones that are just, equitable, feasible, and appropriate in the different contexts and cultures of the world. The global aspiration to meet this challenge is exemplified by the 17 UN Sustainable Development Goals (SDGs) [1]. One of the central and broadly encompassing goals is “responsible consumption and production” of all goods (SDG 12, *ibid*). This requires profoundly reshaping consumption patterns and lifestyles in a way that integrates locally or regionally appropriate policies and practices into a globally coherent, sustainable process.

Making informed decisions about consumption and production, whether as individuals or collectives, requires knowledge of the possibility and consequence of consuming more sustainable products and employing more sustainable production methods. Knowledge of environmental, economic, and societal aspects of sustainability and of the consequences of certain consumption patterns are important factors in the formation of preferences that people express in their choices of consumption. Other factors, including those delineated in theories of psycho-social determinants of pro-environmental behavior [2,3] and biases, heuristics, values, and beliefs [4,5] also strongly influence decisions that either support or hinder more sustainable behaviors.

Though it is recognized that knowledge is crucial for achieving sustainability, much attention has been focused on how knowledge increases productivity in production through green technological innovation. Less attention has been paid to how knowledge influences consumers' behavior through preference changes such that the content of the economy could be shifted to a greener one. In standard economics, technology plays a fundamental role in economic growth in which the role of knowledge in production is heavily stressed. Knowledge is linked more to technology, R&D, specialization, spill-over effects, education, and so on. Arrow, Nelson and Phelps, and Uzawa [6–8] first introduced education and learning into economic growth theory. In particular, the endogenous growth theories stress the crucial role of knowledge in human capital and technological progress (e.g., Lucas [9] and Romer [10]). In addressing the problem of unsustainability caused by economic growth, the same kind of technocratic thinking is applied, in which green technology is seen as the solution for sustainable development [11,12]. For instance, Acemoglu et al. [12] introduce endogenous and directed technical change in a growth model with environment constraints and suggest that sustainable long-run growth can be achieved with new technology through the temporary taxation of dirty innovation and production.

In stressing the importance of technology, much attention has been paid to how knowledge could be effectively translated into action, mainly through communication between scientists and policy-makers, so that the newest technologies can be applied. For instance, a participatory model was proposed with transdisciplinary co-production of knowledge for sustainability transformations [9]. Some authors distill the core lessons about how researchers (scientists, engineers, planners, etc.) could increase the likelihood of producing usable knowledge in promoting sustainable development and how researchers could help in building capacities for stakeholder collaboration, social learning, knowledge governance, and research training [8–10].

Nonetheless, contrary to people's intuition, technological progress does not always lead to sustainable results, and in some cases, it will even exacerbate environmental crises (e.g., [13–16]). The reason is quite simple. Though technological progress, or an increase in efficiency in general, could decrease the environmental intensity per unit output, profit-driven technological innovation tends to expand overall consumption and production. This is why modern economies are built on consumerism and overconsumption. Consequently, the environmental effects of consumption expansion would dominate the effects of environment intensity decrease. Jevons in 1865 [13] was the first who noticed the paradox that the increase in efficiency of British coal use brought about an unanticipated increase rather than a decrease in coal consumption. This is not an isolated case just in the energy sector but a general paradox in development. Another example is the "green revolution" in agriculture, based on a chemically intensive approach that made a significant contribution to addressing global hunger. However, it has become evident that, without meaningful consideration of social and ecological factors, this technological approach itself leads to unsustainable outcomes. The chemically intensive approach has led to land degradation [17,18] and heavy pollution of water bodies from agricultural runoff [19].

Therefore, it is equally important to pay attention to consumption and investigate how "green knowledge" influences consumers' behavior and policy-makers' decisions regarding regulations and policies for the production of goods. Indeed, substantial research literature on sustainable consumption has emerged over the past decade [20–24]. These authors focused on the unsustainable nature of current lifestyles and the ways in which these lifestyles could be steered in a more sustainable direction [11,25–28].

Although the concept of sustainable consumption has been widely embraced and various policy schemes have been initiated worldwide, especially in the SDG framework, the majority of them are conceptual, descriptive, empirical, or focused on specific policy topics, and they lack a solid theoretic basis [29,30]. It seems quite difficult to change consumption patterns and lifestyles according to the standard economic theory, since it assumes that the consumers have stable preferences and that the analysis of consumer choices is usually conducted for a given preference [31–33]. The shift in preference is seen as unlikely by many mainstream economists. As Slutsky [34] famously indicated,

“if we wish to place economic science upon a solid basis, we must make it completely independent of psychological assumptions . . . ” (Contrary to economics taking consumers’ preferences as stable, marketing assumes that preferences are changeable. In marketing, consumer behavior refers to the study of the buying tendencies of consumers. The purpose of marketing is to make every effort, including selecting knowledge, to lead/mislead consumers’ preferences for the purpose of expanding consumption.)

This situation did not change substantially in mainstream economics until a psychologist, Daniel Kahneman, won the Noble Prize in economics in 2002, which contributed to behavioral economics becoming established as a discipline for understanding economic behavior in a wide range of specific contexts [35–38]. Empirical studies found that many consumers act in a manner that is inconsistent with standard economic theory. In these situations, economic theory will make systematic errors in predicting behavior [39]. For instance, Dolan et al. [40] investigated behaviors in different social norms. Akerlof and Kranton [41] investigated how identity influences behaviors. Akerlof and Shiller [42] showed that the preferences of consumers are often manipulated in the market by commercial forces. The mounting evidence from behavioral economics suggests that preferences are not simply a matter of basic tastes, nor are they necessarily stable; they are also influenced by many factors including knowledge, belief, value, culture, and norms that vary across contexts, groups, and time.

How knowledge influences behavior through preference change is yet to be properly investigated in theory. For instance, when discussing consumer choices, knowledge often is seen as a matter only of information. However, information does not involve preference change. Whether or not a consumer has complete information mainly changes the constraints of her decision problem, rather than her decision problem itself. Stiglitz [43] provides a comprehensive introduction to information economics. Some research takes pro-environmental behavior as irrational behavior and tries to fill the “attitude–behavior gap”. According to Young et al. [11], 30% of consumers report that they are very concerned about environmental issues but they are struggling to translate this into purchases. Therefore, without preference changes, pro-environment behavior is often seen as a sacrifice of self-interest and, consequently, it would be very difficult to achieve the systemic transformation of behavior patterns required for the SDGs.

The objective of this paper is to go beyond the standard analysis that takes consumers’ preferences as given and theoretically investigate how “green knowledge” influences sustainability through preference and behavior changes. There is a link between knowledge, preference, behavior, and economic and environmental consequences. People with different knowledge have different preferences and different behaviors, which leads to different economic and environmental consequences. We describe the materials and methods in Section 2 and present the results of the general equilibrium model in Section 3. In Section 4, we further discuss the relevant issues and explore the policy implications of our research. The last section concludes the paper. The details of the model itself are shown in Appendix A.

2. Materials and Methods

In this section, we describe the assumptions, parameters, and structure of the model from which we derive our results. For simplicity, we consider an economy consisting of two types of products, X and Y, that have different long-term effects on the environment and human health. X denotes the type of green products that is beneficial, or at least not harmful, to human health and the environment—for instance, plant-based organically grown foods. The type of products Y is also necessary for the consumers, but they are less healthy and/or not so environmentally friendly, especially when they are overproduced and overconsumed. Product Y might, for example, be high-fat and high-salt fast-food products, animal product-based foods, highly processed foods, or resource-intensive manufactured products. Studies show that modern diets containing too many animal product-based foods, especially red meat, are strongly linked to the so-called modern disease of affluence, while the unhealthy dietary pattern is linked to mass animal production, which has a much higher environmental footprint than vegetable production [25–27]. Therefore, the relatively more product X (e.g., dematerialized services,

sports exercises, plant-based foods) and less product Y (e.g., red meat, junk foods, resource-intensive manufactured products, highly polluting production methods) that are chosen by a consumer, the better is this choice for the health of the consumer and the greater is the benefit for the environment.

Different patterns of preferences for consuming different types of products are generally associated with different lifestyles. There are several factors affecting lifestyles (e.g., knowledge, value, culture, and beliefs) [28,44] and thereby daily choices. Among these factors, knowledge held and considered credible [45] by individuals is important. For simplicity in our model, let us say that there are two types of consumer in the population, M_a and M_b , whose behaviors are strongly influenced by their respective knowledge regarding the products. The total population is $M = M_a + M_b$. The relative share of M_a and M_b will be crucial for achieving sustainability.

We assume that the first type of consumer, M_a , is informed about and trusts available knowledge about the potential impacts of products X and Y on health and environmental sustainability. Based on this knowledge and their lifestyle preferences, consumer M_a prefers product X more than product Y. For instance, they understand the long-term harm of junk foods to their health and wish to maintain a healthy lifestyle. Therefore, the more M_a in the population, the more consumer demand that supports sustainable outcomes.

The second type of consumer, M_b , is unaware of or lacks or distrusts knowledge of the impact of the products on their health and the environment. For instance, they may be unaware of or may not understand the long-term health risk of consuming junk foods frequently and the cause of “disease of affluence” including hypertension, high blood cholesterol, high blood sugar, diabetes [46]. It could also be the case that they do not believe warnings against products like Y, because they appear to conflict with their accepted knowledge, their beliefs, or their identities or because the consumer believes that information about products is intentionally distorted by vested interests [47,48].

After discussing the simple model of how knowledge as part of consumers’ preferences affects the two-product model economy and environment, we will then focus on how knowledge of health and environmental impacts of production methods that are held by policy-makers in government and regulatory agencies affects choices for sustainability through regulation. We further assume that product Y could be produced in two ways. One is a dirty way, with high external, hidden environmental cost, long-term cost, opportunity cost, and wellbeing loss. It will pollute the environment and in turn affect the health of all people in the long term, including both M_a and M_b consumers. The alternative is a clean production method with little external, hidden environmental cost. For example, apples are considered good for health in general, but they may be produced with or without the use of environmentally harmful pesticides [49,50]. We then show how policy and regulation could change with new knowledge with the respective consequences of the two ways of production and how the change would lead to economic pressure to shift production from less to more sustainable outcomes.

3. Results

In this section, we first show how consumers with different knowledge behave differently, leading to different environmental consequences, and then show how the government’s behavior that shifts with new knowledge would lead to different environmental regulations, and consequently to different consumer behaviors. We present the main storyline of the model in this section, while presenting the technical details in the Appendix A.

3.1. How Consumers with Different Knowledge Behave Differently

A representative consumer’s objective is to maximize her utility subject to budget constraints. We assume that the consumers M_a who prefer product X more than Y have the utility function $U_a = x^a y^{1-a}$, with $a > (1 - a)$ or $a > 0.5$, meaning that they spend more income on product X and less on Y. The consumers M_b who prefer products Y more than X have utility function $U_b = x^b y^{1-b}$, where $b < (1 - b)$ or $b < 0.5$, meaning that they spend more income on product Y and less on X.

We can then solve their demand functions of x and y , which is a function of market price that is decided by the interaction between consumers' demand function and producers' supply function in the marketplace (see Equations (A5) and (A6) in Appendix A).

The objective of firms producing X and Y is to maximize profit subject to the marginal cost and marginal benefit in production. We assume that the production function of X is $X = AL_x$, and the firm's objective function is $\max \pi_x = p_x X - \omega L_x$, while for the production of Y , it is $Y = BL_y$, and its objective function is $\max \pi_y = p_y Y - \omega L_y$, where π_x and π_y denote profit, A and B denote technology parameters, L_x and L_y denote labor input, p_x and p_y denote price, and, since there is income equalization in a competitive market, we use ω to denote wage in sectors of X and Y .

We can solve the supply of the firms, which is a function of market price. By using the market clearance condition, i.e., aggregate demand equates to its supply, we have the equilibrium output of X and Y (see technical details in the Appendix A).

$$X = A(aM_a + bM_b), Y = B[(1-a)M_a + (1-b)M_b] \quad (1)$$

Since $M_a + M_b = M$, we have $M_a = M - M_b$. By inserting X and Y and differentiating with respect to M_a , we have

$$\frac{\partial X}{\partial M_a} = A(a-b) > 0, \frac{\partial Y}{\partial M_a} = B(b-a) < 0 \quad (2)$$

For simplicity, we assume that, in theory, product X is completely environmentally friendly and all environment impacts are from product Y . Using e_t to denote the environmental footprint intensity of Y at a point in time, then the overall environmental impact on the economy E_t at a point in time is

$$E_t = e_t Y_t, \text{ and } \frac{\partial E_t}{\partial e_t} > 0, \frac{\partial E_t}{\partial Y} > 0, \frac{\partial E_t}{\partial M_a} < 0 \quad (3)$$

Findings from the results (see Equations (A17) and (A18) in the Appendix A):

Firstly, more people learning about "green knowledge", such that it changes their lifestyle, is crucial for sustainability. From $\frac{\partial X}{\partial M_a} > 0$ and $\frac{\partial Y}{\partial M_a} < 0$, we can see how the increase in M_a increases the share of the green economy and decreases the share of non-green economy, making the economy more aligned with sustainability.

Secondly, more people changing their lifestyles is a more fundamental condition than technological innovation for achieving long-term sustainability, i.e., shifting from M_b to M_a and from $U_b = x^b y^{1-b}$ to $U_a = x^a y^{1-a}$, the economy becomes more product X -based. From $\frac{\partial E_t}{\partial e_t} > 0$ and $\frac{\partial E_t}{\partial Y} > 0$, we can see that, if the environmental intensity of Y decreases through technological progress, it will not necessarily reduce the environmental damage, since Y may increase more quickly. If we further consider the accumulated environmental impact, E , as a consequence of consumption of Y , then no matter how low the intensity e_t is, the environmental impact E will nonetheless exceed the environmental limit \bar{E} over time, i.e., $E = \int_0^t E_t dt = \int_0^t e_t Y_t dt > \bar{E}$.

3.2. Shift in Government's Behavior with New Knowledge

Now, we investigate how a government's knowledge theoretically affects policy-making in regard to sustainability. Indeed, effects on governmental behavior are complicated. Here, we mainly focus on how new knowledge changes governmental behavior. We assume that the objective of the government is to maximize the wellbeing of the citizens through economic growth, so the government can be supported by their constituents. We assume that, in the conventional development concept, both citizens and government believe that high growth is a sufficient condition leading to high wellbeing, so its direct objective is to achieve the highest growth, even at the cost of the environment, i.e., the so-called "polluting first, cleaning-up later" pathway. Once the government experienced environmental crisis shock, it would evolve to a new development concept, with new knowledge showing that the hidden cost of the non-green growth model is actually high and is also detrimental to

citizens' wellbeing. Recognizing the previously unknown benefits of green growth, the government would change their policy to encourage the green way of production.

We continue the story following from Section 3.1. We further assume that Y can be produced in two alternative ways. The first way, represented as Y_1 , is a dirty way, with high external environmental cost. The second way, represented as Y_2 , is a clean way, with expensive green technology and little external environmental cost. In terms of physical quality, the products of Y produced in two alternative ways have no apparent difference, so the consumer does not need to distinguish them in the market. Therefore, the optimal decision of the consumers is made according to price signal.

In the absence of environment regulation, the firm is not forced to internalize its external and hidden costs into the price of Y_1 . Its price will be lower than Y_2 produced in the clean way. Consequently, Y_2 could not survive in the competitive market. Nonetheless, as the environmental consequences accumulate to a certain level, the hidden cost (for instance, health hazard) emerges, and the government would learn that Y_1 actually has a higher cost. At this point, they would start to regulate Y_1 and require the firm to clean up its pollution. This makes Y_2 competitive in the market. Once Y_2 can survive in the market, its cost will gradually decrease, driven by the market force, leading to a more competitive sustainable development. It is easy to formalize the story in a rigorous way. Some interesting results can be drawn from the analysis.

Firstly, without strict government environmental regulation in place and if there is no difference in terms of physical quality between Y_1 and Y_2 , the individual's optimal decision is to choose Y_1 with lower price rather than Y_2 with higher price. Even if the consumers know the different long-term wellbeing effects of Y_1 and Y_2 , the free rider problem prevents them from choosing Y_2 . This is not an issue of information asymmetry, but an interdependence between market failure and government failure. Without the government's environmental regulation, even if information about the production of Y is disclosed, it will not necessarily lead the consumer to choosing Y_2 .

Secondly, in the case in which the negative effect of Y_1 on wellbeing is not recognized, the utility of the consumers in dirty production way appears higher than the real utility in clean production. Obviously, without realizing the invisible effect of wellbeing loss, the model without strict environment regulation looks superior to the model with strict environment regulation. This has been the widely accepted conventional development rationale and practice in the past, based on which the government made its policy.

4. Discussion and Policy Implications

In this section, we further discuss the relevant issues that have not yet been properly investigated in the simple model and explore the policy implications of the study.

4.1. What Is Green Knowledge?

When we discuss how green knowledge influences sustainability, the first question that we need to address is "what is green knowledge?". This is definitely a debatable question on which it is hard to achieve consensus. In theory, whether knowledge is green needs to be judged by its long-term environmental impact, though it is extremely hard in reality to measure which impact derives from which knowledge.

Firstly, from the environment impact formula $E = e \cdot Y$, we can see that there are two complementary ways to reducing environment impact, and, consequently, there are two types of knowledge. The first is the knowledge to decrease the environmental intensity, e . This is related to technological innovation in production that is heavily stressed in mainstream economics. The second is the knowledge to decrease Y and increase X that is free from pollution. This is related to consumers' preference changes and lifestyle changes, which are the focus of this paper. The two types of knowledge are both crucial, but the second type is even more fundamental, since the transition of the economy from a Y-oriented economy to an X-oriented economy could delink economic growth from pollution.

Secondly, a new knowledge system for sustainability is needed. The existing knowledge system, to some extent, is created in the unsustainable traditional era and serves the traditional industrialization model that has led to global unsustainability. Therefore, we need a development paradigm shift and new knowledge system, rather than just marginal improvement to the existing model. For instance, as traditional ecological agriculture was “modernized” with industrial logic to chemical agriculture, the traditional farming knowledge was replaced by chemical farming knowledge. In this case, knowledge about how to marginally reduce the usage of chemicals per unit of land would also be called green knowledge, but this type of knowledge is not really green in regard to the environment or health in the long term.

Thirdly, in many cases, knowledge is manipulated by commercial forces in order to maximize their profit, including what knowledge should be disseminated and what interpretation should be drawn from the same information, etc. For instance, there is no consensus on what constitutes healthy foods and healthy lifestyles. This is not just a question about science. Campbell and Campbell [51] investigated how nutrition knowledge was intentionally distorted by vested interests for the purpose of profit in the food industry in the USA.

4.2. *The Role of the Market in Sustainable Transition*

The free market is the foundation of the modern economy, in which the consumers make free choices. There is little doubt about the importance of the free market. Yet, the fact that the modern consumption pattern has been systemically reshaped by commercial forces remains almost entirely unacknowledged [52]. From the traditional preindustrial to modern industrial economy, a shift in mass psychology and lifestyle to consumerism is a precondition for economic take-off, since mass industrial production requires mass consumption. Eventually, consumerism became the foundation of the modern economy and consumer society become a symbol of modernization [53–55]. Similar to the transition from the industrial economy to sustainable development, a massive transition of social psychology is required as well.

In our paper, we show that knowledge-led preference changes will lead to behavior changes, which will lead to sustainable transition in a well-functioning market. However, this is the case in two senses. On the one hand, if the market functions well, the increase in population M_a could make the economy more sustainable. On the other hand, the unsustainable economy with high M_b is also a market-driven result, since it was the commercial force that led to the formation of product Y-oriented preference. Once the economy has been locked into a Y-oriented economy, it would incur high transition cost to the X-oriented economy.

This highlights the importance of green knowledge and environmental regulation. As we show in Section 3.2, without appropriate green knowledge and environmental regulation, market failure would happen and the firm Y_2 with clean production would not be able to survive in the market. This has particular implications for developing countries wishing to make the transition: if they could be equipped with the appropriate knowledge to improve their market economy while avoiding market failure, they could achieve a late-comer advantage in achieving sustainable development.

4.3. *Policy Implications*

Along the line of “knowledge → preference → behavior → environment consequences”, we investigated the mechanism by which knowledge influences environmental sustainability. We show that the increase in population M_a could make the economy more sustainable, which has the following policy implications.

Firstly, to increase the share of population M_a through green education is crucial for achieving sustainability. It is, to some extent, even more effective compared to introducing new technology. A directed preference evolution towards sustainability through education is possible. What needs to be clarified is that this is consistent with the market principle, since by doing this, the government provides new public goods for sustainability. The government can use its credibility to effectively promote

sustainable lifestyles and regulate the polluting way of production. Innovative, locally and culturally appropriate, and effective learning approaches, including informal, narrative-driven, and game-like methods [56–62], can be introduced.

Secondly, “responsible consumption” is not sufficient, since “responsible” means that sustainable consumption is an externality to the consumer. If the preference could be changed through access to green knowledge, then sustainable consumption could turn into “self-interested consumption” and taking action for sustainability would not just be a moral call.

Thirdly, the leadership’s knowledge and vision are crucial for sustainable transition. We have shown that leadership with appropriate knowledge would realize the actual high hidden cost and long-term cost of the dirty production model and implement strict environmental regulations to improve the social wellbeing. Additionally, although it is not easy for a short-term government to take strong action towards achieving a long-term goal, leadership with a long-term vision would overcome this conundrum.

However, there is still some distance from the policy implications of our research to specific policy initiatives. Our paper assumes that consumers with “different knowledge” have “different preferences”, but the exact relationship between knowledge and preference and how it works is yet to be explored. We need to further open the “black box”, so that the policy can be developed based on solid evidence. More empirical research is yet to be done to ensure that the policy can be carefully designed.

5. Concluding Remarks

This paper investigates how what we refer to as “green knowledge” influences sustainability through the links between knowledge, preferences, behavior, economic, and environmental performance. By employing a general equilibrium economic model, we show that consumers, producers, and industry regulators with different degrees of green knowledge would lead to different economic and environmental consequences. As green knowledge influences consumption patterns and government policy-making, a shift in the content of the economy to one that supports the achievement of long-term sustainability would take place.

Until now, much attention in the literature has been focused on how knowledge increases productivity in production through green technological innovation and less attention has been paid to the theoretical analysis of how knowledge influences consumers’ behavior, especially through preference changes. Based on the mounting evidences from behavioral economics that preferences are not stable but are influenced by many factors including knowledge, this paper introduces preference change into the formal general equilibrium model and shows how the change would lead to sustainability transition. The paper suggests that the effect of knowledge-led preference changes on the sustainability transition would be significant and more fundamental than that of technological innovation alone.

Since empirical studies on preference change need experiments on behavior change, this is beyond the capacity of this theoretical paper. What needs to be done next is careful empirical research to open the “black box” of the assumption that “people with different knowledge have different preferences”, as well as what and how policy interventions would work along the line of “policy interventions → perception → behavior → performance”. In addition to knowledge, empirical studies need to extend to a wide range of factors influencing preference formation and build on the insights derived from the work described in this paper.

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Appendix A. A Model of How Consumers with Different Knowledge Behave Differently

(1) Consumption system.

The decision problem of consumers M_a who prefer X more than Y is

$$\max U_a = x^a y^{1-a} \quad (\text{A1})$$

$$\text{s.t. } p_x x_a + p_y y_a = I = \omega \quad (\text{A2})$$

where U_a is the utility function of a representative consumer of M_a . This type of consumer prefers X more than Y; denoted by $a > (1 - a)$ or $a > 0.5$. p_x is the price of product X, x_a is the amount of product X purchased by M_a , y_a is the amount of Y purchased by M_a . I is the income of the representative consumer of M_a , and ω is the wage.

The decision problem of consumers M_b , who prefer Y more than X is

$$\max U_b = x^b y^{1-b} \quad (\text{A3})$$

$$\text{s.t. } p_x x_b + p_y y_b = I = \omega \quad (\text{A4})$$

where U_b is the utility function of the representative consumer of M_b . This type of consumer prefers product Y more than product X, denoted by $b < (1 - b)$ or $b < 0.5$. x_b is the amount of product X purchased by M_b , and y_b is the amount of Y purchased by M_b .

For simplicity, letting product X be the price numeraire, we have $p_x = 1$. Solving the optimization problem, we have the demand functions and indirect utility functions for M_a and M_b .

$$x_a = a\omega, y_a = \frac{(1-a)\omega}{p_y}, U_a = (a\omega)^a \left[\frac{(1-a)\omega}{p_y} \right]^{1-a} \quad (\text{A5})$$

$$x_b = b\omega, y_b = \frac{(1-b)\omega}{p_y}, U_b = (b\omega)^b \left[\frac{(1-b)\omega}{p_y} \right]^{1-b} \quad (\text{A6})$$

(2) Production system.

The firms producing X and Y have the following decision problems, respectively.

Firm X:

$$\max \pi_x = p_x X - \omega L_x \quad (\text{profit function}) \quad (\text{A7})$$

$$\text{s.t. } X = AL_x \quad (\text{production function}) \quad (\text{A8})$$

Firm Y:

$$\max \pi_y = p_y Y - \omega L_y \quad (\text{profit function}) \quad (\text{A9})$$

$$\text{s.t. } Y = BL_y \quad (\text{production function}) \quad (\text{A10})$$

Since $p_x = 1$, and there is income equalization condition between sectors X and Y in a competitive market, we have the solution of the optimal problems.

$$\omega = A, p_y = \frac{A}{B}$$

(3) General equilibrium.

According to Walrus law, we only need to use one of the two products, say product X, to solve the general equilibrium. We have the following market clearance condition of X, i.e., aggregate demand equates to its supply.

$$M_a x_a + M_b x_b = AL_x \quad (\text{A11})$$

$$L_x + L_y = M \quad (\text{A12})$$

Inserting Equations (A5) and (A6) into (A11) and using (A12), we have the equilibrium labor L_x and L_y .

$$L_x = aM_a + bM_b \quad (\text{A13})$$

$$L_y = (1 - a)M_a + (1 - b)M_b \quad (\text{A14})$$

Inserting (A13) and (A14) into (A8) and (A10), we have

$$X = A(aM_a + bM_b) \quad (\text{A15})$$

$$Y = B[(1 - a)M_a + (1 - b)M_b] \quad (\text{A16})$$

Since $M_a + M_b = M$, we have $M_a = M - M_b$. Inserting it into (A15) and (A16), and differentiating with respect to M_a , we have

$$\frac{\partial X}{\partial M_a} = A(a - b) > 0, \quad \frac{\partial Y}{\partial M_a} = B(b - a) < 0 \quad (\text{A17})$$

For simplicity, we assume that product X is completely environmentally friendly and all environment impacts are from product Y. The environmental footprint intensity of Y at a point in time is denoted by e_t , then the environment impact of Y on the economy at a point of time is

$$E_t = e_t Y_t, \text{ and } \frac{\partial E_t}{\partial e_t} > 0, \frac{\partial E_t}{\partial Y} > 0, \frac{\partial E_t}{\partial M_a} < 0 \quad (\text{A18})$$

which means that the environmental impact increases with the production of Y and M_b .

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