DISCUSSION PAPER

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Sustainability Dynamics of Resource Use and Economic Growth

A Discussion on Sustaining the Dynamic Linkages between Renewable Natural Resources and the Economic System

CONTENTS

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Abstract

All economies of the world depend upon the use of renewable natural resources[1] for their growth. This relationship inherently reflects that continued increase in extraction of resources is a must to sustain economic growth. Inevitably, a tipping point is reached from where the regeneration rates of the resources diminish due to depletion of the resource stock. The resource production peaks and declines which lead to a delayed feedback on the economy, ultimately restricting its ability to grow and sustain its level of output. This discussion paper demonstrates, with the help of system dynamics model, that this feedback from the decline of natural resources into the economic system would lead to economic contraction much before the resources are completely exhausted. The paper provides useful insights through the modelling exercise by testing three of the most popular policy choices to sustain economic growth: (i) Improving resource efficiency of the economy, i.e., dematerialization, (ii) Green Growth, represented here as Conserving/Restoring the resources, and (iii) Resource expansion due to technological advancements or new discoveries. Simulation runs show that none of the policies are able to avoid overshoot of the economy although they are successful in delaying the overshoot and fall. The model demonstrates the counterintuitive outcomes of the above policy choices and makes a strong case to promote empirical research on this subject using system dynamics.

Key Words: Green Growth, Resource Efficiency, System Dynamics, Sustainability, Economics

Introduction

Sustainability of economic growth in a finite resource environment has long been questioned and acknowledged as a complex issue. (Forrester 1971; Meadows *et al.* 1972; Meadows *et al.* 1974). Complexity arises because of potential non-linearities in the relationships among economic and ecological variables (Hoffman 2010). Limited understanding of such complex relationships

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[1] Renewable Natural Resources, such as forest, ground water, and fisheries. Energy is excluded for the purpose of this study.

coupled with the paradigm of continued growth can and has resulted into the over exploitation and degradation of natural resources, including those that are renewable in nature (Millennium Ecosystem Assessment 2005). Unless these resources are infinite their consumption will result in high subtractability,[2] leading to severe resource depletion and ultimately resource exhaustion (Ireland 2013). Therefore, one of the key challenges is to maintain a sustainable stock of resources. This is particularly difficult in an economic system where consumption and production are considered very likeable elements to measure the success and growth of the economy (Boulding 1945). If the resources are not managed well, it could lead to their irreversible decline. This in turn could result into an economic contraction or sustained economic depression (Tverberg 2013). Such impacts of resource depletion on the economy seem implausible due to long-time delays involved from the declining stock of resources to the decrease in the flow of goods. However, it is only prudent to have proactive economic policies which could avoid such impacts and foster a balance between economy and resources.

In this paper, we view economic growth and resources from a systems perspective to learn how the delayed feedback effects from resource depletion will impact the growth of the economy in the long run. It highlights, in a simplified manner, the hidden perils of blindness towards this slow feedback from decline in renewable natural resources to the production of goods in the economy.

Our study is based on the following three postulates which we test through the modelling exercise.

- A stock of renewable resources with a defined carrying capacity would pose binding constraints on the economy to sustain its growth.
- Once these constraints, in form of limits to resource extraction, are reached the economic GDP will peak and decline.
- This peak and decline would arrive much after the resources have already crossed their irreversible decline threshold.

Resource Extraction and Economic Limits

Studies suggest that the trend of collapse of some economies and civilizations (e.g. Easter Island, Sumerians, etc.) have been a phenomenon driven mainly due to environment degradation and resource limits (Tverberg 2013). For instance, until fossil fuels came into widespread use, civilizations regularly grew within their finite spaces before they collapsed due to factors like those of ecological stress, soil degradation, deforestation, climatic changes (Montgomery 2007; Chew 2001; Tainter 1990). The economic process of growth in consumption of resources is a natural progression of an economy moving from cheap and easy to the difficult and costly to extract resources. This process takes the economy towards its limits to growth. The natural preference of nascent economies is usually to begin with the most feasible resources available for extraction (Tverberg 2013). Gradually as the economy expands, these resources begin to deplete and over the years deplete faster than they can regenerate themselves. After years of extraction, the economy is left with less of these resources, making it increasingly difficult for them to extract. This raises the cost of extraction, thus making previously feasible resources uneconomical. The economy now migrates to explore previously unfeasible resource options, thus making the extraction and production expensive. As costs continue to soar and extraction limits are reached, the economy finds it difficult to sustain the level of output. This indicates that economic limits would restrict the resource extraction much before the resources are completely exhausted, but not before the depleting resources have already created a delayed feedback on the economy with a potential to cause economic contraction. Unless the economic policies are proactive and sensitive towards the state of resources, the resources would continue to deplete until their binding constraints are reached which would restrict the economy's growth.

Research Methodology

System Dynamics

Given the complexity involved in the interactions between economy and resources, the problem of management of resources must be seen through the lens of complex systems. Unlike optimizing problems, which lend themselves to analytic solutions, complex systems may be best understood using dynamic simulation techniques (Hoffman 2010).

Long-term simulations of the relationship between economy and resources could provide useful insights about the binding constraints of resources (Hoffman 2010). System dynamics (SD) is an approach best suited to understand such non-linear behaviour of complex systems over time using stocks and flows, internal feedback loops, and dynamic rates of change (Massachusetts Institute of Technology MIT). The methodology was conceived in the late 1950s at the MIT by Jay Forrester (Forrester, 1961, 1969). SD as a modelling discipline holds the potential to unveil the impish nature of complex systems and uncover the relationships between variables which are responsible for behaviour of the system. It also provides the reader with an opportunity to go through the model structure and study the

[2] The degree to which one person's use of resource diminishes other's use.

linkages in a more transparent manner (Wiesmann n.d.). The model structure and parameters used in this study are not meant to provide a forecast or prediction but is intended to set up a model environment where simulations could be used to test assumptions and policy implications. Thus the simulation graphs do not show any value of parameters on the y axis since the emphasis is on the behaviour of parameters over time. The model is launched for 200 years to capture the delayed feedbacks and its long-term impacts on economy and resources.

Model Description[3]

This model consists of two sub systems—Renewable Natural Resources and the Economy.

Renewable Resources

The resource stock is taken as a reservoir of renewable resources comprising of forests, ground water, and fisheries. Its Initial value is kept at 1,000 billion kg and carrying capacity is fixed at twice its initial value, i.e., 2,000 billion kg. These resources regenerate at 2% and can grow upto their carrying capacity.

Economy

The Economy is yet to develop and the pace of its growth represents growing population and economic development. Initial wealth in economy is kept at INR 20 billion split across Producers, Sellers, and Household. Economy's growth rate is assumed to be bell shaped over simulation time. It starts with 1% reaches a maximum of 7% and then falls back to 1%. This represents the five stages of economic growth and development beginning with traditional economy and reaching full prosperity (Rostow 1959). Gross Domestic Product of the Economy is calculated as a sum of flow of production of goods (shown as cost of production) and value addition to the economy (shown as growth in GDP). The economy is considered to be a closed system having no interaction with external environment, synonymous to World Economy or an Isolated Economy.

Resource Intensity of Economy

Resource intensity is an exogenous variable in the model. It is a measure of the resources needed for the production and processing of goods in the economy. It therefore also measures the efficiency of resource use in the economy. Resource intensity is measured as kilograms of resources consumed per unit of economic output. Its initial value is kept at 1 kg/rupee.

[3] Complete model structure, equations, parameter values, and description of each variable are provided in the Annexure.

Parameters for Base Run

Wealth in Economy = INR 20 billion
Economy's Growth Rate Curve = 1% to 7%
Resource Intensity of Economy = 1 kg/rupee
Renewable Resources = 1,000 billion kg (carrying capacity = 2,000 billion kg)
Natural Resource Regeneration Rate = 2%

Endogenous Feedbacks of Renewable Resources and Economy

Figure 1 illustrates the growth dynamics in the natural resource system and the economic system, in the absence of any interactions between them.

The growth of natural resources depends on its own level of stock. An increase in resource stock would result into an increase in its regeneration flow, thus creating a positive reinforcing loop. But its growth is not compounding infinitely. This is because natural resources have a carrying capacity of their own which limits their maximum achievable level of growth (Schreiber n.d.; Ford 2009). In the model, natural resource carrying capacity is assumed to be twice the resource's initial stock indicating that the resource stock has potential to grow. This is expressed in the model by making the regeneration flow a function of the resource stock density (Figure 3). As the density approaches its maximum, the regeneration rate tends towards zero.[4]

Similarly, the regeneration flow also declines due to a decline in the resource stock. If it falls below a particular threshold level, its regeneration rate would tend towards zero. Therefore, a continuous decline in the resource stock could breach the threshold levels leading to non-renewability of the resource. It is in-between these two stages of resource reaching its carrying capacity and irreversible degradation that it is available for sustainable harvest.

The case of economic growth is somewhat different. Its growth is taken as exponential in nature (Johnston 2014). Unlike the resource growth dynamics which has an endogenous growth limit due to its carrying capacity, the economy does not seem to have any such carrying capacity of its own. Although its growth reaches maturity, the rate of growth does not reach zero and the economy continues to grow, albeit at a slow rate. Thus, the economic growth curve represents exponential pattern for most part of the simulation, while the resource stock grows and achieves stagnation.

[4] Dx/dt= r x(1-x/K), where r is the intrinsic rate of growth of the population, K is its carrying capacity and x is the population density. Solving this differential equation would give a functional relationship which depicts the results of the natural resource growth.

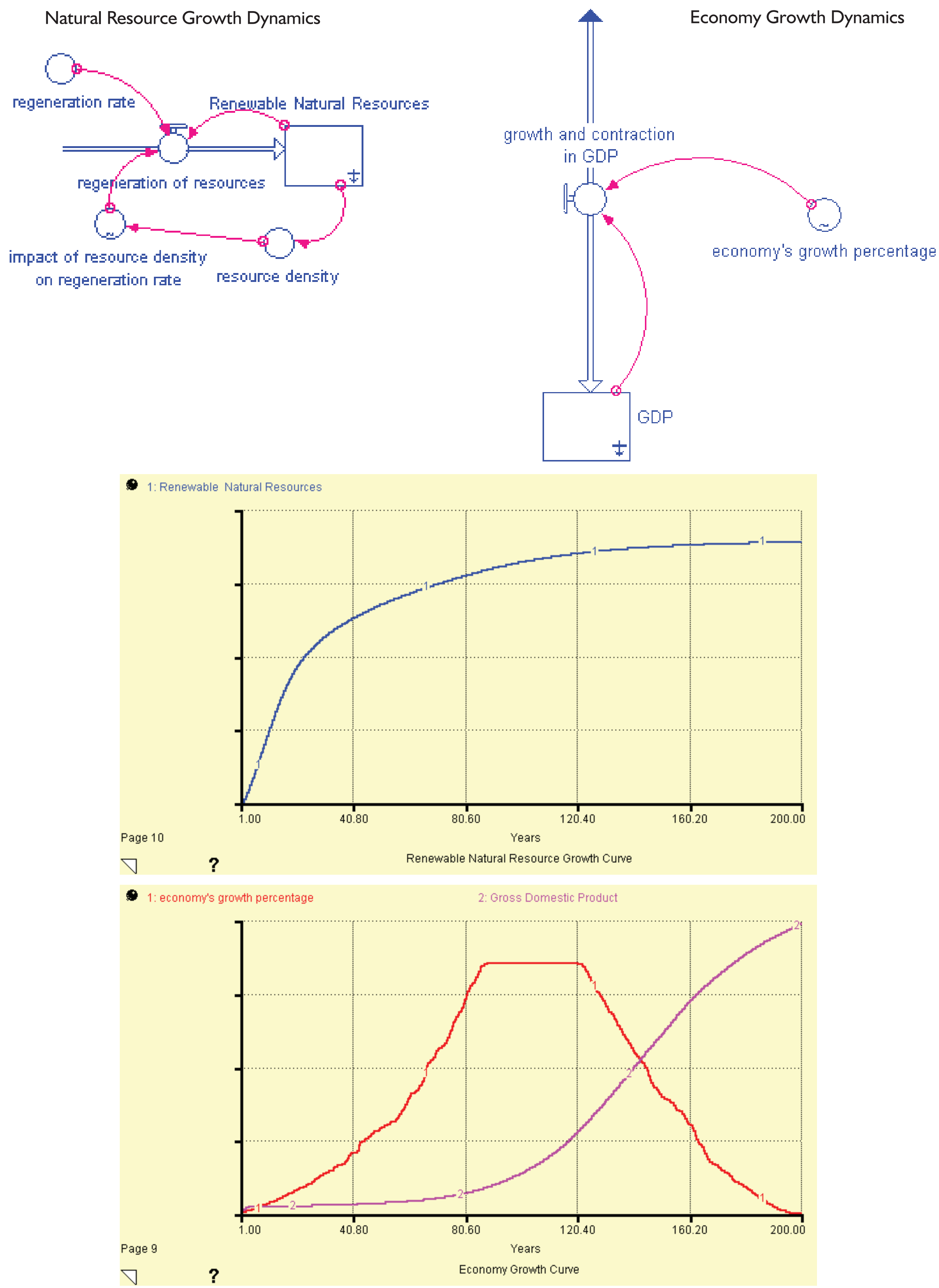

Figure 1: Comparing Natural Resource and Economic Growth as Isolated Systems

Source: TERI Research

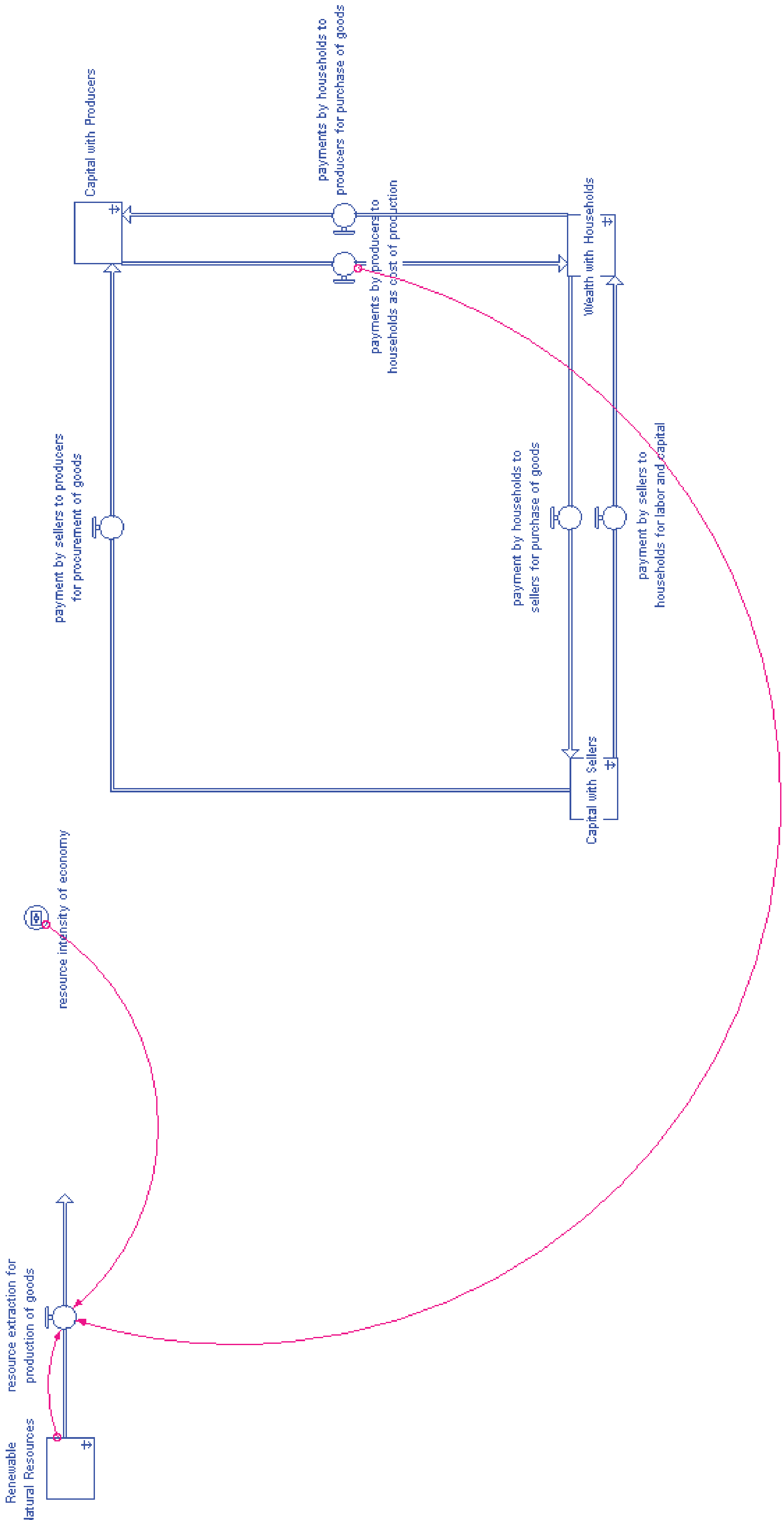

Figure 2: Linking Natural Resources and Economy
Source: TERI Research

Interaction between Resource and Economic System

The economy comprises of households, industry (producers), and the market (vendors and suppliers). The industry uses renewable resources for production of goods using labour and capital from households. The process of production of goods results into flow of income to households (as payments for cost of production). Within the model, the income is spent by households for purchase of goods from the market through vendors/sellers directly through producers. These vendors/suppliers in the market procure goods against payments to the industry. The model has a closed-loop income flow between consumers (households), industry (producers), and the market (vendors and suppliers).

Resource extraction for production of goods is shown as a function of resource intensity of the economy. This means that if the intensity is kept constant, an increase in the rate of growth of economy would result in an increase in the rate of extraction of resources. However, if limits of resource extraction are achieved, then the production of goods is likely to fall. If the resources are degraded beyond repair their regeneration rates would also fall. The resource would start behaving as a non-renewable resource, i.e., it will have no regeneration flow. This would result in a peak of production of goods beyond which production would fall. Under this scenario, a falling production against a growing demand would result in inflationary pressure.

Analysis and Discussion

Base Run: Overshoot and Collapse of Economy and Resources

The base run (Figure 3) shows four phases of growth and collapse in the resources and economy. They are:

Phase I where both Renewable Resources and GDP are growing, followed by phase II where resources achieve a maximum growth rate while GDP continues to grow. In phase III resources begin to decline while GDP growth continues, and finally Phase IV where GDP peaks and collapses accompanied by irreversible decline in resources.

In the simulation run (Figure 3) as long as the resource consumption is lower than its regeneration, the resource stock is able to grow (Phase I). As the economy grows, the extraction of resources for production purposes also increases. This leads to a point where resource extraction equals resource regeneration and resource growth stagnates (Phase II). Further due to continued economic growth the resource extraction becomes greater than resource regeneration. This results into a gradual decline in the resource stock while the GDP continues to grow (Phase III). However, a declining resource stock would pose limits to extraction for production of goods. These limits eventually lead to a peak and fall in GDP accompanied by irreversible decline in resources (Phase IV).

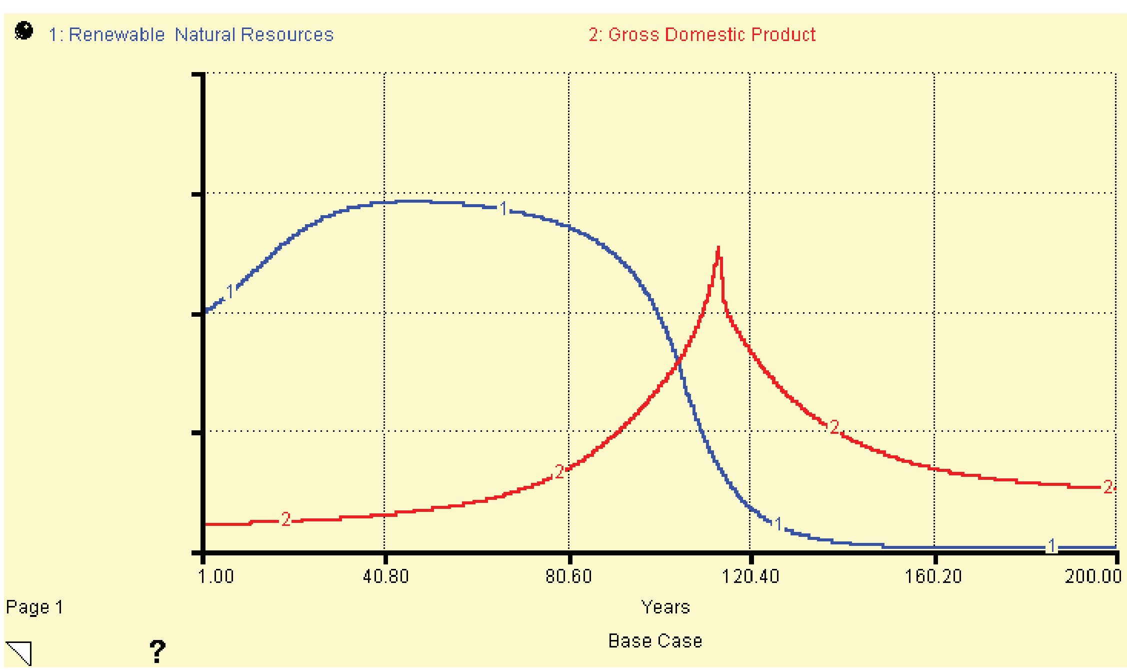

Figure 3: Base Run: Overshoot and Collapse
Source: TERI Research

Base run outcomes confirm our postulates that resources with a defined carrying capacity pose binding constraints on economy's growth, once these constraints are reached the GDP will peak and decline and that this decline would happen much after the resources have crossed their irreversible threshold.

Inflationary Pressure and Demand Correction

As shown in Figure 4 the demand for goods in the economy keeps growing even while the production of goods falls. This creates a gap between demand and supply of goods due to which inflationary pressure starts to build up. This results in growing GDP due to rising prices, despite decreasing production. This is depicted in Figure 3 through the spike in GDP. A persistent rise in prices would result in demand correction. This results in an overall contraction in the GDP due to demand correction and falling production. The economy then moves to a state of reduced demand, reduced production, and a depleted resource stock. This is a situation where the enterprises become unprofitable, unemployment increases, and resources are in their degraded state. It is not a desirable state for any economic and social system.

While there exist policies which aim at preventing such a situation, this paper tests the potential of three key policy measures and analyses if they are able to avoid the overshoot and fall of economy and resources.

Policy Testing

Policies which often surface as popular solutions to sustain economic growth and conserve the environment are tested and enumerated in Figures 5, 6, 7, 8, and 9. They are:

1) Improving resource efficiencies i.e. more economic output per unit of resource
2) Improving resource efficiency and Restoration of resources, i.e., green growth
3) Green growth and expansion of resource base due to technology advancements or new discoveries, i.e., increase in the stock of resources

Policy 1: Improved Resource Efficiency

Model Parameters for Testing Resource Efficiency Policy

Economy's Growth Rate = 1% to 7%

Resource Intensity of Economy = reduced to 0.5 kg/rupee from 1 kg/rupee

Natural Resource Regeneration Rate = 2%

The scenario models outcomes of an intervention which results into increase in resource efficiency of the economy by 50%. This implies that the economy will consume half the resources compared to the base case. The result shows that the economy would grow more and for a relatively longer duration as compared to the base case (Figures 5 and 6). The GDP of the economy nearly doubles against the base case scenario while its peaking gets delayed. However, the four phases of growth and collapse remains the same. This shows that while

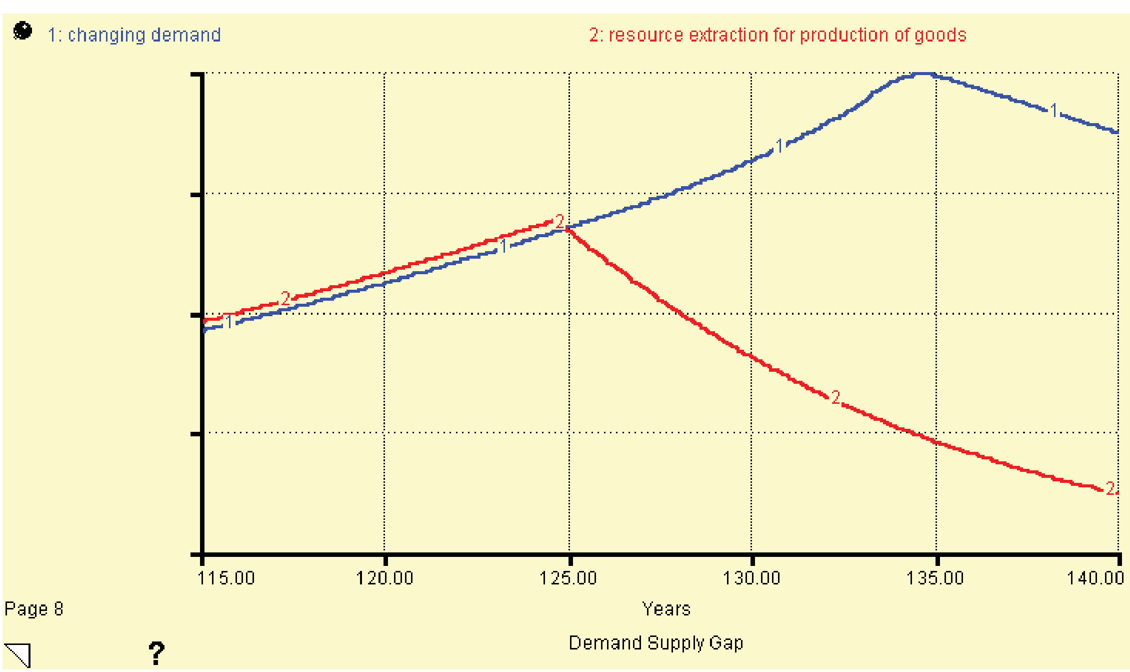

Figure 4: Demand Supply Gap and Demand Correction

Source: TERI Research

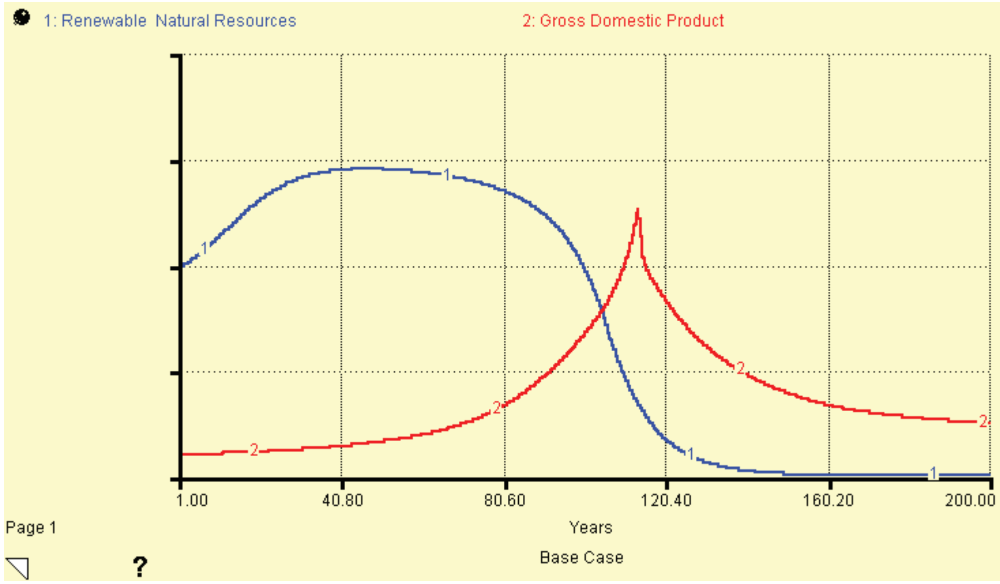

Figure 5: Base Run: Overshoot and Collapse
Source: TERI Research

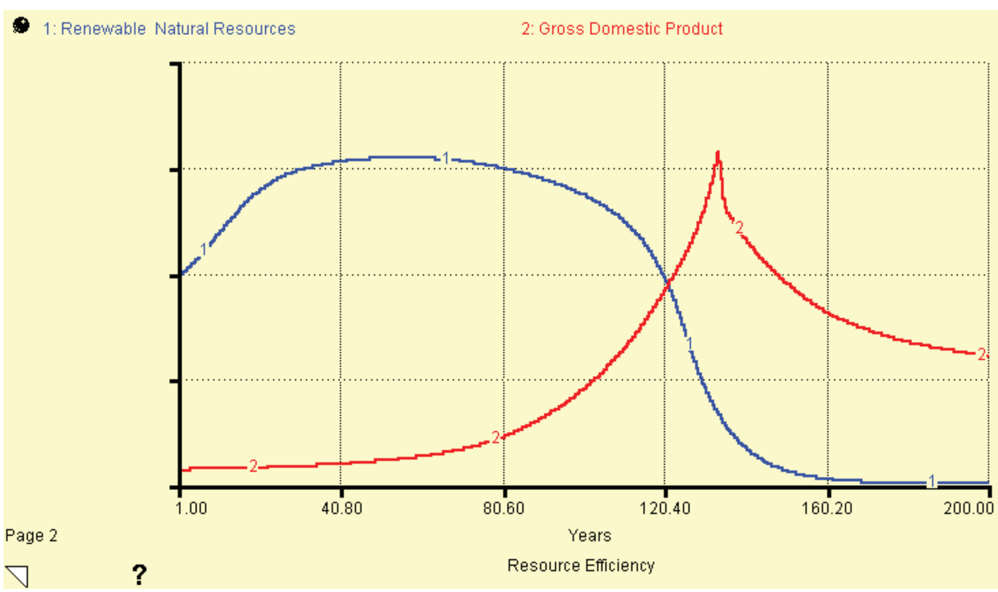

Figure 6: Policy Testing: Increasing Resource Efficiency
Source: TERI Research

improving resource efficiency of the economy is able to sustain growth for relatively longer time it still is unable to avoid the overshoot and fall in the economy.

Policy 2: Resource Regeneration/Restoration and Green Growth

Model Parameters for Testing Green Growth Policy
Economy's Constant Rate = 1% to 7%
Resource Intensity of Economy = reduced to 0.5 kg/rupee from 1 kg/rupee
Natural Resource Regeneration Rate = increased to 3% from 2%

The above scenario models outcomes of an intervention which, in addition to improving the resource efficiency, results into increase in the resource regeneration rate by 50%. This implies that the economy is actively involved in the resource restoration process. However, the carrying capacity of the resource remains the same. Thus, although the rate of regeneration increases, the maximum growth in stock of resources would remain the same. The simulation

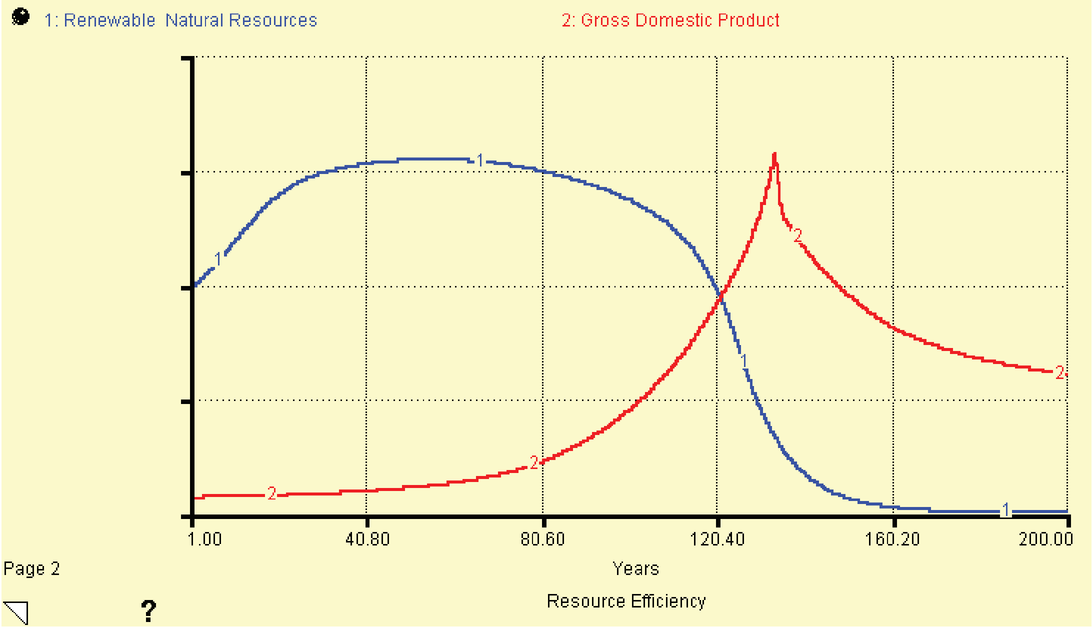

Figure 7: Resource Efficiency Scenario

Source: TERI Research

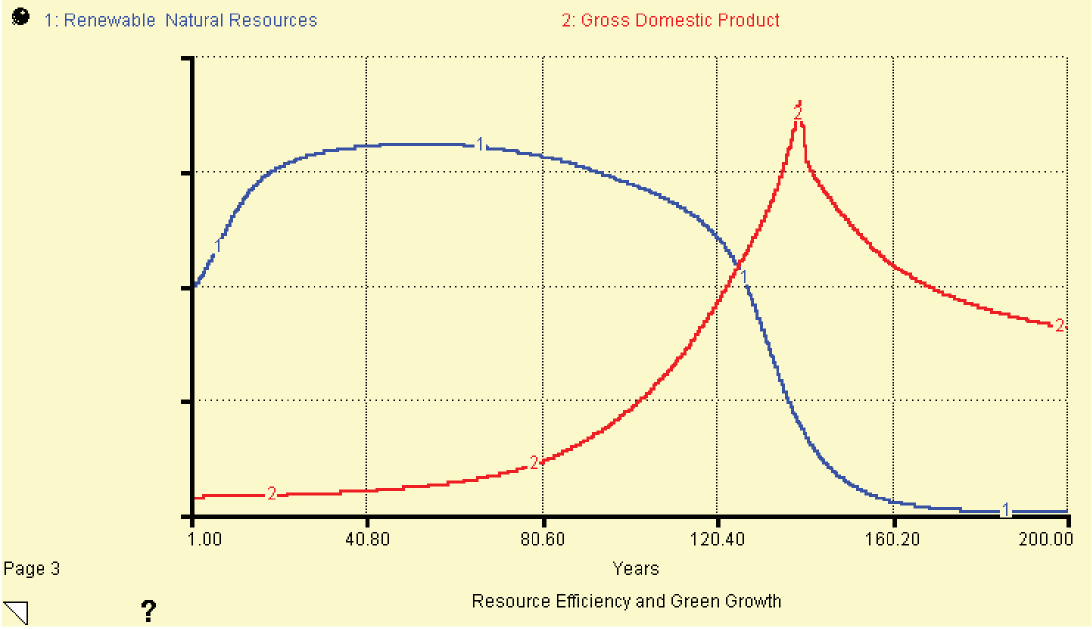

Figure 8: Policy Testing: Resource Efficiency and Green Growth

Source: TERI Research

results indicate that the economy would grow more and for a relatively longer duration (Figures 7 and 8). The GDP of the economy grows relatively more as compared to the resource efficiency scenario while the peaking is delayed by few years. However, the ultimate outcome remains the same, i.e., decline in resource stock and overshoot and decline of economy.

Policy 3: Expansion of Resource Base (technology advancements or new discoveries)

Model Parameters for Testing Expansion of Resource Base

Economy's Growth Rate = 1% to 7%

Resource Intensity of Economy = reduced to 0.5 kg/rupee from 1 kg/rupee

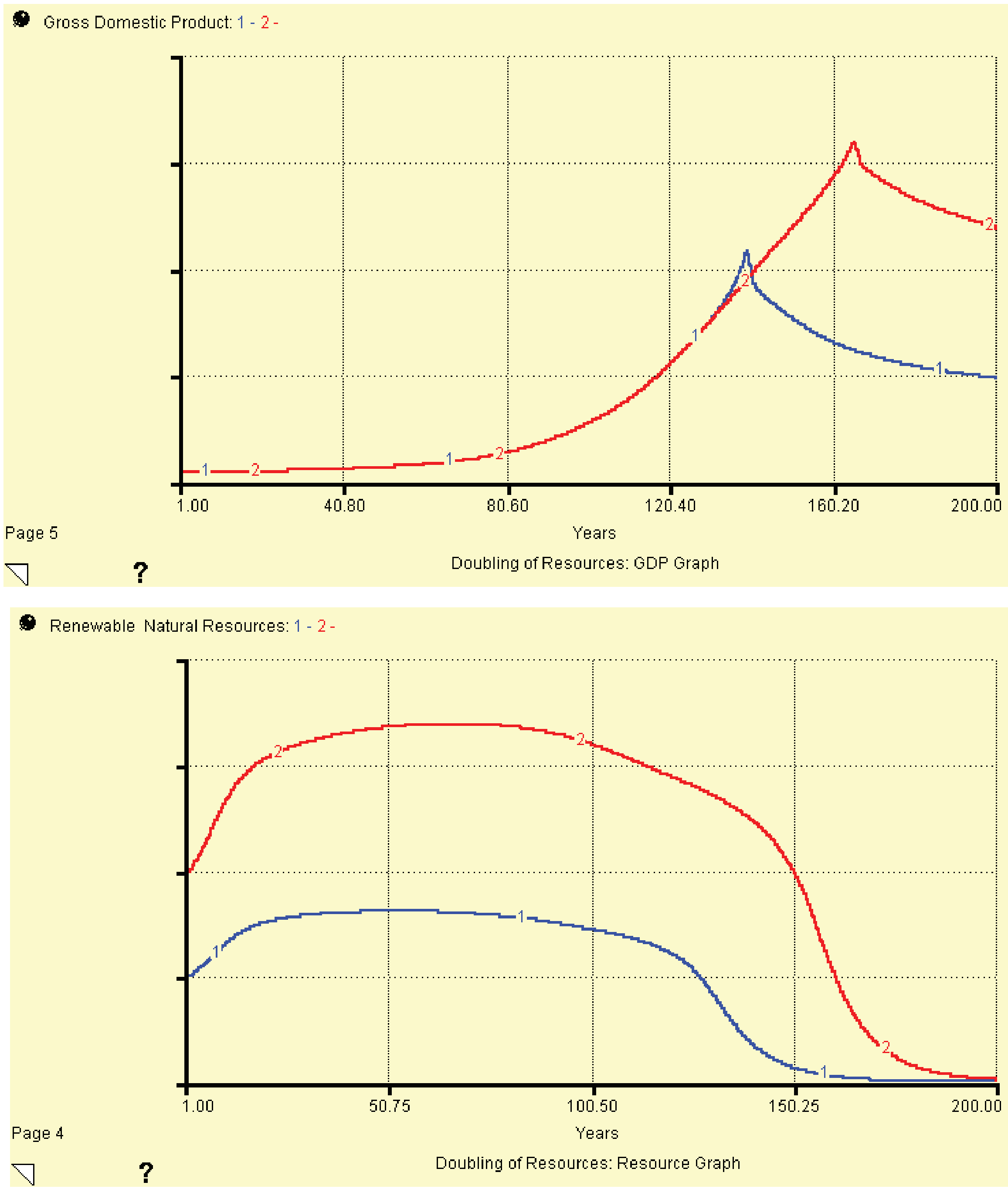

Figure 9: Policy Testing: Expanding Resource Base

Source: TERI Research

Natural Resource Regeneration Rate = increased to 3% from 2%
Initial Stock of Renewable Resource = increased to 2000 trillion kgs from 1000 trillion kgs

In this scenario, doubling of the initial resource stock (red line in the graph) is taken as the hypothesized case resulting from either a quantum leap in technology through continuous policy push towards new R&D initiatives or due to discovery of new resources. This results into increase in the availability of resource stock which also results in an increase in its carrying capacity. Through newer technological innovations/ developments or by identifying a new potential portfolio of resource for the economic growth, an economy is able to sustain its economic growth longer as compared to earlier policies (Figure 9). However, the ultimate outcome still

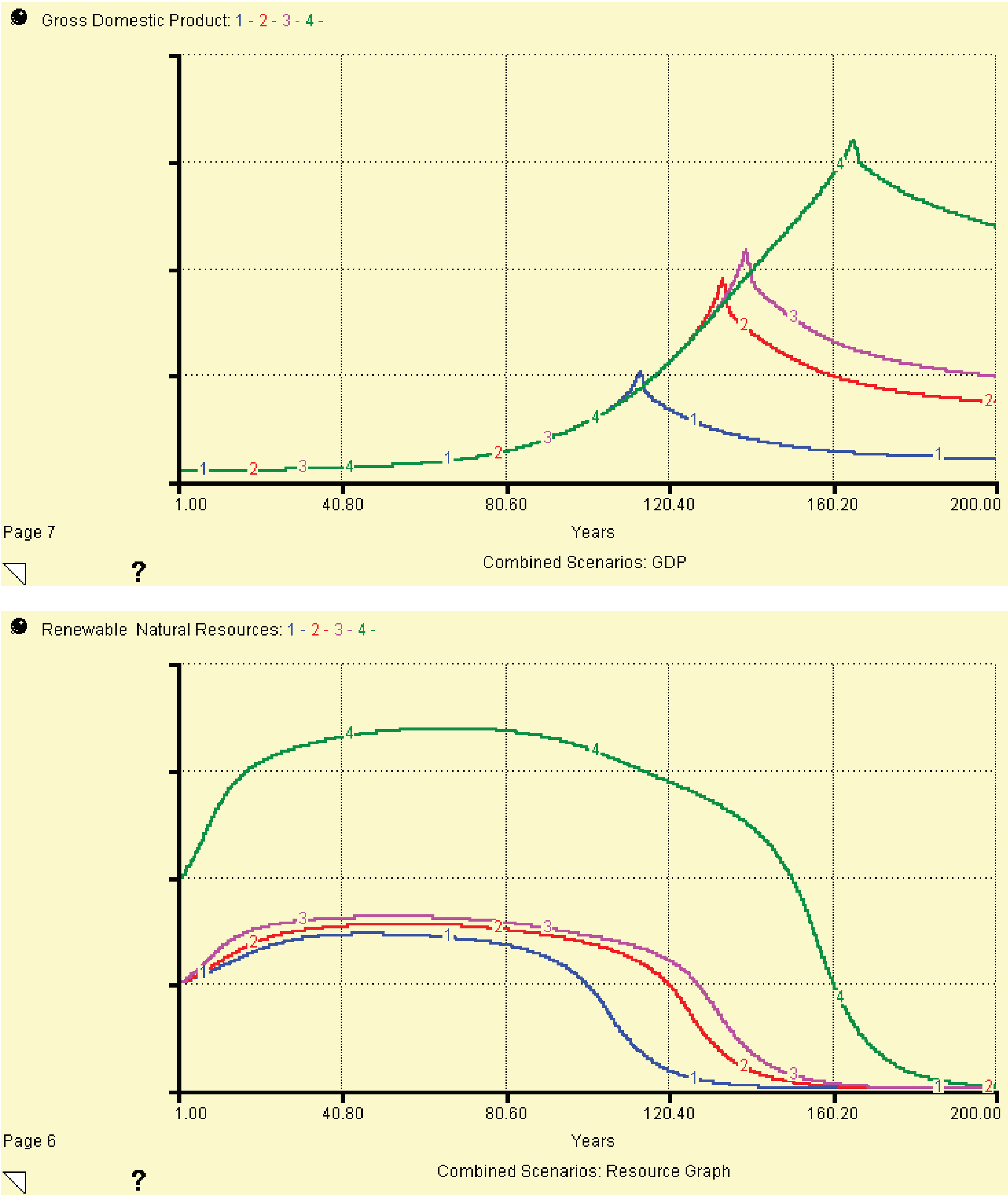

Figure 10: Combined Scenarios

Source: TERI Research

very much remains the same, i.e. fall in resource stock and overshoot and decline of economy. This shows that resource expansion into newer portfolio of options also fails to avoid overshoot. This would be applicable to a scenario even where resource base increases beyond twice its initial value till it has a carrying capacity.

Conclusion

Our model is successful in testing the impact policy choices have on the resources and economy. It also proves our postulates correct. The four stages of growth and collapse hold true even under conditions of improved efficiency, green growth and expanded resource base due to technology advancements.

This indicates that the issue of limits to economic growth is not primarily due to limited resource base or inefficient resource extraction. As long as the economy grows and its resource consumption exceeds the regeneration, over a period of time the resources would deplete. A peak and decline in economy then is an inevitable outcome under any scenario (Figure 10).

The following are the insights derived from this model which help develop a theoretical understanding on the key dynamics responsible for causing the counterintuitive outcomes:

- The stock of resources has a carrying capacity beyond which it cannot grow while there is no carrying capacity of the economy to restrict its own growth.
- If the rate of resource extraction/consumption is more than the regeneration rate of the resources, over a period of time the resource stock will deplete.
- The resource regeneration flows depend on the stock of resources. A continued reduction in resource stock would push the resource towards its threshold level beyond which it would not be able to regenerate itself making the renewable resource behave like non-renewable resource.

If a dynamic equilibrium[5] between the resources and economy is to be achieved then the natural resource consumption rates will have to be moderated through economic policies. At present there are hardly any existing examples in the policy discourse which may have considered reducing the consumption as a measure to achieve the balance between the economy and the resources. In this respect empirical studies, aimed at finding real world solutions, would need to be done based on the theoretical construct that this paper offers. The research could focus on the following questions to improve the body of knowledge using which solutions could be deliberated upon.

- How to identify the threshold levels of natural resources/ ecosystems, on which key economic sectors depend, beyond which the resources can not repair/regenerate themselves?
- What interventions can prevent breaching these thresholds?
- How such interventions could be tested and incorporated into policies to make the economy more proactive?

The Way Forward

The real world complexity of resource regeneration dynamics and economic growth poses serious challenges for policy making. This paper demonstrates this complexity in a simplified manner. However, further empirical research followed up with deliberations on the nature of policies to sustain resources and economy needs to be done. A safe environment where such policies could be tested should be created. Computer modelling techniques which can model complex systems should be used to test policy assumptions. This could make the policymakers aware of some of the side effects or unintended consequences of the proposed policies. A conscious effort of managing consumption in a way to allow the stocks of renewable resources to regenerate, before their decline becomes irreversible, should be made. Designed economic contraction to provide adequate time for renewable resources to regenerate and increase their stock levels could be considered as an option to avoid the overshoot and fall of economy and resources. This of course calls for further research in modelling the dynamics of growth-degrowth of economies and its implications on renewable resources.

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[5] A state of balance between changing processes

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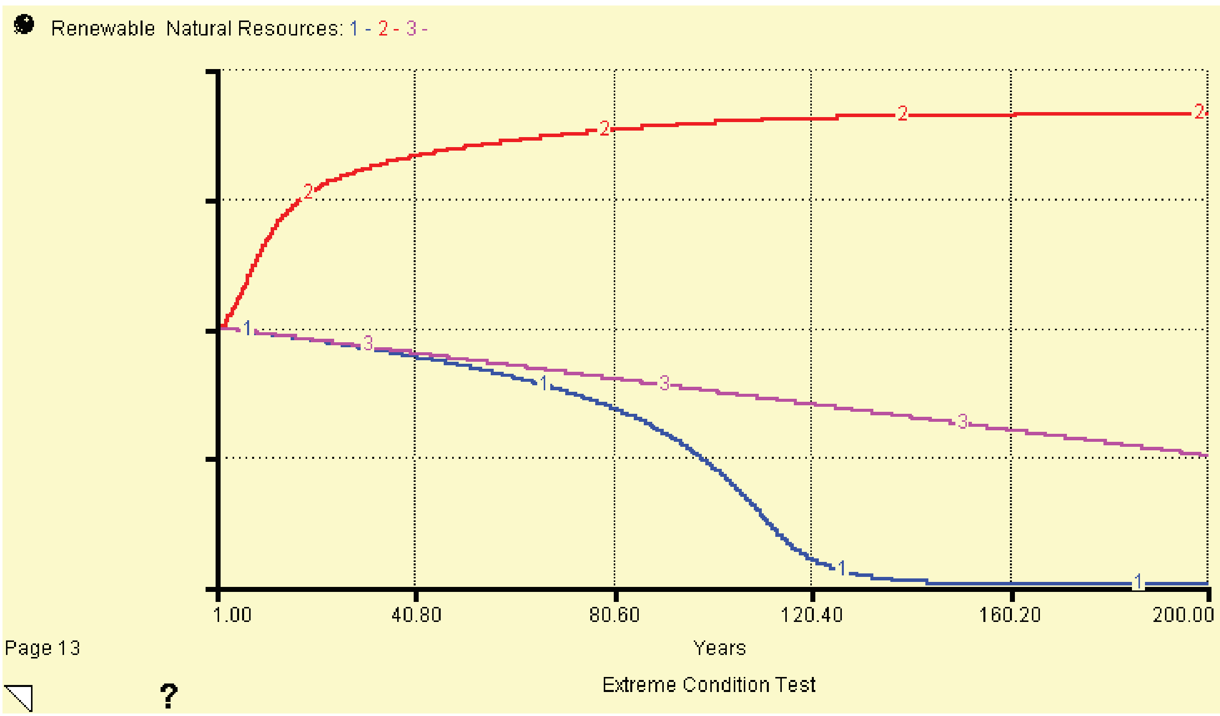
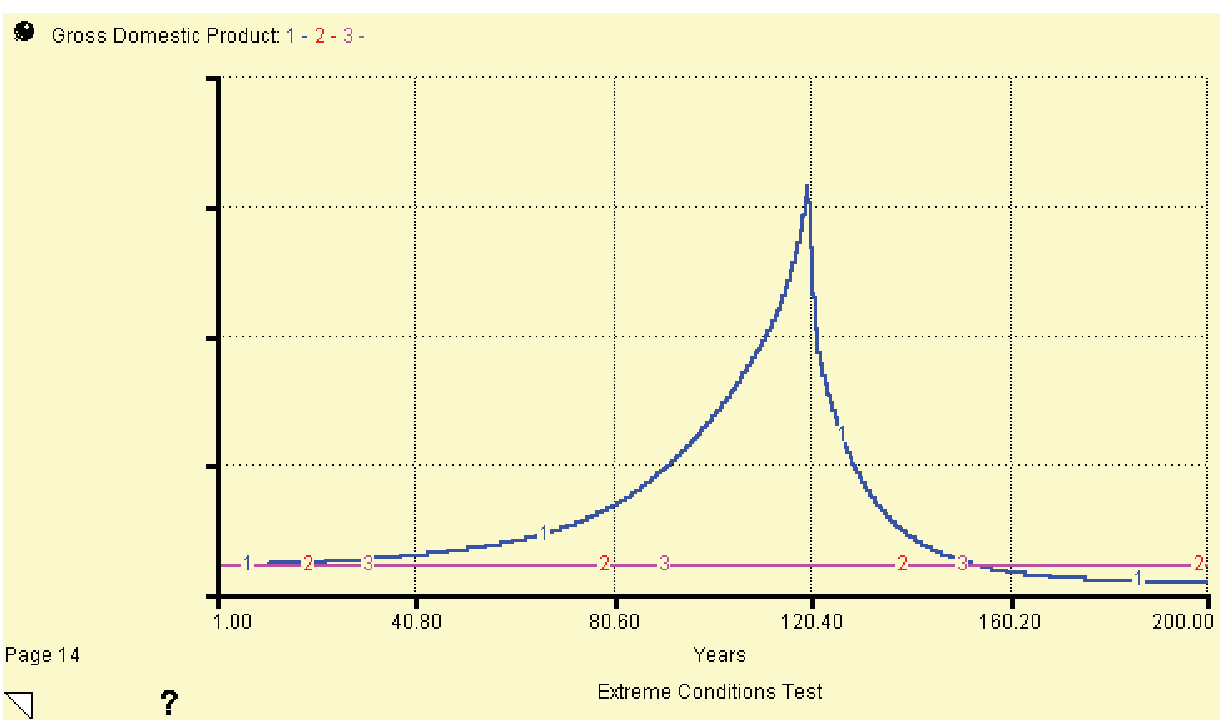
Annexure

Extreme Condition Tests

Parameters

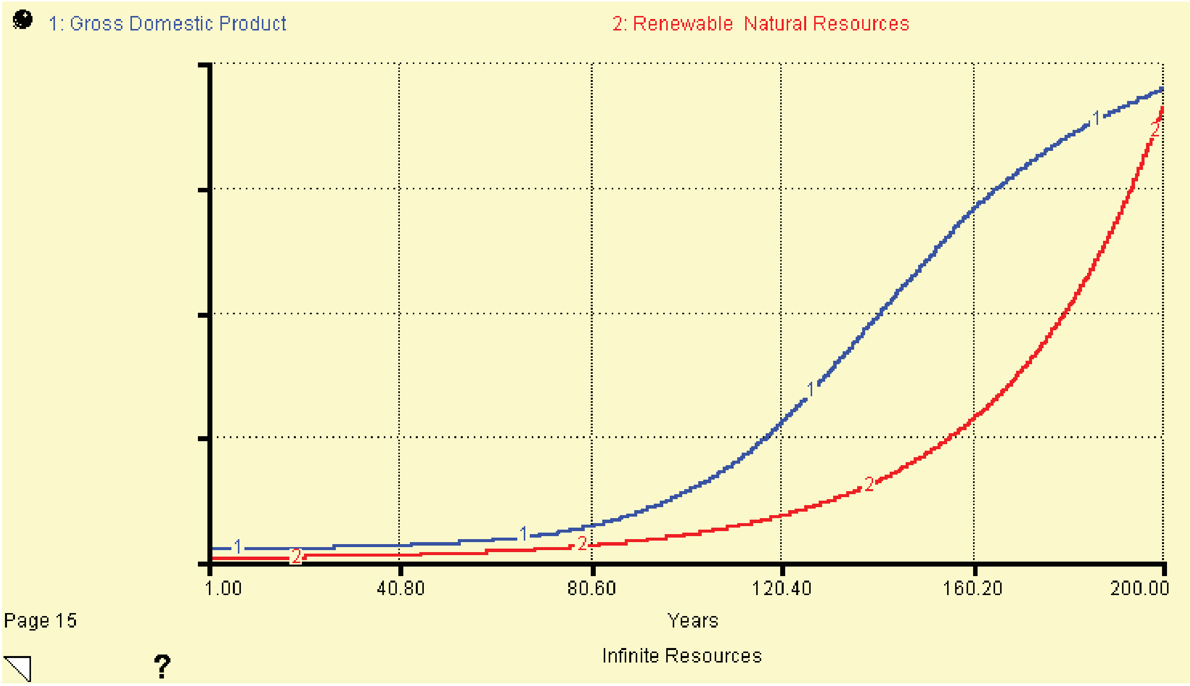
1 Natural Resource Regeneration Rate = 0
2 Constant Economic Growth Rate = 0
3 Regeneration Rate and Economic Growth Rate = 0





Infinite Renewable Resources

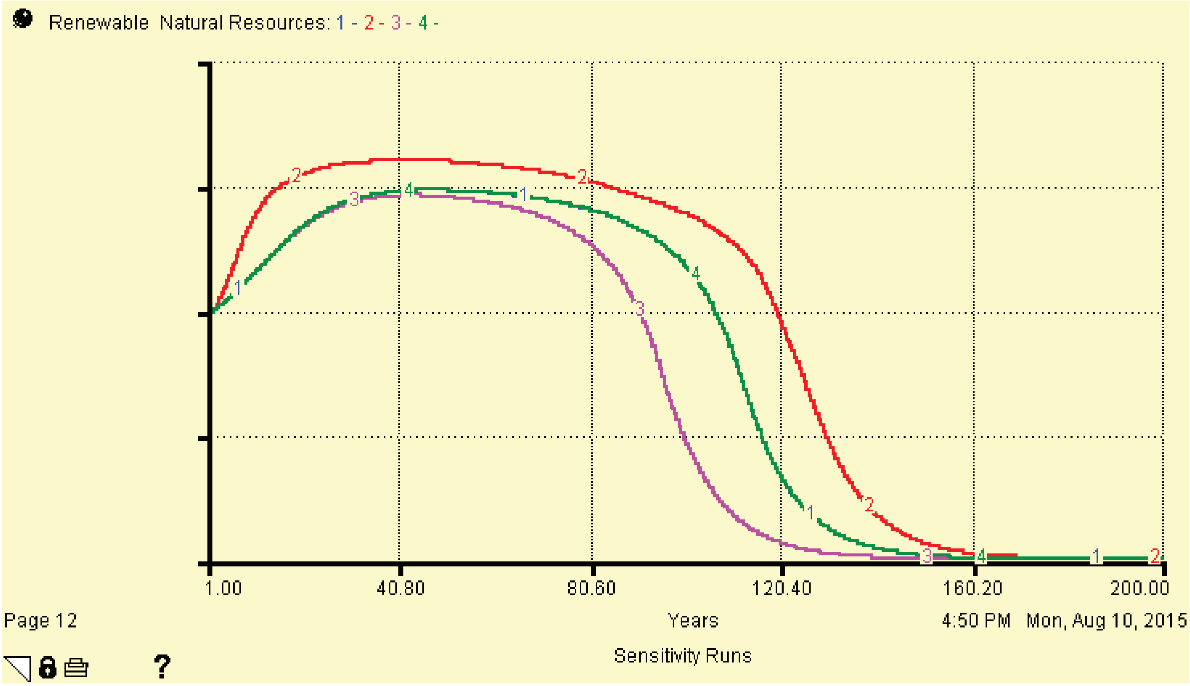
No carrying capacity constraints and no irreversibility of regeneration rate.

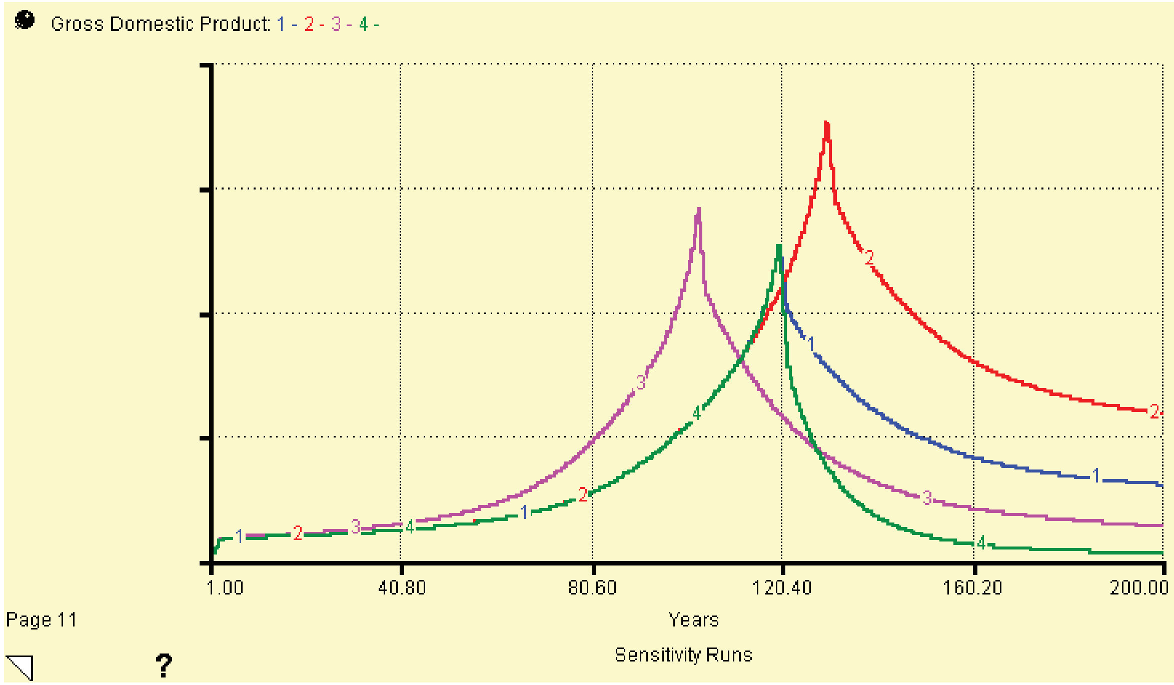


Sensitivity Runs

Parameters

1 Base Run
2 Increased Regeneration Rate from 2% to 4%
3 Increased Economic Growth range 2% to 8%
4 Increased intensity of Inflation and Demand Contraction





Model Equations

STELLA VERSION 10.0.6.
STARTTIME=1, STOPTIME=200, DT=0.1,
INTEGRATION=RK4, RUNMODE=NORMAL,
PAUSEINTERVAL=INF
: S = STOCK, : f = flow, : c = Converter, : b = biflow

INITIAL EQUATIONS

1) : S Capital_with_Producers = 10000000000

UNITS: rupees

DOCUMENT: This is the stock of capital with producers. It is assumed to be ₹1,000 cr.

2) : S Capital_with_Sellers = 5000000000

UNITS: rupees

DOCUMENT: This is the initial stock of capital with sellers. Assumed to be ₹500 cr.

3) : S Renewable__Natural_Resources = 1000000000000

UNITS: kilograms (kg)

DOCUMENT: This is the initial stock of renewable natural resources relevant for producing goods. Initial value is kept at 1,000 million tons. Its carrying capacity is kept at double its initial size i.e., 2,000 million tons.

4) : S Wealth_with_Households = 5000000000

UNITS: rupees

DOCUMENT: This is the initial stock of money with households. Assumed to be ₹500 cr.

5) : c resource_intensity_of_economy = 1

UNITS: kilograms/rupees

DOCUMENT: Resource intensity is a measure of the resources needed for the production and processing of a unit of good or service, or for the completion of a process or activity; it is therefore a measure of the efficiency of resource use. In this case the resource intensity is expressed as % of money flow. It can be changed using slide bars for policy testing.

6) : c total_spending_fraction = 1

UNITS: per year (1/yr)

DOCUMENT: The total spending fraction is assumed to be 1, i.e., 100%. The stocks of wealth i.e. difference between income and expenditure, represent the savings in the economy.

7) : f payments_by_households_to_producers_for_purchase _of_goods = (Wealth_with_Households*total_spending_fraction)

UNITS: rupees/yr

DOCUMENT: Payments made by households for purchase of goods from producer.

8) : f payment_by_sellers_to_producers_for_procurement_of_goods = Capital_with_Sellers*total_spending_fraction

UNITS: rupees/yr

DOCUMENT: Payments made by sellers for procurement of goods from producer.

9) :f changing_demand = ((payment_by_sellers_to_producers_for_procurement_of_goods+payments_by_households_to_producers_for_purchase_of_goods)*(resource_intensity_of_economy))

UNITS: kg/yr

DOCUMENT: Flow of physical demand for goods in the economy. It is a function of payments made multiplied by the resource intensity.

10) :f payments_by_producers_to_households_as_cost_of_production = Capital_with_Producers*total_spending_fraction

UNITS: rupees/yr

DOCUMENT: This is the flow of capital being utilized as payments to households for production of goods. It comprises of Labor and Capital costs.

11) : f resource_extraction_for_production_of_goods = MIN(Renewable__Natural_Resources*.1, resource_intensity_of_economy*payments_by_producers_to_households_as_cost_of_production)

UNITS: kg/yr

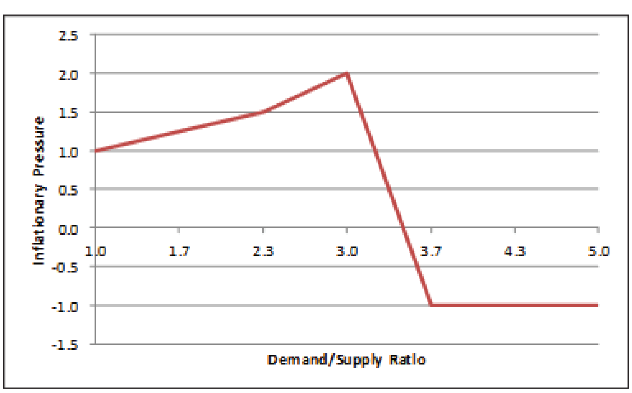
DOCUMENT: Flow of resources being extracted for production of goods. The extraction is a function of payments for cost of production multiplied by resource intensity of economy. Maximum extraction possible at any given time is kept at 10% of the total stock.

12) : c ratio_of_demand_and_supply = changing_demand/resource_extraction_for_production_of_goods

UNITS: Unitless

DOCUMENT: This is the ratio of demand and supply. Ratio of more than 1 indicates demand more than supply depicting shortage of supply of goods.

13) : c impact_of_demand_supply_ratio_on_economic_growth = GRAPH(ratio_of_demand_and_supply)

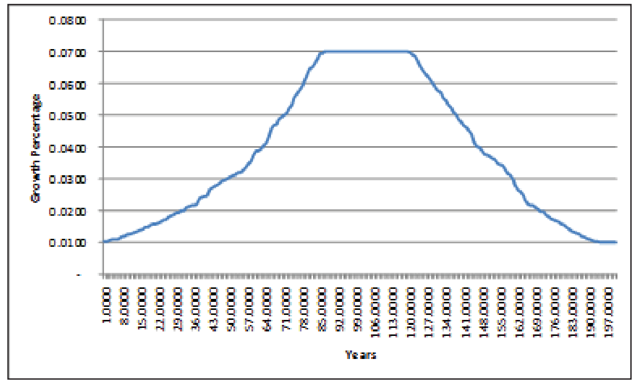


(1, 1), (1.7, 1.3), (2.3, 1.5), (3, 2), (3.7, -1), (4.3, -1), (5, -1)

UNITS: Unitless

DOCUMENT: As the ratio increases beyond 1, there is inflationary pressure depicting increase in prices. The demand does not correct till inflationary pressure reaches a multiplier of 2. After this demand correction happens as shown through the negative figures.

14) : c economy's_growth_percentage = GRAPH(TIME)



(1, 0.0102), (2, 0.0104), (3, 0.0106), (4, 0.0108), (5, 0.0108), (6, 0.011), (7, 0.0114), (8, 0.0118), (9, 0.012), (10, 0.0125), (11, 0.0127), (12, 0.0129), (13, 0.0133), (14, 0.0137), (15, 0.0139), (16, 0.0143), (17, 0.0147), (18, 0.0147), (19, 0.0153), (20, 0.0157), (21, 0.0159), (22, 0.0161), (23, 0.0166), (24, 0.017), (25, 0.0172), (26, 0.018), (27, 0.0184), (28, 0.0188), (29, 0.0192), (30, 0.0194), (31, 0.02), (32, 0.02), (33, 0.0209), (34, 0.0213), (35, 0.0215), (36, 0.0217), (37, 0.0221), (38, 0.0237), (39, 0.0243), (40, 0.0245), (41, 0.0245), (42, 0.0268), (43, 0.0272), (44, 0.0278), (45, 0.028), (46, 0.0286), (47, 0.0295), (48, 0.0297), (49, 0.0301), (50, 0.0307), (51, 0.0309), (52, 0.0313), (53, 0.0318), (54, 0.0319), (55, 0.0325), (56, 0.0335), (57, 0.0346), (58, 0.0356), (59, 0.0372), (60, 0.0387), (61, 0.0389), (62, 0.0393), (63, 0.0403), (64, 0.0413), (65, 0.043), (66, 0.0458), (67, 0.0467), (68, 0.0471), (69, 0.0489), (70, 0.0495), (71, 0.0499), (72, 0.0505), (73, 0.052), (74, 0.0534), (75, 0.0557), (76, 0.0569), (77, 0.0579), (78, 0.0589), (79, 0.0608), (80, 0.063), (81, 0.0645), (82, 0.0651), (83, 0.0663), (84, 0.0677), (85, 0.0694), (86, 0.0696), (87, 0.07), (88, 0.07), (89, 0.07), (90, 0.07), (91, 0.07), (92, 0.07), (93, 0.07), (94, 0.07), (95, 0.07), (96, 0.07), (97, 0.07), (98, 0.07), (99, 0.07), (100, 0.07), (101, 0.07), (102, 0.07), (103, 0.07), (104, 0.07), (105, 0.07), (106, 0.07), (107, 0.07), (108, 0.07), (109, 0.07), (110, 0.07), (111, 0.07), (112, 0.07), (113, 0.07), (114, 0.07), (115, 0.07), (116, 0.07), (117, 0.07), (118, 0.07), (119, 0.07), (120, 0.0698), (121, 0.0692), (122, 0.0684), (123, 0.0671), (124, 0.0651), (125, 0.0643), (126, 0.063), (127, 0.0624), (128, 0.0612), (129, 0.0602), (130, 0.0585), (131, 0.0579), (132, 0.0571), (133, 0.0555), (134, 0.0544), (135, 0.0532), (136, 0.0522), (137, 0.0512), (138, 0.0501), (139, 0.0487), (140, 0.0479), (141, 0.0469), (142, 0.046), (143, 0.0452), (144, 0.0438), (145, 0.0415), (146, 0.0401), (147, 0.04), (148, 0.0387), (149, 0.0376), (150, 0.0375), (151, 0.037), (152, 0.0366), (153, 0.0362), (154, 0.0348), (155, 0.0346), (156, 0.0342), (157, 0.0331), (158, 0.0315), (159, 0.0313), (160, 0.0301), (161, 0.028), (162, 0.0266), (163, 0.0262), (164, 0.0247), (165, 0.0231), (166, 0.0221), (167, 0.0217), (168, 0.0215), (169, 0.0209), (170, 0.0202), (171, 0.0198), (172, 0.0196), (173, 0.0188), (174, 0.018), (175, 0.0174), (176, 0.0172), (177, 0.0168), (178, 0.0163), (179, 0.0159), (180, 0.0153), (181, 0.0147), (182, 0.0143), (183, 0.0137), (184, 0.0133), (185, 0.0129), (186, 0.0125), (187, 0.012), (188, 0.0116), (189, 0.0112), (190, 0.0108), (191, 0.0106), (192, 0.0104), (193, 0.0102), (194, 0.01), (195, 0.01), (196, 0.01), (197, 0.01), (198, 0.01), (199, 0.01), (200, 0.01)

UNITS: Unitless

DOCUMENT: This is the growth curve of economy. The economic development undergoes different stages of growth starting from traditional economy having high growth rates and reaching full prosperity having very low growth rates.

15) : b expansion_and_contraction_in_capital = Capital_with_Producers*economy's_growth_percentage*impact_of_demand_supply_ratio_on_economy

UNITS: rupees/yr

DOCUMENT: This is the flow of growth or contraction in the wealth of the economy. Growth happens when inflationary pressure is 1 and economy is growing at constant growth rate. Growth accelerates when inflationary pressure rises and contracts when demand correction happens in response to inflation.

16) : f payment_by_sellers_to_households_for_labor_and_capital = Capital_with_Sellers*total_spending_fraction

UNITS: rupees/yr

DOCUMENT: Payments made by sellers to households against labor and capital.

17) : f payment_by_households_to_sellers_for_purchase_of_goods = Wealth_with_Households*total_spending_fraction

UNITS: rupees/yr

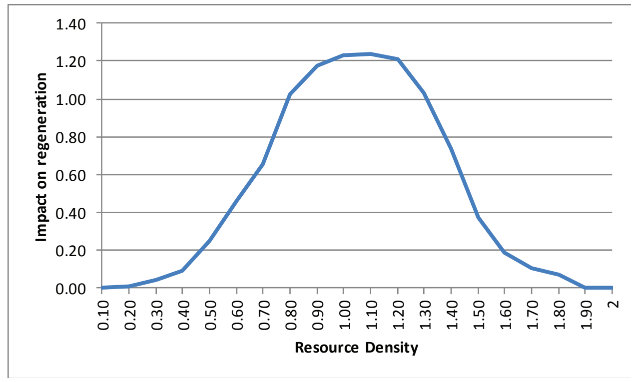
DOCUMENT: Payments made by households for purchase of goods from sellers.

18) : c resource_density = Renewable__Natural_Resources/INIT (Renewable__Natural_Resources)

UNITS: Unitless

DOCUMENT: This is the density of natural resources as against its initial value.

19) : c impact_of_resource_density_on_regeneration_rate = GRAPH(resource_density)



(0.1, 0), (0.2, 0.0127986348123), (0.3, 0.042662116041), (0.4, 0.089590443686), (0.5, 0.251706484642), (0.6, 0.460750853242), (0.7, 0.656996587031), (0.8, 1.02815699659), (0.9, 1.17320819113), (1, 1.23293515358), (1.1, 1.23720136519), (1.2, 1.20733788396), (1.3, 1.03242320819), (1.4, 0.733788395904), (1.5, 0.37542662116), (1.6, 0.18771331058), (1.7, 0.106655290102), (1.8, 0.0682593856655), (1.9, 0), (2, 0)

UNITS: Unitless

DOCUMENT: This shows the impact of resource density on regeneration of resources. If resource density falls or grows to reach its carrying capacity then the regeneration approaches zero. It is in between these two stages that growth happens and even accelerates at certain times.

20) : c normal_regeneration_rate = 0.02

UNITS: per year (1/yr)

DOCUMENT: It is assumed that the normal regeneration rate of natural resources is 2% per year.

21) : c natural_resource_regeneration_intervention = 0

UNITS: Unitless

DOCUMENT: This shows whether policy to regenerate resource base is active or not. Use switch in the interface layer. 0=not active, 1=active.

22) : c green_growth_multiplier = IF natural_resource_regeneration_intervention=1 then 1.5 else 1

UNITS: Unitless

DOCUMENT: If the economy has interventions which help regenerate resources then the growth rate of resources will go up by 50%.

23) : c regeneration_rate = green_growth_multiplier*normal_regeneration_rate

UNITS: per year (1/yr)

DOCUMENT: Actual regeneration rate after considering the impact of green growth multiplier.

24) : f regeneration_of_resources = regeneration_rate*impact_of_resource_density_on_regeneration_rate*Renewable__Natural_Resources

UNITS: kg/yr

DOCUMENT: This is the flow of regeneration of resources. Its rate of regeneration gets impacted by its resource density.

25) : c Gross_Domestic_Product = growth_and_contraction__in_GDP + payments_by_producers_to_households_as_cost_of_production

UNITS: rupees/yr

DOCUMENT: Gross Domestic Product of the Economy

Runtime Equations

: S Capital_with_Sellers(t) = Capital_with_Sellers(t - dt) + (payment_by_households_to_sellers_for_purchase_of_goods - payment_by_sellers_to_households_for_labor_and_capital - payment_by_sellers_to_producers_for_procurement_of_goods) * dt

UNITS: rupees

: S Wealth_with_Households(t) = Wealth_with_Households(t - dt) + (payment_by_sellers_to_households_for_labor_and_capital + payments_by_producers_to_households_as_cost_of_production - payment_by_households_to_sellers_for_purchase_of_goods - payments_by_households_to_producers_for_purchase_of_goods) * dt

UNITS: rupees

: S Capital_with_Producers(t) = Capital_with_Producers(t - dt) + (growth_and_contraction__in_GDP + payment_by_sellers_to_producers_for_procurement_of_goods + payments_by_households_to_producers_for_purchase_of_goods - payments_by_producers_to_households_as_cost_of_production) * dt

UNITS: rupees

: S Renewable__Natural_Resources(t) = Renewable__Natural_Resources(t - dt) + (regeneration_of_resources - resource_extraction_for_production_of_goods) * dt

UNITS: kilograms (kg)

: s Accumulated_Demand(t) = Accumulated_Demand(t - dt) + (changing_demand) * dt

UNITS: kilograms (kg)

: f payment_by_sellers_to_producers_for_procurement_of_goods = Capital_with_Sellers*total_spending_fraction

UNITS: rupees/yr

: f payments_by_households_to_producers_for_purchase_of_goods = (Wealth_with_Households*total_spending_fraction)

UNITS: rupees/yr

: f changing_demand = ((payment_by_sellers_to_producers_for_procurement_of_goods+payments_by_households_to_producers_for_purchase_of_goods)*(resource_intensity_of_economy))

UNITS: kg/yr

: c economy's_growth_percentage = GRAPH(TIME)

(1, 0.0102), (2, 0.0104), (3, 0.0106), (4, 0.0108), (5, 0.0108), (6, 0.011), (7, 0.0114), (8, 0.0118), (9, 0.012), (10, 0.0125), (11, 0.0127), (12, 0.0129), (13, 0.0133), (14, 0.0137), (15, 0.0139), (16, 0.0143), (17, 0.0147), (18, 0.0147), (19, 0.0153), (20, 0.0157), (21, 0.0159), (22, 0.0161), (23, 0.0166), (24, 0.017), (25, 0.0172), (26, 0.018), (27, 0.0184), (28, 0.0188), (29, 0.0192), (30, 0.0194), (31, 0.02), (32, 0.02), (33, 0.0209), (34, 0.0213), (35, 0.0215), (36, 0.0217), (37, 0.0221), (38, 0.0237), (39, 0.0243), (40, 0.0245), (41, 0.0245), (42, 0.0268), (43, 0.0272), (44, 0.0278), (45, 0.028), (46, 0.0286), (47, 0.0295), (48, 0.0297), (49, 0.0301), (50, 0.0307), (51, 0.0309), (52, 0.0313), (53, 0.0318), (54, 0.0319), (55, 0.0325), (56, 0.0335), (57, 0.0346), (58, 0.0356), (59, 0.0372), (60, 0.0387), (61, 0.0389), (62, 0.0393), (63, 0.0403), (64, 0.0413), (65, 0.043), (66, 0.0458), (67, 0.0467), (68, 0.0471), (69, 0.0489), (70, 0.0495), (71, 0.0499), (72, 0.0505), (73, 0.052), (74, 0.0534), (75, 0.0557), (76, 0.0569), (77, 0.0579), (78, 0.0589), (79, 0.0608), (80, 0.063), (81, 0.0645), (82, 0.0651), (83, 0.0663), (84, 0.0677), (85, 0.0694), (86, 0.0696), (87, 0.07), (88, 0.07), (89, 0.07), (90, 0.07), (91, 0.07), (92, 0.07), (93, 0.07), (94, 0.07), (95, 0.07), (96, 0.07), (97, 0.07), (98, 0.07), (99, 0.07), (100, 0.07), (101, 0.07), (102, 0.07), (103, 0.07), (104, 0.07), (105, 0.07), (106, 0.07), (107, 0.07), (108, 0.07), (109, 0.07), (110, 0.07), (111, 0.07), (112, 0.07), (113, 0.07), (114, 0.07), (115, 0.07), (116, 0.07), (117, 0.07), (118, 0.07), (119, 0.07), (120, 0.0698), (121, 0.0692), (122, 0.0684), (123, 0.0671), (124, 0.0651), (125, 0.0643), (126, 0.063), (127, 0.0624), (128, 0.0612), (129, 0.0602), (130, 0.0585), (131, 0.0579), (132, 0.0571), (133, 0.0555), (134, 0.0544), (135, 0.0532), (136, 0.0522), (137, 0.0512), (138, 0.0501), (139, 0.0487), (140, 0.0479), (141, 0.0469), (142, 0.046), (143, 0.0452), (144, 0.0438), (145, 0.0415), (146, 0.0401), (147, 0.04), (148, 0.0387), (149, 0.0376), (150, 0.0375), (151, 0.037), (152, 0.0366), (153, 0.0362), (154, 0.0348), (155, 0.0346), (156, 0.0342), (157, 0.0331), (158, 0.0315), (159, 0.0313), (160, 0.0301), (161, 0.028), (162, 0.0266), (163, 0.0262), (164, 0.0247), (165, 0.0231), (166, 0.0221), (167, 0.0217), (168, 0.0215), (169, 0.0209), (170, 0.0202), (171, 0.0198), (172, 0.0196), (173, 0.0188), (174, 0.018), (175, 0.0174), (176, 0.0172), (177, 0.0168), (178, 0.0163), (179, 0.0159), (180, 0.0153), (181, 0.0147), (182, 0.0143), (183, 0.0137), (184, 0.0133), (185, 0.0129), (186, 0.0125), (187, 0.012), (188, 0.0116), (189, 0.0112), (190, 0.0108), (191, 0.0106), (192, 0.0104), (193, 0.0102), (194, 0.01), (195, 0.01), (196, 0.01), (197, 0.01), (198, 0.01), (199, 0.01), (200, 0.01)

UNITS: Unitless

: f payments_by_producers_to_households_as_cost_of_production = Capital_with_Producers*total_spending_fraction

UNITS: rupees/yr

: f resource_extraction_for_production_of_goods = MIN(Renewable__Natural_Resources*.1, resource_intensity_of_economy*payments_by_producers_to_households_as_cost_of_production)

UNITS: kg/yr

: c ratio_of_demand_and_supply = changing_demand/resource_extraction_for_production_of_goods

UNITS: Unitless

: c impact_of_demand_supply_ratio_on_economic_growth = GRAPH(ratio_of_demand_and_supply)

(1, 1), (1.7, 1.3), (2.3, 1.5), (3, 2), (3.7, -1), (4.3, -1), (5, -1)

UNITS: Unitless

: b growth_and_contraction__in_GDP = Capital_with_Producers*economy's_growth_percentage*impact_of_demand_supply_ratio_on_economic_growth

UNITS: rupees/yr

: f payment_by_households_to_sellers_for_purchase_of_goods = Wealth_with_Households*total_spending_fraction

UNITS: rupees/yr

: f payment_by_sellers_to_households_for_labor_and_capital = Capital_with_Sellers*total_spending_fraction

UNITS: rupees/yr

: c green_growth_multiplier = IF natural_resource_regeneration_intervention=1 then 1.5 else 1

UNITS: Unitless

: c regeneration_rate = green_growth_multiplier*normal_regeneration_rate

UNITS: per year (1/yr)

: c resource_density = Renewable__Natural_Resources/INIT (Renewable__Natural_Resources)

UNITS: Unitless

: c impact_of_resource_density_on_regeneration_rate = GRAPH(resource_density)

(0.1, 0), (0.2, 0.0127986348123), (0.3, 0.042662116041), (0.4, 0.089590443686), (0.5, 0.251706484642), (0.6, 0.460750853242), (0.7, 0.656996587031), (0.8, 1.02815699659), (0.9, 1.17320819113), (1, 1.23293515358), (1.1, 1.23720136519), (1.2, 1.20733788396), (1.3, 1.03242320819), (1.4, 0.733788395904), (1.5, 0.37542662116), (1.6, 0.18771331058), (1.7, 0.106655290102), (1.8, 0.0682593856655), (1.9, 0), (2, 0)

UNITS: Unitless

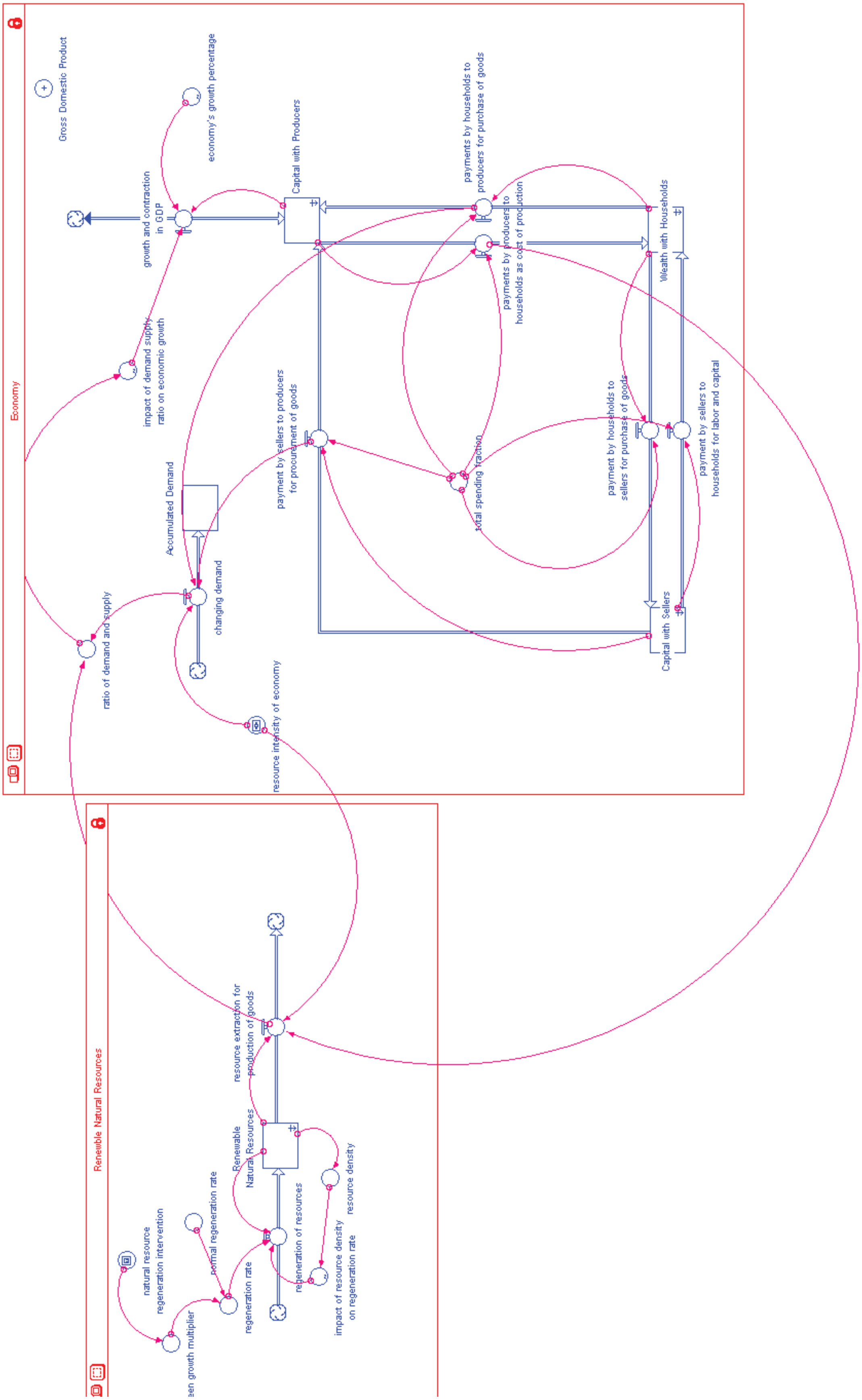
: f regeneration_of_resources = regeneration_rate*Renewable__Natural_Resources*impact_of_resource_density_on_regeneration_rate

UNITS: kg/yr

: c Gross_Domestic_Product = growth_and_contraction__in_GDP + payments_by_producers_to_households_as_cost_of_production

UNITS: rupees/yr

Full Model Structure



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The Energy and Resources Institute

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