3 Causal Loop Diagrams

The concept of causal loop diagram was introduced in Chap. 2, and this chapter presents concepts, methodology and techniques of causal loop diagrams. The cause–effect relationships and reinforcing and balancing loops are highlighted with examples. Steps to construct causal loop diagrams are provided. A good number of worked out examples are included to illustrate the techniques of constructing causal loop diagrams for dynamic systems.

3.1 Introduction

System dynamics methodology is based on feedback concepts of control theory, and causal loop is a convenient way to represent the feedback loop structure of systems. Causal loop diagram is used to represent the feedback loop systems diagrammatically, and it is a communication tool of feedback structure representing the principal feedback loops of the systems which generate the reference dynamic behaviour of the systems.

3.2 Causal Loop Diagrams

Causal loop diagrams identify the principal feedback loops of the systems. The causal loop diagrams are used to describe basic causal mechanisms hypothesised to generate the reference mode of behaviour of the system over time. A feedback loop contains two or more casualty related variables that close back on themselves. The relationship between one variable and next in the loop can be either positive or negative. A positive relationship means that if one variable increases, the other also increases. For example, in Fig. 3.1 the arrow from A to B means that an increase in A causes an increase in B. It can also mean if A decreases, B will also decrease. The arrow starting from A and terminating at B with a (+) sign at the end of the arrow means the cause–effect relationship is positive. In a negative relationship, the two

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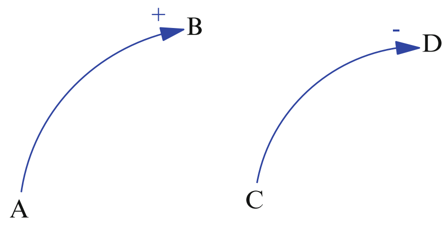

Fig. 3.1 Cause and effect relationships

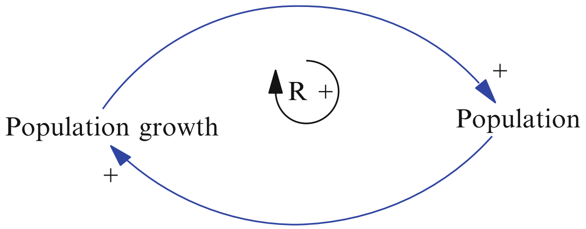

Fig. 3.2 Positive feedback loop

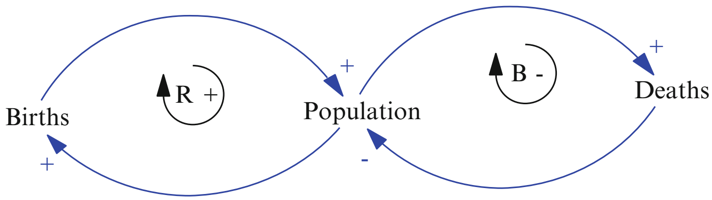

Fig. 3.3 Positive and negative feedback loops

variables change inversely. For example, in Fig. 3.1 the arrow in the direction of C to D means that if C increases, D will decrease. It can also mean if C decreases, D will also increase. The arrow starting from C and terminating at D with a (−) sign at the end of the arrow means the cause–effect relationship is negative.

Figure 3.2 shows an example of causal loop diagram with notation. This simple causal loop diagram of population consists of two variables, population growth and population. This figure illustrates a simple positive feedback loop consisting of two cause–effect relationships. In this example an increase in population will cause an increase in population growth. The cause–effect relationship is positive, and it is indicated by an arrow with a (+) sign starting at population and terminating at population growth. The cause–effect relationship between population growth and population is also positive. An increase in the population growth will cause an increase in population. This is indicated by an arrow with (+) sign staring at population growth and terminating at population. The loop formed from population to population growth and back to population is reinforcing loop and it is indicated by a (+) sign with an arrow inside the causal loop diagram. Figure 3.3 illustrates two feedback loops. In loop 1 the number of births increases with the population, and the births in turn increases population. These are positive relationships and

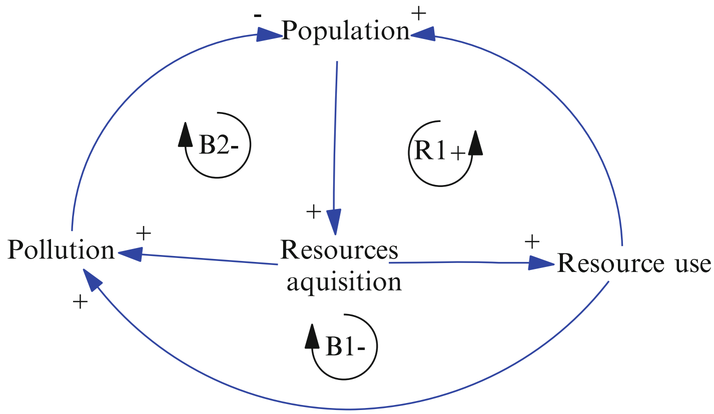

Fig. 3.4 Coupled feedback loops

represented by arrows with a (+) sign. In loop 1 there are two positive relationships. Hence, it is a positive and reinforcing loop. In loop 2 the number of deaths increases with population and the population decreases as the death increases. In loop 2 the first relationship is positive, and it is represented by an arrow (+) sign, while the second relationship is negative, and it is represented by an arrow with (−) sign. One can easily determine if a loop is positive or negative by counting the number of negative relationships in a loop. If there are an even numbers of negative relationships in total in a feedback loop, then the loop is positive; if there are odd numbers of negative relationships, the loop is negative. In fact, positive feedback loops generate growth, i.e. the loop is reinforcing and negative feedback loops are goal seeking. In loop 2 number of negative relationships is odd, i.e. 1. Hence, this loop is negative and goal seeking.

Let us now consider a coupled feedback loop of population, resource use and pollution as shown in Fig. 3.4. Loop at the right corner is positive, i.e. reinforcing, while the loops at the bottom and left corner are negative, i.e. balancing loop. In the positive loop, all the cause–effect relationships are positive, while in negative feedback loops, the number of (−) relationships is 1, i.e. an odd number.

3.3 Steps in Causal Loop Diagram

We must consider the description of the system and dynamic behaviour of the reference modes to construct the causal loop diagram, and these can aid in developing dynamic hypothesis. The following steps are to be followed for developing causal loop diagrams.

1. *Define the problem and the objectives.*

We must first of all study the system based on information collected through interview, focus group discussion, research report and case study. We must describe the system and define the problem with the reference mode of the behaviour of the system.

2. *Identify the most important elements of the systems.*

We should identify the key variables affecting the behaviour of the system, and it should be a good starting point to develop the causal loop diagram. Other variables can be added during later stages of causal loop development.

3. *Identify the secondary important elements of the systems.*

Secondary variables within the system boundary should be added after careful identification of the most important variables. This would provide an opportunity to consider the secondary variables of the system of importance in the causal loop diagram.

4. *Identify the tertiary important elements of the systems.*

Tertiary variables within the system boundary should be added after careful identification of the secondary variables. However, tertiary variables of little importance can be omitted in the later stages once it is established by simulated studies.

5. *Define the cause–effect relationships.*

Find the cause–effect relationships using arrows with polarity for the primary variables first, then for the secondary and tertiary variables.

6. *Identify the closed loops.*

Trace closed loops formed by cause–effect relationships for the variables describing the system.

7. *Identify the balancing and reinforcing loops.*

Identify the number of negative cause–effect relationships in each of the closed loops. The closed loops with odd number of negative relationships are negative, i.e. balancing loops, and the others are positive, i.e. reinforcing loops.

3.4 Examples

3.4.1 Population

Population has been growing exponentially throughout the history. Population increases by a fixed percentage per year, and also it decreases by a fixed percentage per year because of the fact that the human has a limited life. Draw the causal loop diagram of the simple population model.

Solution
Three key variables are population, birth rate and death rate. Birth rate increases with population, and also birth rate adds to population. These two are positive cause–effect relationships. Death rate increases with the increase in population, and it is a positive cause–effect relationship, but population decreases with the increase in death rate, and it is a negative cause–effect relationship. Hence, the model consists of two fundamental loops. The regenerating loop R generates new birth and adds it to population. The balancing loop B creates the death and depletes it from the population. The birth creates a positive loop since all the cause–effect relationships within this loop are positive, while there is an odd number of negative relationships within the balancing loop, and hence it a negative feedback loop. Figure 3.5 shows causal loop diagrams of a simple population model.

3.4.2 Carbon Metabolism in Green Plant

Carbon enters the plant by diffusion as carbon dioxide and is fixed. A labile pool of carbohydrate is produced. The entry and fixation rate is controlled by photosynthetic tissue represented chiefly by the leaves. The carbohydrate from the pool is allocated to the photosynthetic and non-photosynthetic parts of the plant body. Net loss of plant weight from the photosynthetic and non-photosynthetic parts is due to respiration. Draw the causal loop diagram for the description of carbon metabolism in green plant.

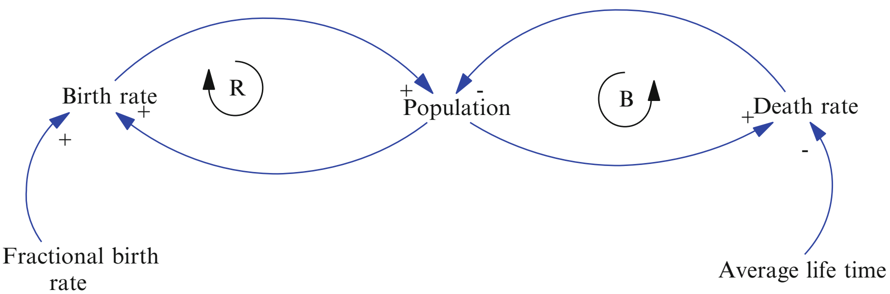

Fig. 3.5 Causal loop diagram of a simple population model

Solution

The carbon enters the plant in the form of carbon dioxide, and the rate of photosynthesis depends on solar radiation, temperature, weight of photosynthetic organs and photosynthetic area. The rate of photosynthesis increases with the increase of the weight of photosynthetic organs. The carbohydrate produced increases with the increase of photosynthesis rate and is translocated to the photosynthetic and non-photosynthetic organs. The carbohydrate pool, weight of photosynthetic organs and photosynthesis rate form a positive feedback loop (R1).

Again, respiration rate increases with carbohydrate in photosynthetic organs. The weight of the organs is decreased by respiration. The photosynthetic organs and respiration rate form a negative feedback loop (B1). Similarly the weight of non-photosynthetic organ and respiration form another negative feedback loop (B2). The resulting causal loop diagram of the carbon metabolism in green plant is shown in Fig. 3.6.

3.4.3 Food Security

Food security is a worldwide problem that has called the attention to governments and the scientific community. It particularly affects developing countries. The scientific community has had increasing concerns for strategic understanding and implementation of food security policies in developing countries, especially since the food crisis in the 1970s and 2009. The process of decision-making is becoming increasingly complex due to the interaction of multiple dimensions related to food

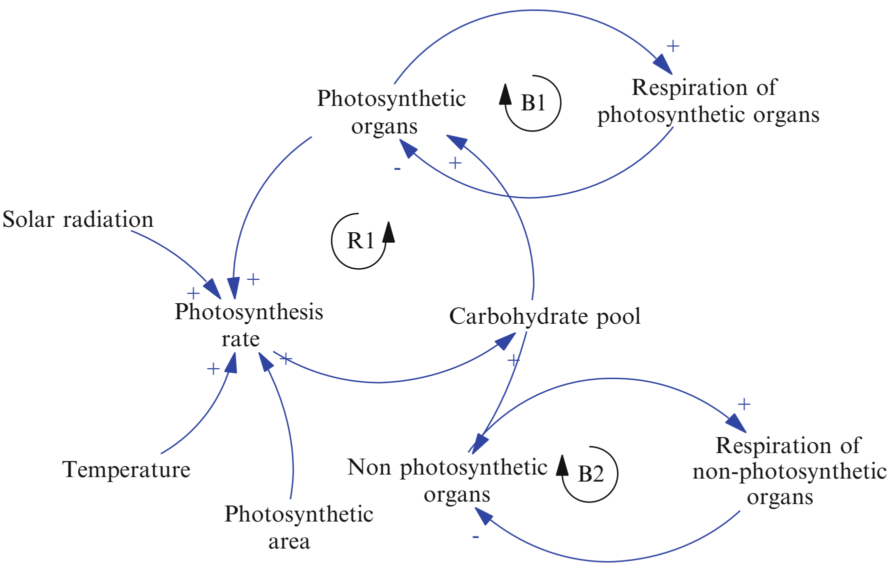

Fig. 3.6 Causal loop diagram of carbon metabolism in green plant

security (Giraldo et al. 2008). There is a need for models to examine the dynamics of this complex food security issues and design policies for sustainable development.

Food security is a situation in which people do not live in hunger or fear of starvation. FAO (1996a, b) defined the objective of food security as assuring to all human beings the physical and economic access to the basic food they need. This implies three different aspects: availability, affordability and access. Food security exists when all people at all times have access to sufficient, safe and nutritional food to meet their dietary needs and food preferences for an active and healthy life (FAO 2002). Draw the causal loop diagram of the food security model.

Solution

Food production depends on area cultivated and yield of the crop. Food production increases food availability. And also food production increases per capita income and hence food affordability. Food availability and food affordability would enhance the food access. Food security would depend on food availability, food affordability and food access.

As mentioned earlier the increased food production increases food availability, per capita food availability and hence food self-sufficiency. The increased food self-sufficiency would reduce the food price. The higher price would motivate the farmers to produce more food. This forms the negative feedback loop B1. Again, increased food self-sufficiency would reduce the deaths, and the increased deaths would reduce the population level. The increased population would reduce per capita food availability, and the increased per capita food availability would increase the food self-sufficiency. This forms the negative loop B2. Population forms one positive feedback loop R1 resulting from births and one negative feedback loop B3 resulting from deaths. The resulting causal loop diagram of the food security model is shown in Fig. 3.7.

3.4.4 Price Determination of a Commodity

Agricultural commodities are sold in highly competitive markets whose prices change yearly, daily, hourly and even by the minute. Farmers are affected by fluctuations of price—good times bring him an increase in income, and depression causes his cash income to drop away to very little. The price received by the farmers is important not only to him; the rate of production depends on it to a large extent. In addition, pigs, and to some extent cattle and chickens show fluctuations in price and supply of a persistent nature at a frequency consistent over long periods of time (Meadows 1970).

Most of the poorer nations are dependent upon the export of primary agricultural commodities as a source of foreign exchange, and the pronounced fluctuations in

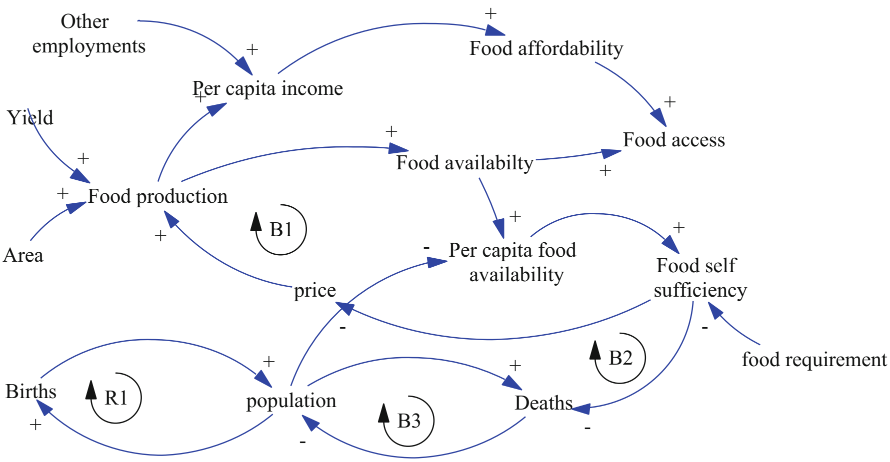

Fig. 3.7 Causal loop diagram of food security

price and supply have aroused much concern. Inflation, disruption of development programmes, loss of investor's confidence and political unrest are only a few of the results of the fluctuations in price and supply. Even developed countries find their economies affected.

Price determination is one of the most difficult challenges in economic modelling. Nerlove (1958) has given an excellent mathematical interpretation, and according to Nerlove farmers revise their previous expectations of normal price in each period in proportion to the difference between actual and what was previously considered normal. Sterman (2000) further modified this model, and according to Sterman the traders revise their expectations based on expectation adjustment and price adjustment. Draw the causal loop diagram of price determination based on the modifications suggested by Sterman.

Solution

The causal loop diagram of price determination of an agricultural commodity is shown in Fig. 3.8. The trader price is settled by price adjustment and expectation adjustment, and these form one positive feedback loop R1 and one negative feedback loop B1. The price depends on relative inventory coverage and trader price and the increase in price would reduce the consumption and thereby forms the negative feedback loop B2. On the production side, price, profitability and production also form a negative feedback loop B3. Also inputs, yield and production form a negative feedback loop B4. R & D, yield and production rate form a positive feedback loop (R2). The increase in population would increase the consumption rate and the population consists of one positive feedback loop R3 and one negative feedback loop B5.

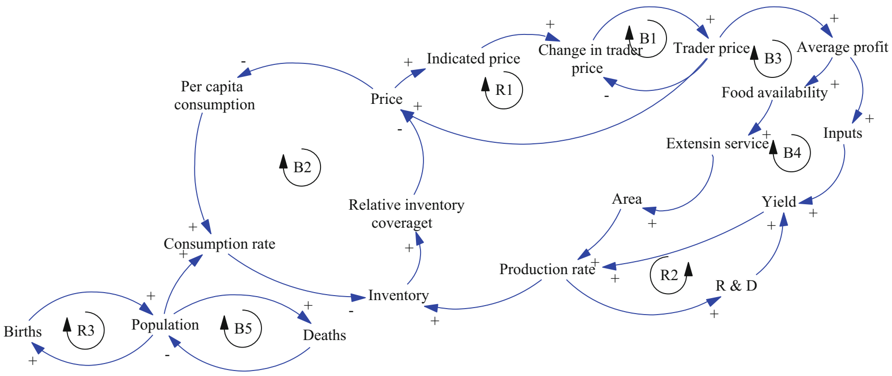

Fig. 3.8 Causal loop diagram of price determination of a commodity

3.4.5 Fishery Dynamics

Many fish stocks are in decline worldwide. Overfishing has led to the complete collapse of numerous fisheries including those for important and well-publicised species. In addition, over-exploitation of fisheries has led to reductions in biodiversity and modified ecosystem functioning. Despite management attempts to reduce overfishing, little progress has been made due to a general inability to endure the short-term economic and social costs of reduced fishing. Indeed, historical analysis reveals that resources are consistently and inevitably over-exploited. There is a need for models to examine the dynamics of this complex fishery issues and design policies for sustainable fishery development (Dudley 2008).

The model developed here is based on the biomass dynamic model (Graham 1935; Schaefer 1954, 1957), in which the population biomass increased due to both growth and the addition of new fish and decreases due to natural mortality and catch. Growth is equal to biomass fractional growth times existing biomass, and the natural decrease is growth multiplied by the ratio of biomass population to maximum biomass population possible. Catch depends on the current level of population biomass, number of gear units and fishing gear efficiency. The fleet entering or leaving depends on catch per unit effort and vessel replacement. In some fisheries, fishing activity decreases ecosystem carrying capacity. Draw the causal loop diagram of the fishery management system.

Solution

The causal loop diagram of fishery dynamics is shown in Fig. 3.9. Fish biomass increases by regeneration and decreases by catch and deaths. The regeneration forms a positive feedback loop (R1) with fish biomass, and the catch and deaths form negative feedback loops (B1 and B2) with fish biomass. Effect of relative fish biomass and deaths has a negative effect on fish biomass (B3). Fish catch, CPUE, fishing unit entry and units of fishing gear form a positive feedback loop (R2). Units

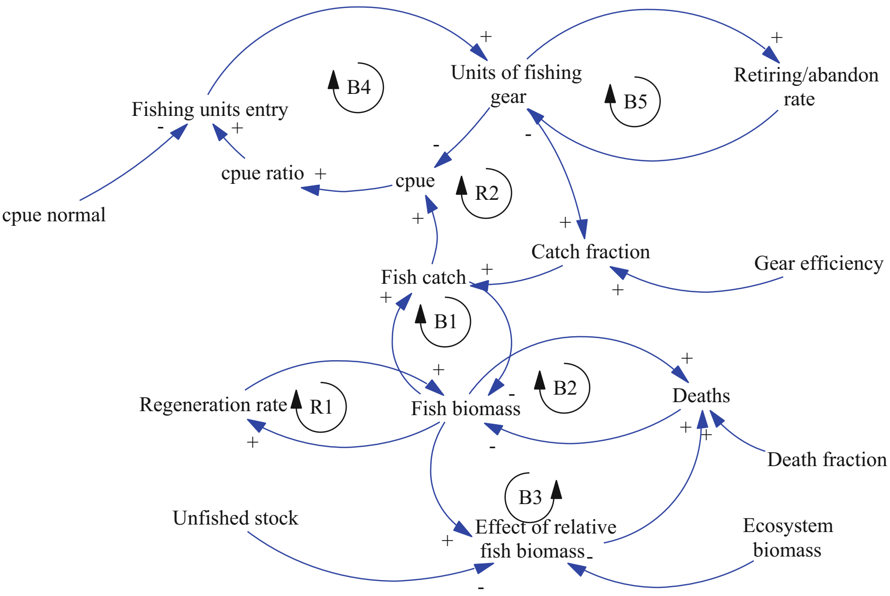

Fig. 3.9 Causal loop diagram of fishery dynamics

of fishing gear form two negative feedback loops with fishing unit entry and retiring/abandon rate (B4 and B5).

3.4.6 Forest Dynamics

Industrialisation, population growth and depletion of natural resources are threatening ecosystems all over the world. Climate change is one of the results of this development. But forests can play an important role in maintaining the global system in balance, and these forests are also the largest carbon sink above the soil. Furthermore, about 70–90 % of the global biodiversity are found in this ecosystem.

Over the last few decades, due to the increasing environmental awareness, the importance of the forest ecosystem has been acknowledged at the global level, which in turn enabled it to become a topic of relevance to the general public. Sustainable forest management, that is, the achievement of long-term economic, social and environmental goals has thus become the basic forestry principle. Forest management is a problem of increasing controversy and difficulty (Rosser Jr 2003).

Forest provides timber and fuel wood. Forest is also a renewable resource and is the largest carbon sink on the earth. Plantation of forest is motivated by profitability and demand for fuel wood and timber, and the harvesting of the mature forest for timbers is triggered by the demand. The saw mills demand logs from harvesting of

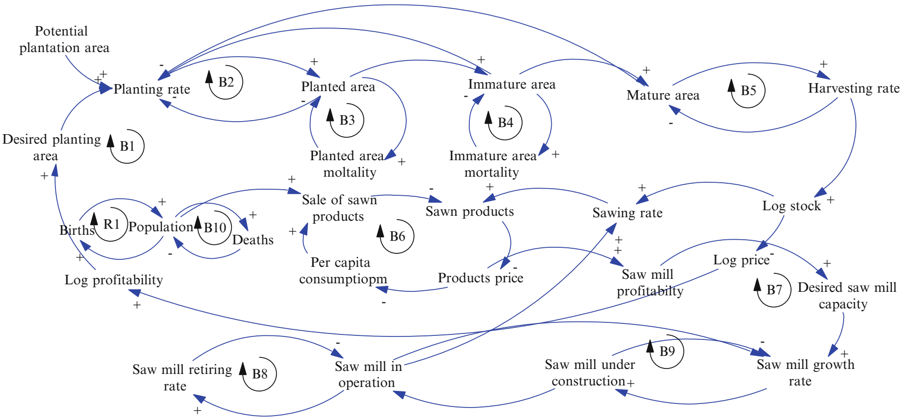

Fig. 3.10 Causal loop diagram of forest dynamics

timbers, and the expansion of the saw mills depends on profitability. Draw a causal loop diagram of the forest dynamics and management.

Solution

The causal loop diagram of forest dynamics is shown in Fig. 3.10. Planting rate increases planting and mature area and higher harvesting rate. The higher log stock would cause to lower the log price and the higher price resulting higher profitability would motivate to increase the planting area. This forms a negative feedback loop B1. The planting area forms negative feedback loop with planting rate (B2). Planted area and immature area are decreased by mortality, and the mature area is decreased by harvesting rate (B3, B4 and B5). Sawn products, products price and sales of sawn products form a negative feedback loop (B6). Increase in saw mill under construction would ultimately increase the saw mill under operation which results in higher sawing rate. This in turn would reduce product price, and the higher product price would result in higher profitability and saw mill growth rate. This forms a negative feedback loop B7. Saw mill under construction with saw mill growth rate and saw under operation with retiring rating rate balance the saw mill under construction and saw mill under operation, respectively (B8 and B9). Sales of sawn products increase with population and population comprises of one reinforcing loop (R1) and one balancing loop (B10).

3.4.7 Electricity Supply

Energy is needed for economic and social development (Bala 1997a, b, 1998). Per capita consumption of energy is a measure of physical quality of life (Bala 1998). Also per capita consumption of electrical energy is a measure of physical quality of life. Energy demands are increasing rapidly. Investments for power plants are triggered by the power supply gap, price and public pressure. Indicated price

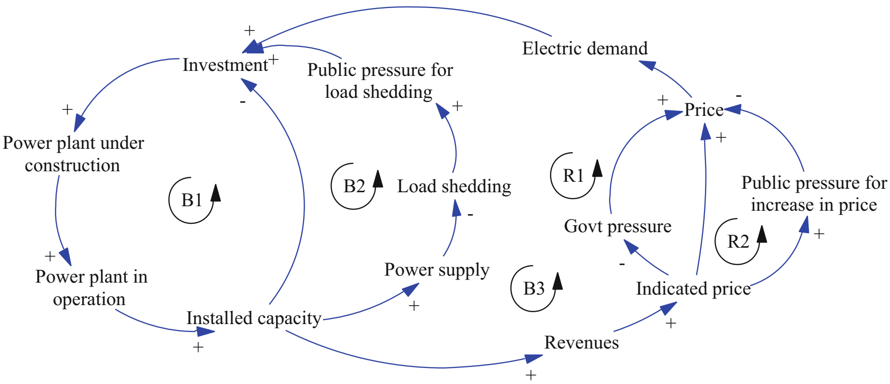

Fig. 3.11 Causal loop diagram of electricity supply system

depends on revenue received which creates govt pressure to increase the price as the indicated price increases while the public pressure for increase in price creates pressure to decrease the price. A power plant under construction becomes operational after some time delay and adds to the installed capacity to supply electricity and hence reduces the pressure on new investments. Draw the causal loop diagram of the simple electric supply system.

Solution

The causal loop diagram of the simple electricity supply system is shown in Fig. 3.11. Investment increases the installed capacity which in turn would invite less investment. This forms a negative feedback loop B1. The increase in installed capacity would increase power supply, and the increased power supply would reduce the load shedding. The load shedding increases public pressure which would increase the investment. The increased investment would result in increased installed capacity. This forms the negative feedback loop B2. Revenues, indicated price, government pressure, public pressure for increase in price, electric demand, investment and installed capacity form two positive feedback loops, and these are indicated R1 and R2.

3.4.8 Global Warming

Global warming refers to an increase in the average temperature of the atmospheric temperature resulting from greenhouse effect, and it is a prime concern in many developing countries. Earth's surface average temperature is increased by emissions of greenhouse gases and incoming solar radiation. The emissions are reduced by carbon sink of plant kingdom and algae in the sea. The water vapour increases the absorbed radiation. Draw the causal loop diagram of this simple global warming model.

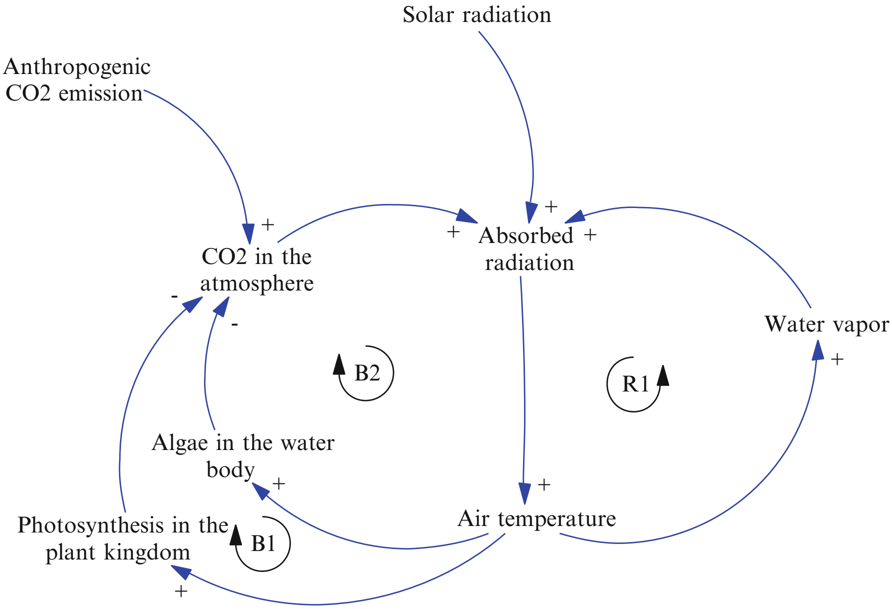

Fig. 3.12 Causal loop diagram of global warming

Solution

The causal loop diagram of the simple global warming model system is shown in Fig. 3.12. Absorbed radiation is increased by solar radiation and CO_2 in the atmosphere and water vapour. The increase in air temperature causes increase in photosynthesis in the plant kingdom and algae in the water body which decrease the CO_2 in the atmosphere (B1 and B2). Air temperature increases water vapour which increases the absorbed radiation. This forms a positive feedback loop (R1). Thus, there are one reinforcing loop and two distinct balancing feedback loops B1 and B2.

Exercises

Exercise 3.1 Rural and urban population

Population is divided into rural and urban. Population increases by birth rate and decreases by death rate. Both the rates are considered to be influenced by the availability of food, crowding and earning. Draw the causal loop diagram for the description of rural and urban population.

Exercise 3.2 Fish pond ecosystem

Fish pond ecosystem can be divided into two parts known as the biotic (living) and abiotic (nonliving) components. The abiotic substances are the water, the nutrients, oxygen, carbon dioxide, etc. The producers in the ecosystems are the large rated plants and the free-floating plants, usually algae, called phytoplankton. These store energy and liberate oxygen. The primary consumers are benthos or bottom form and zooplankton with little or no swimming ability. The phytoplanktons are consumed by zooplankton, which are in turn eaten by large aquatic life such as fish. Other consumers are the insects, frogs, man, etc., and a category called detritivores which live on the organic wastes. All of these forms produce organic waste and dead organisms. The decomposers, bacteria and fungi, utilise the organic carbon and generate CO_2 which in turn is used by the algae. Additional CO_2 is provided from the atmosphere and through the respiration of fish. In a healthy system, the availability of the nutrients, carbon, phosphorus and nitrogen is sufficiently small so as to limit the production of algae. Draw the causal loop diagram for fish pond ecosystem.

Exercise 3.3 Prawn production system
The prawn production system consists of two components: biological component and economic component. The biological component is a dynamic population model. Population of either sex at any time is determined from death rate, population level and harvest size. The number of deaths increases with an increase in population, and again the increase in number of deaths decreases the population. We can divide the population by length and size. Draw the causal loop diagram for prawn production system.

Exercise 3.4 Price forecasting of palm oil
Palm oil production is a highly complex system starting from plantation to export of palm oil. Our starting hypothesis about the market of palm oil should be something to do with the balance of supply and demand as in case with other agricultural commodities. The change in the palm oil price is a result of two major adjustments; change in palm oil price due to expectation adjustment and price adjustment. Short-term pressures arising from imbalance of supply and demand, changes in costs or competitors' prices will cause the traders to bid prices up or down relative to their expectation about equilibrium price. Other factors are such as substitutes, trade liberalisation and export restriction. Our initial dynamic hypothesis of palm oil market structure is based on standard assumptions how commodity markets typically work. If our hypothesis is correct, the model will be able to reproduce the general historical pattern followed by the palm oil price. Draw the causal loop diagram of price forecasting model of palm oil.

Exercise 3.5 Biofuel Promotion
Biofuel inventory and food inventory are key factors which regulate the prices and the profitability for farmers. The inventories act as buffers between production and supply and absorb variations on both sides. An increase in biofuel demand depletes biofuel inventory and causes biofuel price to increase and subsequently biofuel crop land to increase. This increase in land is at the expense of food crop land. The need for cultivable land is reinforced by the simultaneous increase in population. Government policies are represented through the variables such as incentives for biofuels and biofuel technology and management capabilities. The former is a

direct policy instrument, whereas the latter is an indirect one resulting in the funding of related R&D projects. These two instruments are competing for resources and have contrasting effects, as incentives increase land use, whereas technology increases the yield of the existing land. Draw causal the loop diagram.

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