Towards Building Adaptive Capacity in Farm Systems

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1. Introduction

Primary producers are skilled at managing farm systems to remain profitable and sustainable in the face of unpredictable and volatile product prices and unpredictable and variable seasonal conditions (Malcolm et al. 2005). However, the evidence suggests that climate change is likely to increase the variability in seasonal conditions and the frequency of extreme events such as flood, fire and drought (Victorian Government Department of Sustainability and Environment 2006; Sandall et al. 2007; Victorian Government Department of Premier and Cabinet 2008). The Victorian Government has recognised that adaptation to climate change will require policy support (Victorian Government Department of Sustainability and Environment 2006; Victorian Government Department of Premier and Cabinet 2008).

To remain productive, competitive and sustainable, as climate change progresses primary producers will have to become even more flexible (Howden et al. 2007). They will have to progressively adapt their farm systems to accommodate increasing variability in environmental inputs to farm systems as climate change unfolds. This means modifying the structure of farm systems. Specifically, the combination of regulatory mechanisms used in farm systems to control for variability in environmental inputs must be modified in order for farms to successfully adapt to climate change. This suggests that innovations in agricultural technologies and practices, characterised as regulatory mechanisms, are likely to play an important role in increasing the adaptability of farm systems. It also means that the key to developing policies to successfully support flexibility and adaptation in agricultural industries lies in understanding the role of the regulatory mechanisms used in farm systems. We propose that such an understanding can be obtained using insights from general systems theory (von Bertalanffy 1969; Weinberg and Weinberg 1988).

In this study we use general systems theory to, first, define adaptability in terms of production processes within farm systems. We focus on production processes because the path of adaptation that farm systems can take will depend, fundamentally, on the capacity of the farm system to control the impact of input variability on the quantity and quality of farm output through these processes. Understanding how input variability can be controlled through the production processes in farm systems should help scope the outcomes that may need to be sought via policy and other mechanisms for absorbing variability such as financial reserves.

Second, we use general systems theory to understand how innovation in agricultural technologies and practices, characterised as regulatory mechanisms, may increase the adaptability of farm systems, and under what circumstances.

We begin in this paper by using general systems theory to describe farms as open systems. We consider the fundamental capacity of farm systems to absorb variability in the state of the environment through the use of regulatory mechanisms. We then describe the different kinds of regulatory mechanisms used in farms systems and apply this thinking to a number of examples in agriculture. We conclude with some discussion of the insights this work offers to the development of government policy to support agricultural adaptation to climate change.

2. General systems theory and farms as systems

In this section we draw on general systems theory to characterise farms as open systems and define absorption, adaptation and adjustment to variability in the state of the environment. We also use general systems theory to describe how regulatory mechanisms are used to maintain stability in open systems. We then describe three fundamental types of regulatory mechanisms and consider how they contribute to the design of farm systems and the capacity of farm systems to adapt to climate change.

A system is a set of components that are linked together by relationships to form a whole that is more than the sum of the parts (Weinberg 2001). The emphasis in general systems theory is on understanding the behaviour of the system as a whole rather than on understanding the behaviour of individual components or relationships. The significance of system components and relationships is determined by how they are arranged in the system rather than a summation of the system (Angyal 1969; Dillon 1976). General systems theory[1] is a way of

[1] General systems theory should not be confused with Farming Systems Research which is a process for increasing the relevance of research findings to small landholders, especially in developing countries, which is often linked with on-farm experimentation (Wilson et al. 1986; Collinson and Lightfoot 2000).

understanding the behaviour of systems as being the outcome of interactions among the components and relationships (Katz and Kahn 1969; Weinberg 2001).

2.1. Open systems

Open systems are systems that interact with their environment (Katz and Kahn 1969; von Bertalanffy 1969; Weinberg 2001). In open systems the behaviour of the system depends on the state of the environment, as changes in the state of the environment will change the behaviour of the system (Leveson et al. 2003). This means that the behaviour of an open system through time, it's characteristic behaviour, can only be understood in relation to the possible states of the environment with which it interacts (Emery 1969; Katz and Kahn 1969).

The behaviours that are characteristic of an open system are a product of the structure of the system and the environment. The structure of an open system consists of those components and relationships in the system that are not altered by changes in the state of the environment, given the normal functioning of the system (Weinberg and Weinberg 1988). This means then that a change to the structure of an open system will change the behaviour of that system. Conversely, changes in the characteristic behaviour of an open system signal that the structure of the system has changed, given the state of the environment has not changed. Furthermore, the characteristic behaviours of an open system can only be restored by modifying the structure of the system if the changes in system behaviour are triggered by changes in the state of the environment. In principle, the set of behaviours that characterise an open system can be predicted given sufficient information on the structure of the system and the expected states of the environment.

Farms are open systems (Katz and Kahn 1969; von Bertalanffy 1969; CGIAR 1978; Weinberg 2001). They have a structure which consists of a set of components (soil, livestock, and technologies) that are linked together by relationships (farm practices, strategies) and they interact with the natural, economic and social environment (CGIAR 1978; Haines 1982; Norman 2002). Furthermore, farms are managed systems because they have a purpose (van Gigch 1974); they create a stream of product which is used by producers to achieve their utilitarian, social and hedonistic goals (Gasson 1973; Crouch 1981). Consequently, given that climate change entails a shift in the possible states of the natural environment then the structure of farms may have to be modified if farm systems are to continue to exhibit characteristic behaviours that are desired by producers.

2.2. System stability, adaptation and adjustment

An open system can be described as stable when the system is characterised by behaviours that lie within acceptable limits, given a range of expected states for the environment (Weinberg 2001). The limits to the acceptable behaviour of an open system depend on the purpose of the system. When the behaviour of the system falls outside acceptable limits, which can happen when the environment enters an unexpected state (von Bertalanffy 1969) then the structure of the system must be changed to move the behaviour of the system back within those limits. This means that stability and structure are related and that stability can only be defined with respect to a given system structure (Angyal 1969; Feibleman and Friend 1969).

Consequently, the extent to which the system is stable defines the capacity of a system to simply absorb changes in the state of the environment. In other words, the behaviour of the system remains within acceptable limits, despite changes in the state of the environment (Katz and Kahn 1969; Weinberg 2001). For example, the capacity of a farm system to absorb the affects of climate change may be defined by the extent to which the farm system can continue to behave within acceptable limits, without requiring any change to its structure, when the state of the environment changes. More practically, the purpose of a farm system concerns using a stream of product to achieve the utilitarian, social and hedonistic goals of producers. The capacity of a farm system to absorb the affects of climate change may be defined then, as the extent to which the farm system can continue to create a stream of product that generates sufficient income for the producer to meet their goals, without requiring changes in the system structure.

When structural change in the system is required to retain stability, this is called adaptation in general systems theory, provided the purpose of the system is preserved (Weinberg 2001). Hence, adaptation to climate change may be defined as changing the structure of the farm system, while preserving the system's purpose, so that the system continues to generate a stream of product that varies within acceptable limits, given expectations about changes in the state of the environment.

If changes in the state of the environment require a level of structural change to the system that means the system purpose cannot be preserved, then the system must transform into a new system or fail (Weinberg 2001). This aligns with a common conceptualisation of adjustment in agriculture. Adjustment is often used as a euphemism for system failure in the form of farms exiting agriculture (Stayner 1997); but the term also encompasses the various ways that producers change the purpose of their farm systems (Stayner 1997; Harris 2005; Malcolm et al. 2005; Godden 2006). Examples of adjustment in agriculture are offered in Meredith (2003) and include farm diversification, value-adding to farm products, working off-farm, community supported agriculture and alternative forms of land tenure. In these examples the utilitarian, social and hedonistic goals of the producer can only be met by changing the structure of the farm system which involves changing the nature of the stream of product.

Howden et al. (2007) suggest that while adaptation, in the general systems sense, may be sufficient for moderate climate change, more extensive system change may be necessary for severe climate change.

2.3. Regulatory mechanisms in systems

A system relies upon regulatory mechanisms to maintain stability. Regulatory mechanisms form part of the system structure and allow the system to absorb changes in the state of the environment. There are two criteria for determining which regulatory mechanisms are used in the system:

- The ability of the system to predict the cause, timing and extent of variability in the environment and
- The relative cost of regulating.

While regulatory mechanisms allow the system to absorb changes in the state of the environment, they do so at a cost to the system. This cost includes integrating the regulator into the system, the act of regulating, and scanning for information from the environment that signals that regulation is needed. As well, adding regulatory mechanisms may reduce the set of potential behaviours available to the system to achieve a particular outcome (Katz and Kahn 1969).

There are two kinds of regulatory mechanisms – unconditional and conditional (Weinberg and Weinberg 1988). Unconditional regulators are passive mechanisms, they operate continuously whether they are needed or not. Conditional regulators are active mechanisms in the sense that they operate only when required.

2.3.1 Unconditional regulatory mechanisms

The kind of regulatory mechanisms that are used in a system depends first, on whether the cause, timing and extent of variability in the state of an environmental input into the system can be predicted (see Figure 1). If these cannot be predicted then an unconditional regulator must be used. In other words, an unconditional regulator must be used when there is not enough time to find out more about the cause, timing and extent of variability before action must be taken (Weinberg and Weinberg 1988).

Aggregates are the principal type of unconditional regulatory mechanism (Weinberg and Weinberg 1988). Aggregates operate on the principle of redundancy, that is, an excess of parts. The idea here is that the behaviour of the system may be insulated from variability in the state of an environmental input by holding a stock or store of the input, or a satisfactory substitute (i.e. an aggregate). A fodder reserve to offset shortfalls in pasture production is an example of an aggregate regulatory mechanism in a farm system.

Broadly speaking, unconditional regulators function most efficiently when the state of an environmental input changes frequently and along one dimension (such as quantity). If the state of the environmental input only changes intermittently or along more than one dimension (such as quality and quantity) then a conditional regulator may be more efficient (Weinberg and Weinberg 1988).

2.3.2. Conditional regulatory mechanisms

When enough is known about the cause, timing and extent of variability in the state of an environmental input to predict whether regulation is necessary then a conditional regulatory mechanism can be used. Conditional regulatory mechanisms are classified into two types – error control and anticipation. The choice between error control and anticipation depends on a number of factors. These factors characterise the circumstances which suit each type of conditional regulator and so influences their relative cost to the system (see Figure 1).

Error control regulators are used where the cost of regulating when it is unnecessary is less than the cost of not regulating when it is necessary. Error control regulation is activated by detecting a small change in the state of an input which signals the possibility of greater change in the future (Weinberg and Weinberg 1988). Error control operates on two principles: first, that small changes precede large changes in the state of an input; and second, that small changes in the state of the input can be detected early enough for regulatory action to be taken to insulate the behaviour of the system from subsequent larger changes in the state of the input (Weinberg and Weinberg 1988).

The disadvantage of error control regulators is that regulatory action is always taken in response to a small change in the state of an input, even when small changes do not foreshadow large changes. Additionally, the activation of an error control regulator when it is not needed may interrupt the operation of other regulatory mechanisms in the system (Weinberg and Weinberg 1988). Hence, error control mechanisms are most useful when the likelihood is high that large changes will follow small changes in an input, and that the costs of taking regulatory action when it is unnecessary are lower than the costs stemming from not taking regulatory action when it is necessary.

The use of calendar scheduling for irrigation in pear production is an example of an error control regulator in a farm system. In this instance, the potential costs arising from under-watering (reduced yields) are judged to be greater than the potential costs of over-watering (excessive water and labour costs). Calendar irrigation means the soil moisture is maintained above a minimum desirable threshold by watering regularly, irrespective of rainfall. Any relatively small decline in soil moisture that may occur between irrigations is expected, at least sometimes, to foreshadow a relatively larger, damaging decline if the interval between irrigations is extended.

Anticipatory regulatory mechanisms should be used if the cost of regulating when it is unnecessary is greater than the cost of not regulating when it is necessary. Anticipation regulators require information about the causal relationships in the environment so that changes in the state of environmental inputs can be predicted. An anticipation regulator is activated by scanning for changes in variables in the environment that subsequently predict the state of an environmental input to the system (Weinberg and Weinberg 1988). These predictions provide the opportunity to intervene and take regulatory action to insulate the behaviour of the system from changes in the state of the environmental input. These regulatory actions may involve altering the future state of the environmental input (Weinberg and Weinberg 1988).

The use of regulated deficit irrigation in grape production is an example of an anticipation regulator in a farm system. In this instance, the potential costs arising from over-watering (reduced grape yields due to excessive plant vigour) are judged to be greater than the potential costs arising from under-watering (reduced grape yields due to water stress). Regulated deficit irrigation means the soil moisture is kept beneath a maximum desirable threshold by watering on the basis of soil moisture measurements that are correlated with the production of stress hormones in the plant that inhibit vegetative growth. Knowledge of the causal relationship between soil moisture, the production of stress hormones and subsequent vegetative growth provides the opportunity to schedule irrigations to regulate plant growth.

Conditional regulators are subject to two disadvantages. First, they may be triggered to operate when they are not needed. Second, they may not be always be triggered and so may fail to operate when they are needed (Weinberg and Weinberg 1988). In addition, an unconditional regulator may be preferred to a conditional regulator where the use of a conditional regulator is inconsistent with the purpose of the system. For example, the use of broad-spectrum chemical sprays to control pests is inconsistent with the purpose of organic farming.

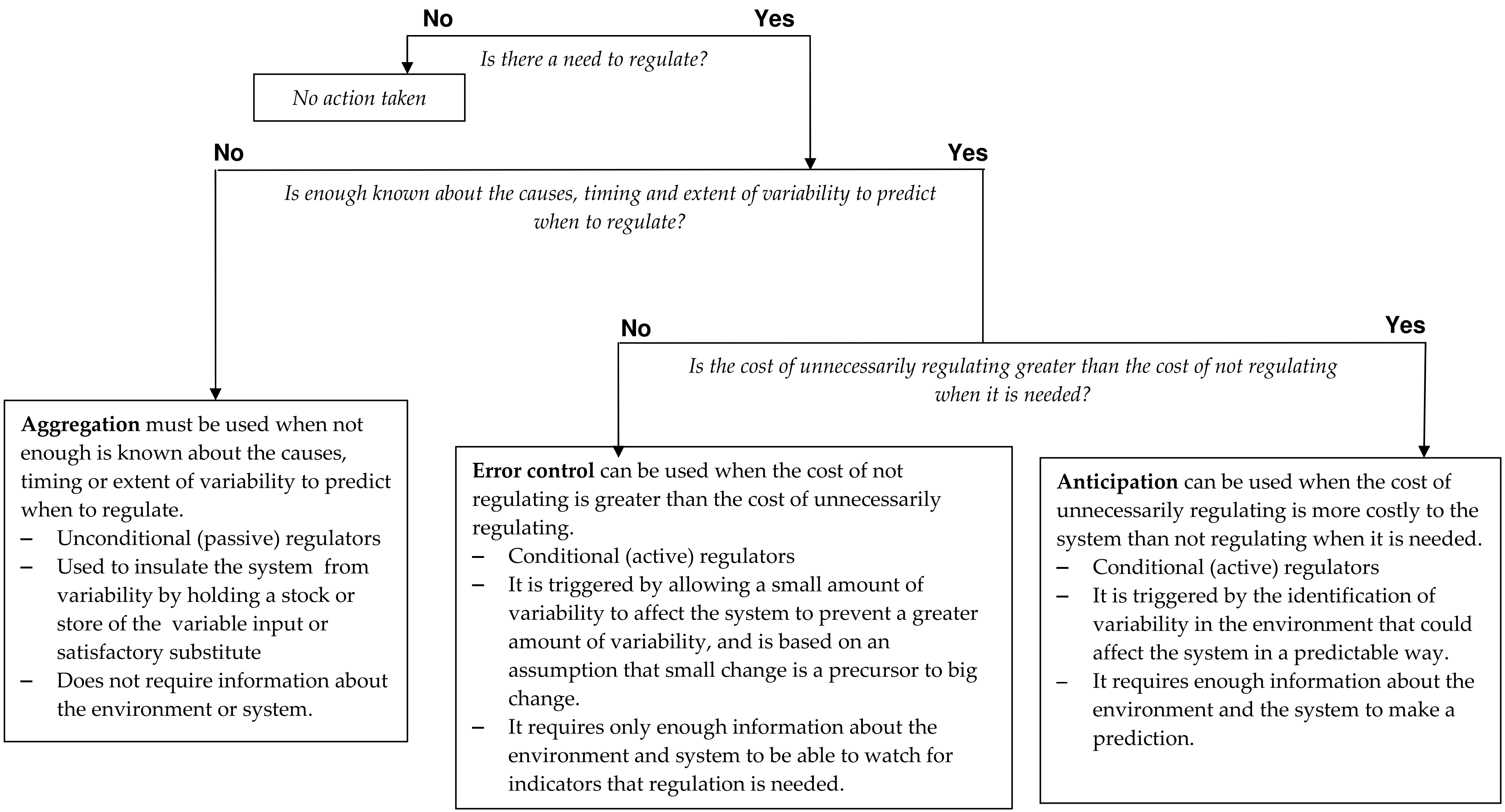

Figure 1: Types of regulatory mechanisms

2.4. Maintaining system stability in farm systems

Given our conceptualisation of farms as systems and the three different types of regulatory mechanisms, we can now consider how regulatory mechanisms contribute to the design of farm systems and their capacity to adapt to climate change.

The fundamental objective of a primary producer is to configure and manage their farm system so that the system is capable, given expectations about the behaviour of the biophysical and business environment, of generating an acceptable flow of product over time (Crouch 1981; Cramb 2005). Hence, the purpose of a farm system is to transform varying environmental inputs (rainfall, temperature, purchased inputs) into a satisfactory flow of product through time. Consequently, the fundamental task of primary producers is to employ their farm system to transform a combination of variable environmental inputs into a suitable flow of product through time. In other words, a farm system can be conceptualised as an elaborate mechanism producers use to control or regulate the transformation of environmental inputs to generate a flow of product.

This conceptualisation has a number of implications. First, that the components and relationships that comprise a farm system can be interpreted as mechanisms that are employed to regulate the behaviour of environmental inputs. These regulatory mechanisms may include strategies, practices, technologies or resources. These regulatory mechanisms will be present in different combinations in farm systems because different regulatory mechanisms will suit different environmental conditions and different farm circumstances.

Second, a farm system can be interpreted then as consisting of a complex mix of regulatory mechanisms. This suggests that the strategies, practices, technologies or resources that are employed to regulate the behaviour of farm systems could be characterised in terms of the three fundamental types identified in systems theory. Furthermore, the criteria from systems theory that influence the choice among these types of mechanisms should be applicable to the regulation of farm systems.

Third, that the value to the producer of the components and relationships in a farm system lies in the way they enable the producer to regulate the transformation of environmental inputs. Hence, the value to the producer of changing components and relationships in a farm system by, for example, adopting innovations will depend on how they change the capacity of the producer to regulate the effects of environmental inputs on the behaviour of the system. This means that the attractiveness of innovations to producers will depend on producers' expectations about the variable behaviour of environmental inputs, given their particular farm circumstances. Differences among producers in these expectations, and their circumstances, mean that the attractiveness of innovations will vary among them. This has been demonstrated by Kaine et al. (1994; 1998) for example in relation to the adoption of farm planning aids; and Kaine and Niall (2001) in relation to the adoption of quantitative methods in sheep breeding.

These implications suggest that producers will find innovations attractive that offer them increased control over environmental inputs they cannot satisfactorily regulate. Kaine et al. (2004) provide evidence for this behaviour in regard to livestock enterprises in New Zealand. These implications also suggest that if climate change were to alter producers' expectations about the dynamics of environmental inputs, then they will seek agricultural innovations that allow them to reconfigure their farm systems to obtain a satisfactory flow of product over time. In other words, should producers' expectations about the dynamics of environmental inputs change then they will seek agricultural innovations that allow them to alter the structure of their farm systems to recreate stability in the sense of a satisfactory flow of product through time.

These considerations suggest that, in a systems sense, producers' will adapt to climate change by seeking agricultural innovations that will allow them to restructure their farm systems. This leads to the conclusion that one of the keys to developing policies to support agricultural adaptation to climate change in agriculture hinges on:

- Understanding how farm systems can be interpreted as mechanisms for regulating the transformation of environmental inputs into product flows and how policy settings affect farm systems in this regard, and
- Understanding how innovations in agricultural technologies and practices function as regulatory mechanisms in farm systems.

In this section we have drawn on general systems theory to provide definitions of absorption, adaptation and adjustment in relation to farm systems and climate change. We have also described three fundamental types of mechanisms for regulating the behaviour of systems. We have considered how these regulatory mechanisms contribute to the design of farm systems and their capacity to adapt to climate change.

In the next section we illustrate the application of systems theory and farm systems as mechanisms for regulating the transformation of environmental inputs into product flows.

3. Regulatory mechanisms in farm systems

In this section we present three examples of the application of general systems theory to the regulation of environmental inputs in farm systems. The examples concern pest control, irrigation scheduling, and the management of reuse dams on farms. These examples were chosen because they are commonly used practices in agriculture and they cover all three types of regulatory mechanisms.

3.1. Control of Codling Moth

Codling moth is the biggest insect pest of the pome fruit industry in Victoria (Williams 2000). The fruit damage caused by uncontrolled populations of codling moth can be extensive (Williams 2000). Hence the population of codling moth in orchards is an environmental input which producers seek to control.

There are a number of regulatory mechanisms available to fruit growers for controlling codling moth, ranging from broad-spectrum chemical spraying to 'softer' approaches that use few or no chemical sprays (Kaine and Bewsell 2008). Growers choose regulatory mechanisms for controlling codling moth that are suited to their particular farm circumstances (Kaine and Bewsell 2008). Four examples of these regulatory mechanisms, two different spraying practices and two biological controls are discussed here. The examples are summarised in Table 1.

3.1.1. Regulation through spraying

Chemical spraying is the most common regulatory mechanism used to control codling moth (Williams et al. 2000). From a general systems theory perspective, the spraying of chemicals is a form of conditional regulator as spraying occurs only when required rather than constantly. The following are examples of conditional regulators that are used to control codling moth, an error control regulator in the form of calendar spraying and an anticipation regulator in the form of strategic spraying.

3.1.1.1. Calendar Spraying

When using calendar spraying the fruit grower follows a set interval for spraying (e.g. every three weeks). The decision to commence spraying at the beginning of the season is triggered by the detection of increased numbers of codling moths in pheromone traps or lure pots. Pheromone traps emit a synthetic pheromone that mimics the chemical emitted by female codling moths to attract males. The traps are used to capture male codling moths in order to identify the presence of codling moths in the orchard (Williams 2000; Williams et al. 2000). Once spraying is initiated the regular schedule is maintained (Williams 2000).

This is an example of regulation by error control. This type of regulator is appropriate if the cost of spraying when it is not necessary (because a small increase in the moth population does not presage a larger, damaging increase) is judged to be less than the cost of not spraying when it is necessary.

While it is likely that the grower may spray more times than may be strictly necessary throughout the spray season this method eliminates the risk that the moth population may increase too rapidly to be controlled, or that the moth population may increase at a time when it cannot be controlled because it is not possible to spray.

Table 1: Examples of regulatory mechanisms in management of codling moth

Example	*Unconditional or conditional*	*Type of regulator*	*Trigger*	*Reason for classification*
Calendar Spraying	Conditional	Error Control	Spray cycle initiated by increased number of codling moths in monitoring traps. Once commenced spraying is repeated after a fixed interval.	With calendar spraying the grower follows a set interval for spraying throughout the season, once spraying has commenced. The first spray is triggered through moth counts trapped in pheromone traps or lure pots. The cost to the farm of spraying too often is judged to be less than the cost of not spraying when necessary.
Strategic Spraying	Conditional	Anticipation	Spraying based on predictions of when the eggs from peak codling moth activity are likely to hatch.	Strategic spraying uses a combination of pheromone traps, knowledge of codling moth physiological and temperature records to determine when it is necessary to spray. Strategic spraying reduces the likelihood of spraying when it is unnecessary. The cost of spraying too often (secondary pests, chemicals, labour) is judged by the grower to be higher than the cost of not spraying enough (codling moth damage from not predicting the timing of spraying correctly).
Maintaining Biodiversity	Unconditional	Aggregation	n/a	This regulator relies on constantly maintaining a balanced system of soil, plants, and wildlife to help keep codling moth populations within satisfactory thresholds. This is an unconditional regulator that is constantly operating in an orchard to eliminate damaging changes in pest populations irrespective of their cause and timing.
Mating disruption	Conditional	Error control	First codling moth trapped in pheromone trap	This method uses slow release pheromones in the orchard throughout the season so that male moths cannot locate and mate with females. The cost of releasing pheromones when it is not necessary (i.e. outside the three peak activity periods in the season) is less than the cost of not releasing them when necessary.

3.1.1.2. Strategic spraying

Strategic spraying is based on the premise that there are peak periods of codling moth activity in a year, depending on seasonal temperatures, which must be controlled to avoid considerable damage to fruit crops (Williams 2000). Therefore the population of codling moth in the peak periods is an environmental input which the farmer seeks to control.

Certain physiological conditions must be met for codling moths to enter each stage of their development. These include minimum temperature thresholds for activities such as flying, mating, egg laying, hatching and pupation (Williams 2000; Williams et al. 2000). On the basis of the number of male codling moths trapped and temperature records the grower can predict when the eggs from peak codling moth activity are likely to hatch, and therefore the time when the application of chemical sprays will be most effective (Williams 2000). Hence the farmer uses information about the environment to predict when to activate the regulatory mechanism.

Strategic spraying reduces the likelihood of spraying when it is not necessary because conditions, such as temperature, will not support a large increase in the population of moths (Williams et al. 2000). Strategic spraying also lowers costs to the farm system by reducing the likelihood of problems with secondary pests (Cutwright and Pfeiffer 2002). Problems with secondary pest can occur when chemical sprays kill beneficial insects that naturally control other pests. This can then result in a need for spraying even more frequently to control these other pests.

Strategic spraying is an example of control by anticipation. This type of regulator is appropriate if the cost of spraying when it is unnecessary (because a small increase in the moth population does not presage a larger, damaging increase) is judged to be higher than the cost of not spraying when it is necessary. This suggests that the grower believes the risk that the moth population may increase too rapidly to be controlled, or that the moth population may increase at a time when it cannot be controlled because it is not possible to spray, is relatively low. To be successful strategic spraying requires knowledge of causal links in the environment, in this case the link between temperature and the physiology of moth development, so that changes in the state of inputs, the population of moths, can be predicted.

3.1.2. Regulation through biological control

There are a number of alternatives to using chemical sprays to control codling moth. These other regulatory mechanisms include the introduction of predator insects, removal of codling moth over-wintering sites, artificial cocooning sites for trapping larvae, mating disruption and maintaining biodiversity (Williams 2000). In the following section we describe biological examples of the regulation of codling moth populations using aggregation in the form of maintaining biodiversity and by error control in the form of mating disruption.

3.1.2.1. Maintaining biodiversity

Maintaining biodiversity in orchards is a method for biological control of codling moth. This method is based on a view that having a balanced system of soil, plants and wildlife will help keep the population of codling moth and other pest species within manageable levels throughout the year (Williams 2000; Michaels nd).

Codling moth are the prey of a range of wildlife including other insects, birds, frogs and bats (Williams 2000; Cutwright and Pfeiffer 2002; Michaels nd). The use of biodiversity in the orchard involves establishing and maintaining understorey plants, including nectar and pollen producing plants, to increase and sustain a mix of wildlife in the orchard, including predators of codling moth (Michaels nd). The population of codling moth is controlled through the natural interaction of the codling moth and their predator populations. Chemical spraying is avoided as much as possible since spraying may kill beneficial insects and upset the natural dynamics of predator-prey systems (Michaels nd).

Maintaining biodiversity may not offer the same degree of protection in a particular season from codling moth damage as chemical sprays (Williams et al. 2000). For example, control through maintaining biodiversity is less likely to be successful for bigger commercial operations and in areas prone to heavy infestations of codling moths (Williams 2000). However, the use of conditional regulators, such as chemical sprays, may not be possible in some farm systems, such as organic and biodynamic systems, because their use is not consistent with the purpose of the farm system (Williams et al. 2000).

Maintaining biodiversity is an example of an aggregation strategy. In principle, once established, the predator populations constantly interact with the moth population. Variations in the moth population automatically trigger offsetting variations in the population of predators. Hence, biodiversity is a form of unconditional regulator.

3.1.2.2. Mating disruption

Mating disruption is a strategy for controlling codling moth through the use of slow release pheromones (Williams 2000; Williams et al. 2000; Alway 2002; Cutwright and Pfeiffer 2002). Mating disruption involves saturating orchards with a synthetic version of the chemical used by the female codling moth to attract males. The saturation of the orchard means the male codling moth is unable to locate and mate with females (Williams 2000; Williams et al. 2000; Alway 2002; Cutwright and Pfeiffer 2002).

Pheromone traps are placed in the orchard prior to bud break (Cutwright and Pfeiffer 2002). When the first codling moth is trapped pheromone dispensers are then distributed throughout the orchard and remain active throughout the season (Cutwright and Pfeiffer 2002).

Mating disruption is most effective in orchards that have a fairly uniform tree structure and size, and in which the population density of codling moth does not exceed moderate levels (Cutwright and Pfeiffer 2002). In addition, the area around the pheromone-controlled zone cannot be a significant source of immigrating codling moths (Cutwright and Pfeiffer 2002). Mating disruption is less time consuming than other methods of moth control as the pheromone dispensers operate independently and continuously throughout the growing season (Alway 2002; Cutwright and Pfeiffer 2002). Mating disruption does not lead to secondary pest problems and is seen as a non-toxic, safe alternative to spraying (Alway 2002; Cutwright and Pfeiffer 2002).

Mating disruption is an example of regulation by error control. This type of regulator is appropriate if the cost of using disruption when it is not necessary (because a small increase in the moth population does not presage a period of peak activity) is judged to be less than the cost of not using disruption when it would be necessary, during an unanticipated period of peak activity for example. Saturation of the orchard during the entire season eliminates the risk of uncontrollable increases in the moth population.

3.2. Irrigation management

Irrigation scheduling, that is, the timing and duration of watering, is the most important mechanism for regulating soil moisture on irrigation properties (Qassim and Ashcroft 2006). Maintaining the level of soil moisture within appropriate thresholds is crucial for maximising productivity, as both over-watering and under-watering can have detrimental impacts on plant growth (Goodwin 2000; Alway 2002; Qassim and Ashcroft 2006).

Four examples of irrigation scheduling as mechanisms for regulating farm systems are discussed here. The first three examples, namely calendar irrigation, subjective assessment of soil moisture and objective monitoring of soil moisture; are all used to maintain the soil moisture above a minimum threshold. In contrast the fourth practice, regulated deficit irrigation, is used to maintain the soil moisture between a minimum and a maximum threshold. The examples are summarised in Table 2.

3.2.1. Maintaining soil moisture above a minimum threshold

In this section we describe three regulatory mechanisms for ensuring that soil moisture is maintained above a minimum threshold: calendar irrigation, subjective assessment of soil moisture and objective monitoring of soil moisture.

The relative volume of moisture in the soil moisture can be measured and described as a percentage of field capacity (Qassim and Ashcroft 2006). At 100 per cent field capacity the soil is saturated. At 50 per cent of field capacity there is just enough water available to meet the needs of growing plants. At 25 per cent plants cease to grow. If soil moisture falls below 25 per cent of capacity plants begin to wilt and die (Qassim and Ashcroft 2006). While 25 per cent of field capacity can be seen as the minimum biological threshold for soil moisture, the minimum economic threshold for a particular enterprise may be greater than this depending on, for instance, the stage of plant growth, weather conditions, and the reliability and the timeliness of supplies of water for irrigation.

Table 2: Examples of regulatory mechanisms in irrigation scheduling

Example	*Unconditional or conditional*	*Type of regulator*	*Trigger*	*Reason for classification*
Calender irrigation	Conditional	Error control	Fixed schedule	Calender irrigating relies on historical weather and plant data to establish a fixed irrigation schedule or pattern. The cost of not watering before the soil gets too dry is judged to be greater than the cost of irrigating when it is unnecessary.
Irrigation using subjective assessment of soil moisture	Conditional	Error Control	Farm-specific soil moisture threshold	With this irrigation method the soil is subjectively assessed to decide what percentage of field capacity the soil has reached and when irrigation is necessary. The cost of not watering and allowing the field capacity to drop below a minimum threshold is greater than the cost of unnecessarily watering.
Irrigation using objective monitoring of soil moisture	Conditional	Error Control	Farm-specific soil moisture threshold	Objective monitoring uses scientific techniques to measuring soil moisture. Watering commences when a minimum soil moisture threshold is reached. Objective measurement can be more precise than subjective assessment for measuring soil moisture. This creates the possibility of reducing the likelihood of over-watering and under-watering.
Regulated Deficit Irrigation	Conditional	Anticipation	Farm-specific soil moisture threshold linked with the stage of fruit growth.	RDI focuses on reducing vigorous plant growth caused by over-watering thereby reducing pruning costs and increasing yields. Here the cost of irrigating unnecessarily is judged to be greater than the cost of not irrigating when necessary.

The three methods for maintaining soil moisture above a minimum threshold that we describe in this section are all conditional regulators. That is, they are active mechanisms in the sense that they operate only when required and their operation is triggered by changes in soil moisture; they do not operate continuously.

Since the purpose of these methods is to avoid productivity losses caused by under-watering then these methods are a form of error control, though each is triggered differently. Recall that error control is used when the costs of regulating when it is unnecessary (productivity losses from over-watering in this instance) are less than the costs of not regulating when it is necessary (productivity losses from under-watering in this instance).

3.2.1.1. Calendar irrigation

Calender irrigation is an irrigation method that involves using historical weather data (such as relative humidity, temperature, wind speed and sunshine hours) and an understanding of plant physiology to establish a relatively fixed interval between irrigations (Qassim and Ashcroft 2006). This interval may be subject to planned modifications over the irrigation season in line with stages in the plant growth cycle (Goodwin 2000). While it is likely that the farmer may irrigate more times than may be strictly necessary during the irrigation season this method eliminates the risk that soil moisture may decline below the minimum economic threshold.

3.2.1.2. Irrigation using subjective assessment of soil moisture

Subjective assessment of soil moisture by direct observation of the soil is the most common method of assessing the need to irrigate (Qassim and Ashcroft 2006). When using this method the grower looks at, and feels, the soil itself to decide what proportion of field capacity the moisture in the soil has reached (Qassim and Ashcroft 2006). Irrigation is triggered when this assessment indicates the soil moisture has dropped to the minimum economic threshold. Compared to the calendar method, soil assessment is less likely to mean that the farmer will irrigate more times than may be necessary during the irrigation season. On the other hand, there is a greater risk with soil assessment that soil moisture could drop below the minimum economic threshold.

3.2.1.3. Irrigation using objective monitoring of soil moisture

There are a number of techniques that can be used to objectively monitor soil moisture by measuring soil moisture suction such as tensiometers and resistance blocks, or soil moisture content such as neutron probes (Qassim and Ashcroft 2006). Regardless of how moisture is measured the aim is to identify when soil moisture falls to the minimum threshold that triggers irrigation.

Objective monitoring may be used by producers to calibrate their subjective assessments of soil moisture; hence monitoring may only be employed for a relatively short period of time by some producers (Ambrosio and Linehan 2007).

Objective monitoring is seen by some as a more accurate method for measuring soil moisture than subjective assessment (Qassim and Ashcroft 2006). In principle, objective assessment may allow producers to be more precise in measuring soil moisture and so improving the timeliness and duration of irrigations. If objective monitoring is more accurate than subjective assessment then the use of objective monitoring means the likelihood of irrigating when it is unnecessary is reduced. Whether this is worthwhile depends on the frequency of experiencing a decrease in soil moisture that is too rapid to be controlled, the consequences associated with such experiences, relative to the costs associated with irrigating more frequently than is necessary.

3.2.2. Maintaining soil moisture between a minimum and a maximum threshold

We have described three irrigation scheduling practices that are all used to maintain soil moisture above a minimum threshold. We will now describe a forth regulatory mechanism, regulated deficit irrigation, which is used to ensure soil moisture is maintained below a maximum threshold as well as above a minimum threshold. In this instance over-watering can have an equally, or even more, detrimental impact on farm productivity as under-watering.

3.2.2.1. Regulated deficit irrigation

Regulated deficit irrigation (RDI) is a form of irrigation scheduling for orchards and vineyards. It is used to reduce vigour in plant growth. It is based on the premise that excessive vigour increases pruning costs and reduces yields (Goodwin 2000).

With RDI the irrigation season is divided into different stages with different irrigation patterns in each stage based on the physiology of fruit growth (Goodwin 2000). Generally, water is applied sparingly to plants at times of slow fruit growth and after harvesting, while ample water is applied during rapid fruit growth (Goodwin 2000). The trigger for irrigating with RDI is the level of soil moisture coupled with the stage of fruit growth. In principle, a farmer may use any method for measuring soil moisture with RDI (Goodwin 2000).

RDI is an example of control by anticipation. This type of regulator is appropriate if the cost of irrigating when it is unnecessary (because a small decrease in soil moisture does not foreshadow a potentially damaging decrease) is judged to be higher than the cost of failing to irrigate when it is necessary. This suggests that the grower believes the risk that soil moisture may decrease below the minimum economic threshold is relatively low. To be successful RDI requires knowledge of causal links in the environment, in this case the link between soil moisture and the physiology of plant and fruit growth, so that changes in the state of inputs, moisture stress and subsequent hormone production in the plant, can be predicted. In addition, RDI requires having sufficient control over access and delivery of irrigation water to avoid the risk of uncontrolled, damaging declines in soil moisture.

3.3. The management of reuse dams

3.3.1. Reuse dams for capturing runoff

To improve water use efficiency and limit nutrient pollution the Victorian government promotes the adoption of reuse dams by dairy producers who use flood irrigation (Kaine and Johnson 2004; Kaine and Higson 2006; McDonald 2008). In some districts incentives have been offered to encourage producers to incorporate reuse dams into their farm irrigation and drainage system (Kaine and Johnson 2004; Kaine and Higson 2006). Reuse dams can be installed to capture runoff from over-watering during an irrigation and from rainfall, which is a major cause of unpredictable runoff from farms (Kaine and Johnson 2004; Kaine and Higson 2006). This water is stored and used in subsequent irrigations.

In addition to water, a reuse dam contains soluble nutrients that can have a detrimental affect on waterways if they leave the farm (Kaine and Johnson 2004; Kaine and Higson 2006). By re-applying the water fewer nutrients leave the farm. These nutrients have the potential offer fertilising and soil conditioning benefits (McDonald 2008).

Reuse dam guidelines suggest that any captured and stored runoff should be used at the end of an irrigation so that the dam is always empty and ready to capture run-off whenever it is needed (Kaine and Johnson 2004; Kaine and Higson 2006). When managed in this way a reuse dam is being employed as an unconditional regulator. In principle, the dam is intended to be an aggregate of space, an empty vessel that is maintained in a constant state of readiness for the purpose of preventing the uncontrolled release of water and nutrients from the farm.

3.3.2. Reuse dams for managing irrigation

In practice, many dairy producers who installed reuse dams found that the dam could be employed to regulate variability in the supply of irrigation water and so improve the timing of irrigation (Kaine and Johnson 2004; Kaine and Higson 2006). The reliability of irrigation supplies is crucial to farm viability (Kaine and Johnson 2004). Producers may have to order water several days in advance because of the time it takes for water to move from public storages to the farm, putting limits on the precision with which irrigations may be scheduled (Kaine and Johnson 2004). The ability to control irrigation timing may also be limited by the capacity of channel structures and the needs of other irrigators on the channel system. Producers manage this variability in the supply of irrigation and seek to avoid losses associated with under-watering by ordering in advance and watering too early. Hence, forward ordering is an error control regulator for managing unreliability in the supply of irrigation water.

Producers that have experienced difficulties with the supply of water for irrigation supply may use their reuse dam to manage the timing of irrigation by ordering water earlier than necessary, and storing the water in their dam ready for use at the appropriate time (Kaine and Johnson 2004; Kaine and Higson 2006). When used in this way the reuse dam is filled with water before irrigation commences. This limits the potential to employ the reuse dam to capture and store irrigation and rainfall runoff (Kaine and Johnson 2004).

When reuse dams are employed to improve irrigation scheduling they function as error control regulators to manage unreliability in the supply of irrigation water. This means that, in these circumstances, producers are substituting one error control regulator for another, namely reuse dams are substituted for forward ordering. The capital investment in the dam should allow greater precision in the scheduling of irrigations, resulting in productivity improvements.

In this section we have presented examples of the application of general systems theory to the regulation of environmental inputs in farm systems. The examples concerned pest control, irrigation scheduling, and the management of reuse dams on farms and covered all three types of regulatory mechanisms.

Table 3: Examples of variety in reuse dam

Example	*Unconditional or conditional*	*Type of regulator*	*Trigger*	*Reason for classification*
Reuse dam – capturing run-off	Unconditional	Aggregate	n/a	The reuse dam is used to collect any rainfall or irrigation water that would otherwise be lost as runoff. Once built the dam is continuously regulating as it is always available to catch runoff whenever it occurs. The dam should be empty when irrigation commences.
Reuse dam – improving the scheduling of irrigation	Conditional	Control-by-error	A period prior to irrigating that reduces the risk that water will not be available when needed to an acceptable level. This period depends on circumstances, weather patterns, and time of year.	The reuse dam is used to store water ready for irrigation when the delivery of irrigation water is uncertain. Irrigation water is ordered in advance and stored in the dam ready for application at the appropriate time. This allows the dairy farmer to reduce the chances of having to irrigate earlier than is necessary while avoiding the risk of being unable to irrigate when it is necessary.

4. Discussion

We have described three different types of regulatory mechanisms that are used to manage farm systems. In reality primary producers use combinations of these mechanisms to balance the regulation of the many sources of variability in a farm system (Weinberg and Weinberg 1988). The combination of regulators in a farm system determines the extent to which environmental inputs can vary before the flow of product becomes too disrupted. Hence, the combination of regulatory mechanisms in a farm system at a point in time sets the capacity of the farm system to absorb variability in the environment (Weinberg and Weinberg 1988).

The capacity of the farm system to absorb variability in the environment can be changed by changing the combination of regulatory mechanisms. Hence, adaptation to changes in the variability of the environment involves changing the combination of regulators in a system (Weinberg and Weinberg 1988). In other words, adaptation entails modifying the structure of the farm system, by changing the regulatory mechanisms within it. The structure of the farm system is changed so that it may continue to produce an acceptable flow of product by better absorbing the new regime of variability in the environment. Hence, the adaptive capacity of a farm system can be understood by identifying the degree to which the combination of regulators in the farm system can be changed such that the system continues to produce an acceptable flow of product.

Climate change is expected to increase the variability in environmental inputs into farm systems. This means the structure of farm systems must be modified if they are to adapt to climate change. That is, the combination of regulatory mechanisms of which farm systems are composed must be changed in order for farms to successfully adapt to climate change. Consequently, a prerequisite for increasing the capacity of farm systems to adapt to climate change is the identification and, possibly, the creation of alternative regulatory mechanisms.

This raises a number of implications for agricultural policy in general and investment in agricultural research and extension in particular.

4.1. Implications for research and extension

First, producers are likely to switch strategically between the different types of regulatory mechanisms depending on their confidence in their expectations of the environment. The critical factor in preferring unconditional regulators (aggregation) to conditional regulators (error control and anticipation) is the unpredictability of the environment and the inability to respond in a timely manner to changes in the environment. To the degree that climate change heightens the unpredictability of the environment by altering causal relationships in the environment in ways we do not understand, and increases the rate of change in the environment, then adaptation to climate change may mean replacing error control and anticipation regulators with aggregation regulators. For example, climate change may change the population dynamics of pests and diseases to such a degree that an anticipation regulator such as strategic spraying cannot function effectively.

It follows then that the capacity of farm systems to adapt to climate change will be improved by investing in the identification and development of techniques and technologies that allow farm systems to better anticipate changes in environmental inputs and to react in a timely manner to those changes. This would require investment in research to understand precisely how causal relationships in the environment have been altered by climate change.

Second, the critical factor in choosing between anticipation regulators and error control regulators is the cost of regulating unnecessarily relative to the cost of not regulating when it is necessary. Since these relative costs depend on the precise distribution through time of variations in environmental inputs, climate change may well reverse these relative costs. This will alter the attractiveness of anticipation regulators relative to error control regulators. This may mean that agricultural technologies and practices that have been regarded as epitomising good management may no longer be considered attractive propositions. For example, climate change may alter the variability of environmental inputs to such a degree that an error control regulator such as irrigation using objective monitoring may generate more benefits than an anticipation regulator such as regulated deficit irrigation. In other words, climate change may alter the environment to such a degree that the risks associated with under-watering outweigh the gains from avoiding over-watering.

It follows then that the capacity of farm systems to adapt to climate change would be improved by investing in the identification and development of techniques and technologies that allow farm systems to better assess changes in the relative costs of different types of regulators. Relatedly, error control regulators could be made more attractive by the development of innovations that shorten response times. Anticipation regulators could be made more attractive by the development of innovations that improve the predictability of environmental inputs. For example, the attractiveness of a crop variety that offers superior performance in extremely dry conditions is enhanced the more accurately the occurrence of dry conditions can be predicted.

Third, since farms are systems then different regulatory mechanisms interact with each other. Consequently, producers will have priorities in regard to the relative importance of different regulators. This means producers are likely to avoid using a mechanism for regulating a relatively less important input that fundamentally weakens the effectiveness of the regulator of a relatively more important input. For instance, fruit growers that rely on strategic spraying to control major insect pests may wish to avoid using calendar spraying to control infestations of secondary pests.

Consequently, the attractiveness of new regulatory mechanisms will depend, in part, on their interaction with other regulatory mechanisms in the farm system. For example, producers that use forward ordering and calendar irrigation to avoid the risk of under-watering are unlikely to switch to irrigation scheduling using objective measurement of soil moisture if this would increase the risk of under-watering. The switch may become worthwhile if, at the same time, the risk of under-watering was reduced by adopting another regulator, for example, a reuse dam. It would be desirable if considerations of the interactions among regulatory mechanisms could be incorporated into the setting of priorities for investment in research and extension.

4.2. Implications for policy

There are implications for the design and setting of policy instruments that influence farm systems. Instruments such as regulation of farming practice and technology, the implementation of market based instruments, the levying of charges, the offering of incentives and financial assistance, infrastructure upgrades and the public provision of extension and emergency services may all be interpreted as influencing the composition and operation of aggregation, error control and anticipation regulators in farm systems. The banning of pesticides and the modernisation of irrigation infrastructure are examples. The capacity of farm systems to adapt to climate change will be also be practically influenced by such policy settings. Consequently, the preceding discussion is equally applicable to the design and setting of policy instruments.

Central to policy analysis will be the practical meaning of 'an acceptable flow of product over time'. Further research is needed to identify the determinants of tolerable output variability and interactions amongst those determinants.

5. Further Work

The implications for research, extension and policy flowing from conceptualising farms as systems composed of regulatory mechanisms suggest a variety of areas for further work. One important area for further work would, for example, be to develop methods for modelling regulatory mechanisms in farm systems. Such methods could be employed to test the arguments presented here in terms of the conditions under which the different types of regulatory mechanisms are preferred. These methods could also be used to evaluate the relative performance of the different regulatory mechanisms under varying environmental scenarios associated with climate change.

Methods for modelling regulatory mechanisms could be employed to evaluate the potential impact on the adaptive capacity of farm systems of government policy in regard to regulation of farm technology and practice, infrastructure upgrades and so on. They could also be used to evaluate the potential impact on the adaptive capacity of farm systems of agricultural innovations; or to identify the features of innovations that would improve the adaptive capacity of farm systems.

Another area for further research is to integrate the approach taken here with other applications of systems theory to agriculture. For instance, the approach taken here could be linked with systems-based approaches to adoption and compliance behaviour in agriculture (Murdoch et al. ; Bewsell et al. 2007; Kaine et al. 2007; Kaine and Bewsell 2008) and systems approaches to classifying innovations for extension (Kaine et al. 2008).

Finally, as noted above, further research is needed to identify the determinants of tolerable output variability, and interactions amongst those determinants, in order to provide a practical meaning of 'an acceptable flow of product over time'.

6. Conclusion

In this study we used general systems theory to formulate a definition of adaptability in farm systems and to understand how innovation in agricultural technologies and practices may increase the adaptability of farm systems, and under what circumstances. We proposed that farm systems are managed, open systems and that their purpose is to transform variable environmental inputs into a satisfactory flow of product. Farm systems were characterised as being composed of combinations of the three types of mechanisms for regulating systems; aggregation, error control and anticipation. The criteria for choosing between these types of mechanisms were described. We then provided examples of the different types of mechanisms drawn from pest management, irrigation management and the management of reuse dams.

The results of applying the theory raise some implications for assessing when agricultural innovations are likely to increase the capacity of farm systems to adapt to climate change. They also highlight the potential for the selection, design and setting of policy instruments to practically affect the adaptive capacity of farm systems. In summary the suggestions are:

- Adaptation to climate change is likely to require that producers modify the structure of their farm systems by changing their combination of regulatory mechanisms
- Adaptation to climate change may favour aggregation mechanisms over error control and anticipation mechanisms, and error control mechanisms over anticipation mechanisms
- The capacity of farm systems to adapt to climate change could be improved by developing innovations that allow farm systems to better anticipate changes in environmental inputs and to react in a timely manner to those changes.
- Error control regulators could be made more attractive by the development of innovations that shorten response times

- Anticipation regulators could be made more attractive by the development of innovations that improve the predictability of environmental inputs. This would require research to understand how causal relationships in the environment have been altered by climate change.

These implications could assist policy makers in considering options for investing public funds in research and extension activities to promote adaptation to climate change in agriculture and for responding to the novel, unmanageable implications of climate change.

7. References

Alway, T 2002, 'Codling Moth Mating Disruption Revisted in 2002', Retrieved 30/05/08, from http://entomology.tfrec.wsu.edu/stableipm/news040102.html.

Ambrosio, C and Linehan, C 2007, 'Insight into the relevence of Precision Agriculture technologies in Victoria's grain, dairy and horticulture industries. A report for Our Rural Landscape Key Project 2, Sub-project 2.5 Future Farming Systems; Optimising Production & Environmental Outcomes'. State of Victoria, Department of Primary Industries.

Angyal, A 1969, 'A Logic of Systems', in F Emery (ed.), *Systems Thinking*, Richard Clay (The Chaucer Press) Ltd., Suffolk, pp. 17-29.

Bewsell, D, Monaghan, R and Kaine, G 2007, 'Adoption of stream fencing among dairy farmers in four catchments in New Zealand', *Environmental Management*, vol. 40, no. 2, pp. 201-209.

CGIAR 1978, 'Farming Systems Research at the International Agricultural Research Centers' paper presented at: *CGIAR*, Washington.

Collinson, M and Lightfoot, C 2000, 'The Future of Farming Systems Research', in M Collinson (ed.), *A History of Farming Systems Research*, CAB International, pp. 391-419.

Cramb, RA 2005, 'Farmers' strategies for managing acid upland soils in Southeast Asia: an evolutionary perspective', *Agriculture, Ecosystems and Environment*, vol. 106, pp. 69-87.

Crouch, BR 1981, 'Innovation and Farm Development: A Multi-dimensional Model', in BRCaS Chamala (ed.), *Extension Education and Rural Development*, Wiley and Sons, Brisbane.

Cutwright, r and Pfeiffer, D 2002, 'Control of Codling Moth in Apple by Use of Pheromone Dispensers', Retrieved 30/05/08, from http://www.virginiafruit.ento.vt.edu/moth.html.

Dillon, J 1976, 'The Economics of Systems Research', *Agricultural Systems*, vol. 1, pp. 5-22.

Emery, F 1969, 'Introduction', in F Emery (ed.), *Systems Thinking*, Richard Clay (The Chauser Press) Ltd, Suffolk.

Feibleman, J and Friend, JW 1969, 'The Structure and Function of Organization', in F Emery (ed.), *Systems thinking*, Richard Clay (The Chaucer Press) Ltd., Suffolk, pp. 30-55.

Gasson, R 1973, 'Goals and values of farmers', *Journal of Agricultural Economics*, vol. 24, pp. 521-537.

Godden, D 2006, *Agricultural ane Resource Policy: Principles and practice*, 2nd Edition edn, Sydney University Press, Sydney.

Goodwin, I 2000, 'Irrigation scheduling for regulated deficit irrigation (RDI)'. State of Victoria, Department of Primary Industries.

Haines, MR 1982, *Introduction to Farming Systems*, Longman House, Essex.

Harris, D 2005, 'Industry Adjustment to Policy Reform: A case study of the Australian dairy industry', RIRDC Publication No 05/110, Rural Industries Research and Development Corporation, pp. 99.

Howden, SM, Soussana, J-F, Tubiello, FN, Chhetri, N and Dunlop, M 2007, 'Adapting agriculture to climate change', *Preceedings fo the National Acadamy of Science*, vol. 104, no. 50, pp. 19691-19696.

Kaine, G and Bewsell, D 2008, 'Adoption of Integrated Pest Management by apple growers: the role of context', *International Journal of Pest Management* vol. 54, no. 3, pp. 11.

Kaine, G and Higson, M 2006, 'Understanding Variety in Landholders' Responses to Resource Policy', *Australasian Agribusiness Review*, vol. 14.

Kaine, G, Hill, M and Rowbottom, B 2008, 'Types of Agricultural Innovations and the Design of Extension Programs' Practice Change Research Working Paper 02-08

Kaine, G and Johnson, F 2004, 'Water Policy in New Zealand and Australia: We're not playing for tiddlywinks', In *Proceedings of the New Zealand Grassland Association*, pp. 25-29.

Kaine, G, Lees, J and Sandall, J 1994, 'Planning and Performance: An exploration of farm business strategy and perceptions of control', The Rural Development Centre, University of New England, Armidale.

Kaine, G, Lees, J and Sandall, J 1998, 'Planning and strategy on family farms', *Bond Management Review*, vol. 5, no. 2, pp. 35-45.

Kaine, G, Lees, J and Wright, V 2007, 'An Approach to Predicting Demand for an Agricultural Innovation', *Australasian Agribusiness Review*, vol. 15, pp. 94-107.

Kaine, G, McDermott, A, Bewsell, D, Sheath, G and Binnie, B 2004, 'Strategic needs of sheep and beef farmers with respect to strengthening the growth and development of their farm businesses '.

Kaine, G and Niall, E 2001, 'Sheep Breeding: Complex Decision Making and Brand Loyalty. A report for Natural Resources and Environment, Victoria', UNE, School of Marketing and Management and Department of Natural Resources and Environment, Armidale NSW and Ballarat VIC.

Katz, D and Kahn, R 1969, 'Common Characteristics of Open Systems', in F Emery (ed.), *Systems Thinking*, Richard Clay (The Chaucer Press) Ltd., Suffolk, pp. 86-104.

Malcolm, B, Makeham, J and Wright, V 2005, *The Farming Game: Agricultural Managment and Marketing*, 2nd edn, Cambridge University Press, New York.

McDonald, S 2008, 'Dairy Effluent: Flood Irrigation of Dairy Shed Effluent'. State of Victoria, Department of Primary Industries.

Meredith, R (ed.) 2003, *Options for Change: New ideas for Australian farmers*, Rural Industries Research and Development Corporation, ACT.

Michaels, F nd, 'Organic Codling Moth Control', Retrieved 30/05/08, from http://www.greenharvest.com.au/pestcontrol/codling_moth_info.html.

Murdoch, H, Bewsell, D, Lourey, R and Kaine, G 'Understanding people's response to biosecurity regulation', In *Decision Making in Uncertain Times 3rd National Conference on Risk Management*, Auckland, 2006, The New Zealand Society for Risk Management Inc.

Norman, DW 2002, 'The farming systems approach: a historical perspective' paper presented at: *17th Symposium of the International Farming Systems Association, November 17th-20th*, Lake Buena Vista, Florida.

Qassim, A and Ashcroft, B 2006, 'Irrigation scheduling for vegetable crops'. State of Victoria, Department of Primary Industries.

Sandall, J, Johnson, F, Kaine, G and Higson, M 2007, 'A Review of Climate Change Policy: United Nations, Australia, New Zealand, China and Brazil', Department of Primary Industries, Victoria.

Stayner, R 1997, 'Families and the Farm Adjustment Process', in J Lees (ed.), *A legacy under threat?*, University of New England Press, University of New England NSW 2351, pp. 121-146.

van Gigch, J 1974, *Applied General Systems Theory*, Harper and Row, New York, Evanston, San Francisco, London.

Victorian Government Department of Premier and Cabinet 2008, 'A Climate of Opportunity Summit Paper' paper presented at: *Victorian Climate Change Summit*, Melbourne, April 2008, State of Victoria Department of Premier and Cabinet.

Victorian Government Department of Sustainability and Environment 2006, 'Our Environment Our Future: Sustainabiliy Action Statement 2006'. State of Victoria, Department of Sustainability and Environment,.

von Bertalanffy, L 1969, 'The Theory of Open Systems in Physics and Biology', in F Emery (ed.), *Systems Thinking*, Richard Clay (The Chaucer Press) Ltd., Suffolk, pp. 70-85.

Weinberg, GM 2001, *An Introduction to General Systems Thinking*, Silver anniversary ed. edn, Dorset House Publishing, New York.

Weinberg, GM and Weinberg, D 1988, *General Principles of Systems Design*, 2nd Edition edn, Dorset House Publishing, New York.

Williams, D 2000, 'Codling Moth'. State of Victoria, Department of Primary Industries.

Williams, D, Harrison, G, James, P, Washington, W, Holmes, R, Bates, V, Nardi, D, McFarlane, P and Ranford, T (eds) 2000, *Orchard Pest and Disease Handbook, 2000-2002*, Deciduous Fruit Austrlia, Inc.

Wilson, KK, Phillipp, PF and Shaner, WW 1986, 'Socio-cultural Effects on the Farming Systems Research and Development Approach', *Agricultural Systems*, vol. 19, pp. 83-110.