Chapter 16
When Is a Rice Insect a Pest: Yield Loss and the Green Revolution

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Abstract As land area to expand rice production is limited most increases in crop production in Asia must come from increasing yields on farms already under production. Insect pests are among the most important biological constraints limiting yield potential of modern rices but the extent of damage depends on how vigorous the crop is growing as well as the number of biotic and abiotic stresses affecting the crop that season. Yield loss data is useful for farmers, extension workers, researchers, and policy makers. A number of methods to estimate losses are available and more than one should be used. As accurate crop loss assessments are expensive to obtain for a nation on a regular basis, estimates are only available for limited areas of countries. Insect pest resistance exists for epidemic pests but not for chronic pests, the insect pest group that causes greater losses every year. Modern high tillering rices have greater capacity than traditional rices for compensation from insect pest damage and that capacity is enhanced by agronomic practices thus integrated pest management should be thought of within the context of crop management. For making better control decisions farmers need to assess the compensatory status of the crop and severity of crop stress acting on it. Due to crop compensation capacity, farmers need not correct all stresses to obtain high yields thus can combat the easiest or least expensive constraints and let the crop compensate for the rest. If nations are to get a handle on the extent of losses, farmers will need to be involved in the data gathering.

Keywords Rice yield loss · Asia · Insect pests · Crop loss assessment methods · Yield gaps · Biological constraints · Integrated pest management · Rice environments · Compensation and tolerance

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R. Peshin, A.K. Dhawan (eds.), *Integrated Pest Management: Innovation-Development Process*, DOI 10.1007/978-1-4020-8992-3_16,

16.1 Introduction

On a worldwide basis, rice is the most important food crop, constituting the staple for over half of the people. It is primarily a subsistence crop as more than half of the world's harvest is consumed on the farms where it is grown. In Asia most land suitable for growing rice is already dedicated and only limited additional land is available for expansion. Irrigation, which would allow an extra rice crop to be planted, is dependent on an increasingly scarce commodity, water. Ultimately the world must now focus on increasing the yield potential on existing fields as a means of increasing production (Barr et al., 1975). Yet world production has barely been able to keep pace with its increasing population setting off a vicious cycle as adequate nourishment is seen by some as a prerequisite for self regulation of human reproduction (Way, 1976).

World production of rice continues to face a critical stage as the Green Revolution's contribution has been declining in light of increasing population and urbanization. World population increase has also meant that the average farm size is steadily decreasing thus greater production is needed on an ever smaller land base. The past 10 years has witnessed a fatigue in the Green Revolution with the growth rate in food grain production falling below population growth (Swaminathan, 2006). A famine of jobs/livelihoods is the result of poor growth of opportunities for employment in the rural non-farm and off-farm sectors, and along with rising prices is leading to a famine of food at the household level.

Globally food production will need to double in the next 25–30 years (Tillman, 1999). The Indian prime minister recently emphasized the need to double that nation's annual food grain production from the present 160 million tons of rice by 2015 (Swaminathan, 2006). Since farm sizes are shrinking, this job is made even harder as in India 80% of farms belong to the marginal and small farmer ($<$ 1 ha) categories. The cost of agricultural production is rising higher than the minimum support price due to ever-increasing prices of inputs including energy. Investment in agriculture has declined over the past two decades. This has affected irrigation and rural infrastructure development. Due to the constellation of hardships faced by small-scale farmers, the number of Indian farmer suicides has reached alarming numbers. Farm indebtedness is rising. Average monthly per capita consumption expenditure of farm households nationally is around \$12. Endemic hunger is high both in families without assets of land or livestock, as well as in families with small holdings without access to irrigation.

In response to the food needs of developing countries in the 1960s, international agriculture research centers were established in Mexico for wheat (CIMMYT) and the Philippines for rice (IRRI). Soon new high yielding rices were bred which doubled the yield potential, and as they were photoperiod insensitive, two rice crops could be grown instead of one. Production thus was quadrupled. The optimism produced by the modern rices of the Green Revolution was quickly dashed by the large insect pest and vectored disease outbreaks throughout Asia (Litsinger, 1989). In the 1970s, a combination of bad weather and planthopper and leafhopper induced epidemics caused production in a number of countries to fall by an order of 30%

or more (Barr et al., 1975). Outbreaks from insect pests have been recorded on rice since 18 AD in Korea and from 701 AD in Japan with the most frequently recorded from rice planthoppers leading in some years to localized famine (Mochida et al., 1977). These calamities showed that sudden unpredictable events can shake the confidence of seemingly normal conditions. The world's food supply is always under threat from such unknown events. With the effects of global warming upon us we can expect an increase of such situations worldwide.

Until the population growth rate stabilizes worldwide, food production will have to be accelerated to keep up with demand. This increase in production can be achieved in four ways: (1) expansion of cultivated land, (2) annual multiple cropping, (3) increase in yields obtained from inputs (varieties, fertilizers, irrigation, etc.), or (4) reduction in losses due to crop stresses including pests. In the latter case large increases in food supplies can be achieved rather rapidly simply through wider adoption of current technology. Losses from all types of pests each year in grain alone are estimated to exceed the gross and net food grain deficits of the developing world (NRI, 1991). It is clear that if these losses could be reduced, food supplies would be increased without bringing new land or other limited resources into play.

In order to cope with the burgeoning pest problems in the 1970s, the concept of integrated pest management (IPM) based on ecological principles was introduced into Asia from industrialized countries and over time the new knowledge gained has resulted in management systems that have mostly pacified the once turbulent pest outbreak situation (Matteson et al., 1984, Gallagher et al., 1994). Savary et al. (2006) wondered why there are so few crop loss studies despite the fact that the basis for economic entomology is quantitative knowledge of losses. Still few reliable estimates exist in the literature as so many of us take for granted the need to control a pest. The first step in IPM is to identify the problems to be managed (Apple, 1980) which includes a determination of losses as well as the correct identity of the pests responsible. Thus crop loss assessment may be viewed as a problem definition discipline providing the necessary information for assessing and evaluating system performance. Crop loss assessment links pest injuries to possible qualitative and quantitative damage and yield loss to resulting economic cost. The framework advocated by Savary et al. (2006) links different types of knowledge on crop loss (e.g., damage functions, compensation/crop tolerance, injury profiles, multi-pests and multi-stresses, crop management, weather, and plant maturity and genetics) to a range of decision categories from tactical and short and long term strategic decisions including probabilistic treatments of injury-damage relationships. Neither insect pest populations nor crop losses are static – they tend to vary by season and location. Even when infestation/damage to rice appears high, the losses may be small and control would be uneconomical. The intensity and effect of damage depends on the stage of the crop and confluence of the many biotic and abiotic factors that influence crop growth. Entomologists can measure plant damage but often do not know the relationship between yield loss and infestation level needed in the design of corrective control decision-making thresholds.

Information on the amount of food lost to insect pests and vectored diseases is even more unreliable or has simply never been assessed in some countries because of the lack of manpower, knowledge, or resources (Walker, 1975). Crop loss assessment requires data on pest density, their biology, distribution in space and time, and the relation between pest damage and yield. Estimates of crop losses are few and scattered in the literature (Cohen et al., 1998). Wide areas of uncertainty exist which can and do influence assessments from:

1. Influence of climate that can upset food production projections,
2. Problem of the interaction of losses due to several factors such as two insects, a disease, lack of fertilizer, drought, and flooding where the contribution of each may or may not be additive,
3. Effect of rapid changes in normal crop production from introduction of new varieties, a new irrigation system, etc. and
4. Influence of economic factors such as price changes.

There are some 800 insect pest species that have been recorded to feed on rice (Grist and Lever, 1969). In tropical Asia there are some 18–20 species that are considered to be pests of major importance and regular occurrence (Pathak, 1968). Rice stemborers are probably the most serious group and usually 1–4 species are important in any given area.

Among the pest groups (weeds, diseases, etc.), rice suffers the most losses from insects. In Japan, where farmers utilize maximum crop protection measures, loss from insect pests is $< 2\%$ annually (Cramer, 1967); if India adopted these measures it could double food production as Cramer calculated a 36% annual loss there. Despite impressive technological advances during the first decade of the International Rice Research Institute's (IRRI's) existence, national production data showed increases barely able to keep pace with population growth in developing countries despite the Green Revolution (Barker, 1979).

There is tendency, however, for rice loss figures once published, to get passed on through the years in the literature, to become often quoted values for want of anything else, when its relevancy to the average annual situation or to current conditions should probably be suspect (Barr et al., 1975). The literature abounds with phases such as 'most destructive pest', 'serious pest', 'heavy crop losses' and 'major losses annually' rather than precise figures. Estimates of crop losses caused by insect pests are generally based on educated guesses or on a small number of experiments in limited locations and therefore are not reliable and objective (Khosla, 1977; Cohen et al., 1998).

Even when figures are available, often a distinction is not made as to whether the losses given pertain to a particularly bad year or to a more normal year, and often estimates appear to apply to the area badly affected by the pest with no accompanying information as to the extent of the affected area (Barr et al., 1975). Despite these obvious shortcomings, the information which exists when taken together gives a sense of the enormity of losses in developing countries although the magnitude of the enormity may not be known precisely. Due to great methodological difficulties of accurately sampling and measuring levels of pests of all kinds and correlating these with losses in yield, no detailed statistical studies have been made to consider the collective importance of all rice pests over sizeable areas.

16.2 Dynamic Nature of Yield and Loss

The dynamics of harmful pests may lead to plant injury on the standing crop which may or may not be visible to the observer. Injury leads to damage which may or may not lead to yield loss or reduction of crop value in economic terms (Litsinger, 1991). Pest assessment studies frequently show that crops vary greatly between sites and between years in their response to attacks even by similar densities of insects (Litsinger et al., 2005). At the other end of the scale there can also be great variability in the reaction of individual plants of the same crop. Damage is not always proportional to the size of the pest population, and therefore productivity (ie., food consumption and utilization) is no index of the damage done (Bardner and Fletcher, 1974). Studying the effects of insects on crop yield usually entails investigating the effects of populations of insects on populations of plants. These effects cannot often be predicted by extrapolation from the results of experiments with individual insects or individual plants because they are usually in competition with others of the same species for resources needed to grow, survive, and reproduce. Even individual organs on plants are in competition with each other for light and photosynthetic assimilates.

The damage from rice stemborers such as the larva of the stalk-eyed fly *Diopsis* spp. may be compensated if conditions are favorable, thus all insect damage is not necessarily negative (Feijen, 1979). There are reports of indirect yield benefits from insect damage (Brown and Marten, 1986). Akinsola (1984) found field studies sometimes gave erratic results as there were instances where hills containing tillers bored by *Maliarpha separatella* in Ivory Coast produced higher yields than unattacked hills. In addition some varieties recuperated more than others after a severe infestation of rice hispa *Dicladispa armigera* in Madhya Pradesh, India protected with insecticide sprays (Rawat et al., 1980a). The variety Ratna recouped almost six-fold compared to untreated. Both of these examples show the importance of basic data on losses in relation to insect infestation, and that data are often lacking or conflicting (Schulten, 1989).

Another observation that influences the dynamic nature of crop loss assessment is the large variation in field to field yields common within Asian rice farm communities. A normal result from a large sample is that yield will vary between 1 and 9 t/ha over a population of farmers (DeDatta et al., 1979; Pingali et al., 1990). The range of yields in the Filipino farmer populations of three sites is shown in Fig. 16.1 for the wet and dry seasons confirming these results. The data are averages of individual crops as reported by 20–40 farmer respondents randomly selected over the range of planting dates each season for over a decade. Due to the monsoon climate affecting Luzon Island, the yield ranges between Zaragoza and Guimba sites in Nueva Ecija were on average 1 t/ha lower than in Koronadal, the Mindanao Island site, which is under the influence of the Intertropical Convergence Zone climate. Differences relaxed in the dry season for all three sites. The range in yields was between 2 and 8 t/ha. Such large differences are often attributed to differences in management skills between farmers. Some farmers in such a sample equaled or surpassed yields registered on research stations, while others mismanaged their

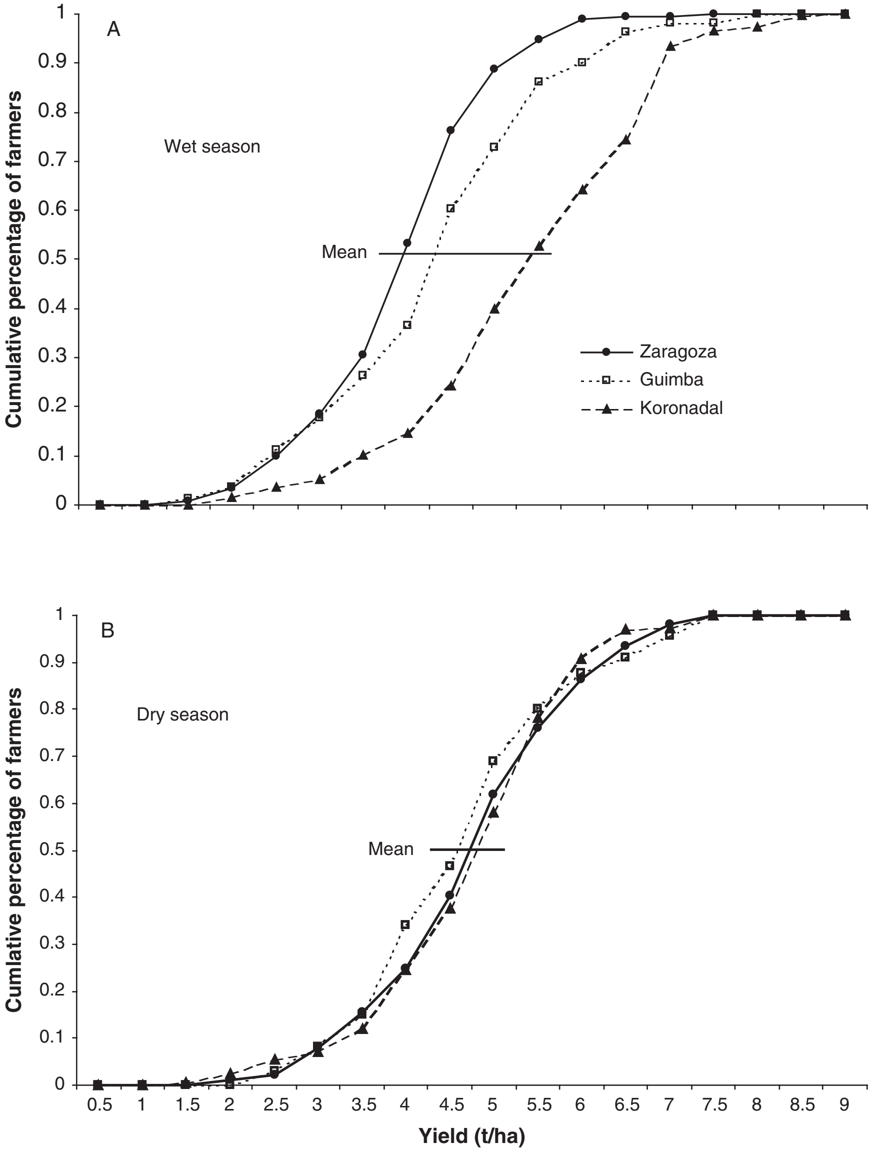

Fig. 16.1 Range of yield as reported in the wet (**A**) and dry (**B**) seasons by farmers surveyed in three irrigated rice sites in the Philippines 1981–1991. Some 20–40 farmers were interviewed per crop over 14 crops in Zaragoza, 11 in Guimba, and 18 in Koronadal (after Litsinger et al., 2005)

fields through poor pest, water, and fertility management among other causes or experienced unfavorable weather. The wide range of yields points to a large proportion of rice crops in the Philippines being under stress from a number of potential causes.

Analysis of the above farm record keeping database revealed a surprisingly different reality: the same farmer can experience yield swings of the magnitude shown above from season to season (Table 16.1). With each of the four farmers from two provinces, one can note the disparity of yield even within the same season for a pair farmers from the same location. This calls to question DeDatta's and Pingali's classifications of farmers which inferred that the best managers always attained the highest yields. This classification perhaps should be amended to the best managers 'per crop'. It also points out that even the best managers can get very low yields from

Table 16.1 Survey results of four farmers from two locations over a decade showing the season to season yield variability, Zaragoza and Koronadal, Philippines, 1982–1991[1]

		Zaragoza, Nueva Ecija				Koronadal, South Cotabato			
		Mr. Espiritu, 2.5 ha		Mr. Legazon, 2.5 ha		Mr. Rombaoa, 1.75 ha		Mr. Nelmeda, 1.5 ha	
Year	Crop	Cultivar	Yield (t/ha)	Cultivar	Yield (t/ha)	Cultivar	Yield (t/ha)	Cultivar	Yield (t/ha)
′82	WS	IR36							
′83	DS	IR42	2.5			IR56	4.7	"43"	5.1
′83	WS					IR60	4.4	IR60	5.9
′84	DS					"4.3"	5.5	Ri-10	4.8
′84	WS	IR42	2.4	IR42	4.5	IR60	7.1	IR60	5.7
′85	DS	IR56	5.4	IR36 IR42	4.4	IR60	1.8	IR60	4.7
′85	WS	IR62	3.5			IR64		IR60	5.3
′86	DS	IR64	6.0	IR64	5.4	IR60	4.8		
′86	WS	IR64	4.3	IR64	2.9	IR60	3.7		
′87	DS	IR42	6.5	IR64	5.0	IR64	5.0	IR66	5.6
′87	WS	IR66	5.1	IR42	4.2	"56"	4.3	"–6"	5.6
′88	DS					"43" "56"	6.4	IR72	2.7
	WS								
′88	DS					"56"	5.0		
′89	WS					IR74		"36"	5.5
′89	DS					IR74	6.2	"–36"	3.9
′90	WS					IR64	6.0	"90"	5.3
′90	DS					"90"	5.3	"90"	5.0
′91	DS					"90"	6.6	IR72	4.8
′91	WS	IR64 RC2	4.4	IR60 AG-O-O Milagrosa	2.8	IR60	5.6	"–33"	5.1

[1] WS = wet season, DS = dry season. Farm size in hectares is given for each farmer, yields in bold font show extremes per farmer.

forces apparently beyond their control. Thus the level of risk that irrigated wetland farmers face, which is the most stable of rice environments, is high.

There are also a number of issues that affect the interpretation of crop loss data as spelled out by Teng and Revilla (1996). The first is the time frame over which the data is collected. Most crop loss assessments are carried out for only a few crop seasons while they advocate that an ideal time series would be at best 10 years. Also the area covered in the studies is often very limited in geographic scale and may not be representative of major rice growing regions in the nation. Controlled studies are carried out in greenhouses may not be reliably extrapolated to farmers' fields. Finally the data are only applicable to certain crop management practices such as transplanted rice and may need to be recalculated if direct seeding were introduced, new genetic plant types grown, or IPM was introduced. Even when data are collected from many years or over a whole country the results can vary tremendously, for example stemborers in India and Indonesia losses were found to vary between 0 and 95%. Teng and Revilla (1996) point out that most data relates to small geographic areas as in no case did a country suffer 95% loss in rice production in a given year.

16.3 Framework of Yield Loss Concepts and Aims of Crop Loss Assessment

Teng and Revilla (1996) outlined a schematic diagram that defined the various yield gaps associated with crop loss assessment. They recognized three yield levels, the first of which is the actual farmer's yield that is under influence of yield reducing biotic and abiotic stresses. Farmers have the potential to reduce pest losses to obtain an economic yield potential which gap represents the crop loss measured by most national programs. A higher yield level can be obtained in most research stations where yield reducing constraints can be eliminated to a greater extent than can be done on farmers' fields to attain yield level 2 and the gap between farmers' actual yield and researchers' attainable yield is the crop loss measured by FAO. An even higher yield level 3 is the maximum potential yield that can be obtained in a certain environment as determined theoretically by crop modelling which defines the last yield gap if abiotic and genetic inputs were optimal.

Savary et al. (2006) outlined a series of steps in the evolution of crop loss assessment aims reflecting context and use. The first is empirical knowledge of environment-pest injury relationships that often lead to insecticide decisions based on assumptions on harmfulness. These are often wrong leading to overprotection or underprotection. A second step is empirically derived decision models and economic thresholds. The third is mechanistic single pest simulation models linking single pests to crop growth models to understand plant physiological relationships while the fourth introduces multiple pests and stresses. The fifth step is to scale up from the field level to larger geographic units that allow relating field survey data to crop loss estimates. Finally probabalistic data regarding a particular location that includes levels of risk of pest damage.

16.4 Rationale for Measuring Yield Losses

Pest populations building up in crops may have economic, social, and even political consequences. These consequences stem from the diversity of effects or injuries caused by pests: direct losses (in yield, in quality, or costs of replanting), or indirect losses (at the farm, community, or consumer level). Government food grain agencies need to manage buffer stocks based on predicted crop production to ensure steady food supply (Schulten, 1989). Errors in this calculation can have serious consequences which in times past have led to riots resulting from rice shortages causing changes in governments in Liberia and the Philippines. Defining the economic status of pests is also needed to budget public funding for research, extension, and training activities in plant protection (Agyen-Sampong, 1988).

Crop loss assessment is also central to one of the basic tenets of IPM which is to minimize insecticide usage. The main tools for insecticide decisions are economic thresholds which are pest densities that trigger a corrective action before the damage reaches the critical economic injury level (Norton and Mumford, 1993; Morse and Buhler, 1997). These tools are based on the economic injury levels determined from the relationship between increasing pest densities and yield loss termed the damage function. Action thresholds are surrogates for an economic threshold that are determined empirically if the damage function is not known (Bandong and Litsinger, 1988; Smith et al., 1988). Savary et al. (2006) categorized this as tactical decision making. The economic injury level concept is unique in that it integrates the disciplines of biology and economics.

In addition crop loss assessment is useful to estimate the effectiveness of control measures and introduced strategies and methods of pest control. Loss data can also play an important role in creating awareness of the need for pest control and the need to improve management strategies. Savary et al. (2006) distinguished short and long term strategic goals. Short term includes decisions on the choice of variety, planting time, prophylactic insecticides, nutrient management to bolster tolerance, and avoid resurgence causing insecticide. Long term strategic goals guide in selecting between highly resistant or moderately resistant genotypes or creating pest risk zones. Yield loss data attributable to pests are all the more necessary when agricultural systems are undergoing rapid and important transformations, such as from changes to direct seeding in place of transplanting or with hybrid rices instead of open pollinated types, so that the risk associated with such changes can be assessed from a plant protection viewpoint (Walker, 1975).

16.5 Crop Loss Information for Whom?

Clients of IPM programs such as farmers, extension workers, and agricultural policy makers want more management options to respond to pest threats they perceive (Kenmore, 1987). Such clients have been managing pests for years, using their own perceptions of crop losses and developing attitudes to crop losses from pests. They want to know what to do for the crop at hand and possibly for one crop in the future. Farmers and administrators usually perceive pest losses to be intolerable. They regard chemicals and especially insecticides as essential to rice production. In contrast field data suggest that insecticides are not essential in every rice crop. No more than half of the crops studied in Filipino farmers' fields exhibit significant yield increases with insecticides (Litsinger, 1984). Practical IPM programs must stay close to the clients and provide advice that they can understand and use. Where these large discrepancies between clients' perceptions and IPM field results come from needs to be addressed.

16.5.1 Researchers

A number of researchers studied crop losses to determine the causes due to injury from single insect pests or multiple pests or all types including abiotic crop stresses. This line of research should lead to better pest control technologies which will produce the greatest yield gains. From the scientists' point of view, identifications of discrete pest entities and their causal relationships to yield losses are pre-requisites for successful understanding and use of IPM (Goodell, 1984). A pillar of IPM is knowledge of the contribution of each pest to total yield loss. If the loss is sub-economic then there is no value in attempting control. Often crop loss assessment is added after the IPM program is already launched, thus programs have to rely on scientists' viewpoints which are largely best guesses. Normally neither extensionists nor farmers are consulted.

There are also researchers who have been publishing articles on losses using more refined approaches, most of which seem to be written for other scientists and not for clients with problems. Researchers' main concern when doing yield loss studies is to determine which pests warrant expenditure of scarce funding. One needs to justify this to research managers. When researchers speak to clients they present formulations full of internal rigor but with little evidence of the clients' expressed needs. Practical IPM programs and research managers must borrow from the literature to answer some of the questions asked by clients.

16.5.2 Extensionists

Without crop loss assessment, extensionists who are invariably blamed for the failure of such campaigns have no means of estimating the difficulty they actually face in promoting IPM, no means of measuring what proportion of yield increases can be attributed to IPM adoption, and no means appraising different IPM measures (Goodell, 1984). Most extension workers, let alone farmers, are not able to distinguish between damage and decision thresholds due to lack of training. While researchers have more skills to assess losses they are ill equipped to do so due to budget and manpower constraints. Extension agents, however, have the manpower to measure losses and are stationed throughout rice growing areas but such a job is highly demanding and is a low priority activity in most countries (Teng and Revilla, 1996). If yield loss relationships were determined, all the extension workers would need to do would be to monitor pest abundance.

16.5.3 Farmers

Goodell (1984) concluded more research is needed to measure crop loss and it is time to incorporate the farmers' perception of loss. Farmers' perceptions of crop loss should be compared to replicated yield loss studies to assess accuracy. Farmers tend to overestimate losses from chronic pests probably based on their experience from epidemic pests prompting insecticide overuse (Heong and Escalada, 1997).

When crop loss assessments of rainfed rice farmers are placed in the context of their entire economic portfolio, many may find any type of insect control unrealistic (Goodell, 1984). If farmers are already suffering yield reductions of 50% or more due to drought stress and declining soil fertility, and if for centuries they have kept livestock to buffer them during periods of crisis, then even a 30% loss to pests may not justify their adopting IPM. To estimate these felt crop losses for the purpose of planning, extension entomologists probably need to enlist social scientists. Occasionally the attitudes and perceptions of farmers can be changed through training (Escalada et al., 1999). Awareness training may bring the clients closer to what analytical or reductionist scientists can offer (Kenmore, 1987).

When farmers misidentify the causes of damage observed in their fields, they may spray an insecticide to combat a fungus. Without objective standards for evaluating the impact of yield and profits of each chemical treatment, they may conclude that their yield was saved even when there was no effect (Kenmore, 1987).

As some of these interactions may take place at low densities, the farmer has reason to feel insecure about ignoring low density populations, even though IPM demonstrations show that yields will not be affected by such low populations. If farmers apply insecticides and yields are high because pest populations never reached yield reducing levels, they will be reinforced in this behavior, all because practical field assessments of crop losses have not been done (Kenmore, 1987).

The majority of irrigated rice farmers in the Philippines regard pest damage as intolerable and unavoidable if no action is taken (Marciano et al., 1981; Brunold, 1981). This is true of farmers worldwide whose motivation is apply insecticide to their crops as insurance against loss rather than as an investment because they always perceive the pest threat as quite serious. More rice farmers use pesticides in irrigated rice than fertilizers in some areas. In a survey in Leyte 65% of farmers said calendar spraying was the best method and in addition 67% said the more one sprays the higher the profit, while 71% said sighting a few butterflies in the field meant to start spraying (Kenmore, 1987).

In the same study, there were different responses by farmers with different income levels: 56% of richer farmers said prevention was their biggest problem while none in the poorer villages said so but named specific pests as threats that had already invaded their fields (Kenmore, 1987). Thus richer farmers overestimated the threat as compared to field trial results far more than poorer farmers. Richer farmers tend to hire others to do crop monitoring and have more money invested so they want insurance. They also want to protect their social status as progressive farmers and impress the extension worker. Poorer farmers know what pests are present and have less money invested.

To answer our question of why the difference in farmers' behavior with field evidence:

1. One reason may be they have misidentified pest damage,
2. Farmers also want insurance (due to their ignorance) and feel that pests, unlike weather, can be controlled with insecticides,
3. Some of it is the interaction of crop growth stage with multiple pests, and
4. Also yield is very difficult to estimate as the difference may be 30% due to solar radiation from planting a month later or earlier (Evans and DeDatta, 1979)

With these uncertainties it is reasonable for farmers to conclude that losses are unavoidable and treatment is always needed (Kenmore, 1987). Farmers still need better crop loss assessment to help them rank and select their crop management options before and after each season.

16.5.4 Administrators

The objectives of administrators and policy makers is to ensure adequate food supplies for a nation. They are even several steps removed from the field, and must rely on reports from overworked or unreliable field scouts, thus are even in weaker positions to judge the benefits derived from chemical treatment (Kenmore, 1987). As they often prefer to act quickly and appear decisive they may order treatments and never evaluate them because the action alone serves their political purpose and a negative evaluation can only weaken that purpose. Clients continue to perceive pesticides as essential and act accordingly without testing that perception.

Like farmers their attitude is qualitative not quantitative and they tend to exaggerate damage (e.g., epidemics of tungro and brown planthopper *Nilaparvata lugens*) when there was little evidence of any yield actually loss. Thus they order insecticides before the season to prepare for a 'panic threshold' to be reached and as essential production boosters. Rice is a political crop, as cheap rice means political stability in the urban areas.

16.6 Where to Measure Losses

16.6.1 Research Stations

Research stations have been used as reference points to determine the yield potential of rice compared to farmers' fields. In the 1970s there was a lag phase in the adoption of modern rices and their management which was measured as the yield gap between research stations and farmers' fields (Barker, 1979). The yields taken on research stations were considered to be the highest attainable because of the more optimal conditions of water management, soil, and pest control that could be attained there. IRRI launched the Constraints Program to determine why farmers' yields were not reaching the potential of research stations. The constraints were categorized as environmental, technical, economic, and institutional (DeDatta et al., 1979). A number of environmental constraints are recognized to keep farmers' yields low: lack of sufficient and timely rains, floods, problem soils, and low solar radiation in the wet season. Technical and management constraints are inadequate irrigation water and pest control, use of lodging varieties, and ill timed and low fertilizer rates. Economic constraints include high costs of inputs, increased labor requirements, farmers' education level, and unavailability of inputs. Institutional constraints include lack of affordable credit, lack of timely input supply, irrigation system in disrepair.

Trials were set out in experiment stations and farmers' fields that looked at the contribution of fertilizer, weed control, and insect control on yield in the Constraints Program. The results differed by location but in general highest yields were obtained at research stations (IRRI, 1979). Barker (1979) described the phenomenon. The introduction of a new technology creates a yield gap and what economists call 'economic slack'. This is the difference between the present product of a sector and the product that could be realized if all resources were optimally utilized. It took Filipino farmers until the late 1980s to master the management of agro-inputs. The illuminative study in Luzon of Pingali et al. (1990) showed that by the late 1980s yields of the top one third of farmers matched those of research stations where the top one third of farmers achieved yields over 5.5 t/ha in the dry season and 4.5 t/ha in the wet season. As was seen in Fig. 16.1 but not appreciated by the study is that the top and bottom yielders could be the same farmer in a different season.

Research stations, however, are not always the most ideal of environments to attain high yields. On the IRRI Experimental Farm breeders grow susceptible cultivars in order to subject the latest lines to insect pest and disease pressure. Consequently the IRRI Farm had a high endemic tungro incidence which can affect the estimation of pest losses as yield of the untreated check will be lower than normal. Pathak and Dyck (1973) reported insect pest losses measured by the insecticide check method on the IRRI Farm from 1964 to 1971 where protected trials averaged 5.8 t/ha compared to 3.1 t/ha without. This resulted in almost 50% yield loss determination. However the fields were planted to susceptible varieties in order to test insecticides and thus were not representative of farmers' conditions. These high losses were widely circulated as were others from Philippine research stations that led the perception that insecticides were 'required' for high yields. The government therefore recommended prophylactic insecticide protection in its Masagana 99 rice production program. It was concluded from this data that to grow rice one needed to apply 4–5 insecticide applications. Studies later showed that this was a misconception (Gallagher et al., 1994). Cramer's (1967) often quoted losses were also taken from insecticide trials, many of which were conducted on research stations and timed when the highest populations occur.

16.6.2 Farmers' Fields

The Constraints Program early on identified two common concepts (Barker, 1979). One is to compare the potential yield from experiment stations with the present yield in farmers' fields as explained above. The second was to compare the yield of the best farms with the poorest. He concluded that yield gaps need to be determined within each location with its own yield ceiling. We saw from Fig. 16.1 if one measured the yield gap between the best and poorest farmers the wrong conclusion would emerge. It is not necessarily that the farmers with the lowest yield do not know how to manage their farms but that other factors are to blame. Economists should now determine what these are but high on the list should be effects of the weather. Zaragoza is located at the end of a large irrigation system and the wet season crop often matures at the time of the arrival of large scale typhoons. On the other hand Koronadal under the influence of the Intertropical Convergence Zone is regularly affected by El Niño droughts. Farmers often are not in charge of determining the timing of irrigation water delivery so chance plays a large role.

Constraints to high yield can be classified into two categories: those that affect the yield potential of the crop under the farmers' environment and those that affect the farmers' ability and willingness to achieve the yield potential on their own farms. The first is related to the potential of the new technology itself based on research and the local environment while the second encompasses the ability of farmers to learn how to apply the new technologies with optimal results (extension success) and knowledge building as well as overcoming institutional constraints of input supply, credit, water delivery, and land ownership.

16.7 Typology of Insect Plant Injury

Metcalf and Flint (1962) provide the most comprehensive description of the multitude of insect injuries to crops. The most conspicuous are those caused by insects feeding on plant tissue or sap (Bardner and Fletcher, 1974). Aside from direct plant injuries other major causes associated with feeding are injection of toxins, infection by plant pathogens, and the fouling of plant organs with insect bodies and insect products. Injuries less frequently encountered include laying of eggs on or in plants and the use of plants for the construction of shelters.

The reactions of plants to injury are often very complex. Although the nature, site, and intensity of the injury are important, the effects of injuries on yield depend very much on the growth process of the plant, its genetic constitution, stage of development, and on various environmental factors affecting its growth (Bardner and Fletcher, 1974). An understanding of some of these processes is provided by the results and theories of crop physiology, especially the techniques of plant growth analysis, which evaluate growth in terms of effective photosynthetic area and the production of dry matter and its distribution between various plant organs.

Differentiation of insect pest guilds can be made based on the effect of plant injury on the growth processes of a plant (Litsinger, 1991):

1. Tissue consumers = defoliators
2. Leaf senescence accelerators = planthoppers, leafhoppers
3. Stand reducers = armyworms, caseworms
4. Light stealers = planthopper honeydew and sooty mold
5. Photosynthetic rate reducers = whorl maggot *Hydrellia philippina* and stemborers
6. Assimilate sappers = planthoppers, leafhoppers, seed bugs
7. Turgor reducers = root feeders and stemborers

As can be seen a single insect pest may affect more than one physiological pathway. The first four guilds affect the amount of solar radiation intercepted while the last three on how efficiently it is used. Tissue removers do more damage than sappers because the plant has to allocate energy for tissue replacement as well as photosynthate. Plants are not passive recipients of damage and can repair, regenerate, and compensate.

The causes of decreased yields are easily identified when attacks kill plants or destroy yield-forming organs. Even so the quantitative relationship between the number of pests or injuries and yield can be complex if there is compensatory growth in the surviving plants, or if resistance to attack varies with crop age. For example, damage by both an armyworm larva and rice caseworm, injuries are confined to the destruction of leaf tissue and can be simulated artificially. Differences between the effects on yield of various combinations of insect injuries were shown to be caused by variations in the amount of leaves eaten and the distribution of injuries between leaves, both of which affected the production of dry matter. The growth pattern of the plant was also important as it determined the distribution of dry matter between roots and leaves. The decreased yield of roots and leaves resulting from attack by one larva was between 0 and 22 times the energy content of the leaf tissue eaten by the insect, depending on the effectiveness of compensation (Bardner and Fletcher, 1974).

Plant physiologists have found that in some cases the yield of the rice grain (metabolic sink) is limited by its inability to store all the photosynthate produced by green tissues and stems (the source) (Bardner and Fletcher, 1974). Under these conditions some loss of foliage might be tolerated without affecting yield. Yield formation in rice provides an explanation of the effects of attacks by stemborers. In unattacked crops wide variation in sowing rate results in similar numbers of panicles per hectare and similar yields. But the maximum number of shoots is usually several times as great as those which survive to produce panicles, many dying at an early stage through competition for light, nutrients, and space (Yoshida, 1981). Larvae feed during the period of shoot production and they cannot affect yield directly as very little of the dry matter produced by the plant before panicle emergence finds its way into the grain, which obtains most of its dry matter from photosynthesis in the flag leaf, the stem above this, and the panicle itself. The principal effect of the larvae is to kill potential ear bearing shoots, and as these are produced in excess, considerable compensation by the crop is possible.

One effect of sucking insects is to create an extra sink for assimilates which interferes with the normal partition of these products among the various plant organs. The effects on growth are complex especially as many sucking insects also have toxic saliva. Fouling of honeydew and subsequent sooty mold can be a secondary cause of loss in crops attacked by planthoppers because this encourages the growth of molds and lessens the amount of light reaching chloroplasts.

16.8 Methods to Measure Yield Loss

Barr et al. (1975) concluded that it is not surprising that most developing countries do not have the capability to conduct comprehensive surveys designed to assess losses due to various types of pests on any reliable and consistent basis, let alone on a detailed annual basis. A serious pest in the wet season rice crop may not occur in the dry season and vice versa. An insect pest which greatly damages dryland or rainfed wetland rice will not affect an irrigated crop as much and vice versa. One variety under cultivation may be devastated if a pest occurs in large numbers while another may have inherent resistance or tolerance and sustain relatively minor damage. Since the size of losses may vary with the year, the growing season, the type of culture, the variety being cultivated, the composition of the pest complex, etc., the design of an experiment to estimate loss needs careful examination and once determined needs to be defined under specific conditions. Crop loss assessment is a science in itself, requiring the best efforts of crop protection specialists, statisticians, and other experts to arrive at reasonably sound figures. Many projections of losses lack corroborative data on actual field losses. Zadoks (1987) outlined its historical development.

Serious and often catastrophic attacks by insects on crops have been recorded throughout history, though objective attempts to measure losses caused by insects only began in the 20th century. Pest assessment both on a local and on a national scale is now a well established branch of agricultural entomology and many methodologies of crop loss assessment have been developed. FAO pioneered efforts to standarize concepts, methods, and estimates of losses on a global basis (Litsinger, 1991).

Crop loss assessment researchers need to take note of the following factors that may influence the validity on loss data before extrapolating results from small scale trials to regional loss figures (Litsinger, 1991):

- Experimental fields are not representative,
- Influence of crop management which should be tested under typical conditions,
- Low yields may be viewed as normal due to hidden damage,
- Damage by several pests on the same crop may be synergistic, neutral, or antagonistic,
- Losses may be due to other causes than pests, and
- Methods to measure losses may be inaccurate.

Accurate estimates of insect damage and the economics of preventing pest damage are difficult to make because pest populations vary from season to season. Given the importance of variability in insect pressure, valid indicators of yield losses must be based on large samples of observations and be representative of some particular area. Moreover data should be analyzed as a sample from a population: no observation should be considered as separate or unrelated. Yield loss determinations for a single pest when other pests are present is particularly difficult.

Many methods to estimate yield loss from insects were reviewed by Litsinger (1991) and the present discourse will be an update. Estimation of the crop response (yield loss or gain) to a single pest attack or abiotic stress factor (moisture availability, temperature, etc.) is an equally difficult research objective. Conventional approaches that have been used to assess crop response to insect attack can be grouped into one of four categories: (1) observation of natural populations, (2) modification of natural populations, (3) establishment of artificial populations, and (4) damage simulation.

16.8.1 Key Informant Surveys

The relative importance of rice pests was determined in Indonesia (Geddes, 1992) and from five countries in South Asia (Geddes and Iles, 1991) where the country or region was divided into agro-climate zones and a large number of experts were interviewed to rank all categories of pests on the main crops from each region. A scale was made to rank the responses and summarize the results from all categories of pests ranked together. This method is the least analytical as perceptions are involved rather than field studies.

16.8.2 Comparing Damaged and Undamaged Plants

This method usually involves taking insect counts on individual plants from several fields, first exemplified by Ishikura (1967) in Japan to assess losses from second generation rice stemborers. Samples of damaged and undamaged panicles were taken and the decrease in grain weight of infested stems was multiplied by the number of infested tillers per unit area. This method seemed satisfactory, except if the infestation is light or when infestation occurs late in the crop cycle. But Ishikura noted that moths generally prefer rice plants of luxuriant growth for oviposition, thus assessment of loss is influenced by the selective nature of the pest and as such losses are underestimated when selecting panicles from both infested and uninfested ones.

Brenière and Walker (1971) assessed the loss due to *Maliarpha* stemborer in Madagascar by recording the number of tillers bearing filled panicles, partly empty panicles, and dry empty panicles. The weight of fully developed panicles and partly empty panicles was also recorded to give the yield reduction ratio. Yield loss was calculated by multiplying the total yield/ha by the yield reduction ratio. This method gives loss in terms of real yield but overestimates loss due to *Maliarpha* as it does not eliminate loss from other causes.

van Dinther (1971) assessed losses from two stemborer species *Rupela albinella* and *Diatraea saccharalis* in Surinam that best exemplifies this method. He selected 200 plants one week before harvest and by dissecting the tillers he quantified the number that were infested or uninfested. The density of panicles was assessed per m^2. He noted compensation would have little role in the plantations as the crop is harvested right at physiological maturity thus late developing tillers do not have time for their panicles to mature. A formula was used to estimate yield loss by each species: loss = (A–B) NP where A = mean panicle weight of uninfested panicles and B = weight of infested panicles, with N = no. panicles/m^2 and P = % infested panicles.

Lim et al. (1980) sampled damaged and undamaged areas of brown planthopper affected fields in an outbreak situation in Malaysia. They took 100 m^2 yield cuts from 6 to 15 fields in each of three sites from heavily infested (20–30 hoppers/hill) and highly infested (500–1000 hoppers/hill) fields and compared them with uninfested fields in the same irrigation system. These fields had become heavily infested 30–45 days after transplanting, but samples taken from sites where similar infestation levels occurred near harvest had much lower losses.

16.8.3 Extrapolation of Damage Caused by Individual Insects

This method is best exemplified by the rice bug *Leptocorisa* where Rothschild (1970a), through field and screen house cage experiments with traditional varieties, determined the feeding rates of individual adults and nymphs. He found that only the last instar nymphs and adults damaged the rice plant. Damage of the last instar nymph was found to be only equivalent to 0.4 adults so he used the term of ‘adult equivalent’ so that both mature and immature stages could be measured together. The difference between the feeding rates of both sexes was not significant. He also found that adults and last instar stadia lasted 13 and 5 days, respectively. He also determined the percentage of grains attacked and calculated that 1 adult equivalent/m^2 would cause 1% yield loss in a traditional variety. The calculations were questioned by van den Berg and Soehardi (2000) as subsequent studies by Litsinger et al. (1998) showed lower feeding rates in general and by males specifically and that compensation was not taken into account. Modern rices although have lower 1000 grain weights produce greater densities of spikelets. Furthermore van den Berg and Soehardi (2000) point out that adults, being highly mobile, also feed in grassy areas and shade provided by the cages extended the feeding periods during daytime.

16.8.4 Compare to Potential Yield

The first example of this method which assesses the potential yield of a wheat crop in an area comes from disease management in wheat in Montana in the US (Nissen and

Juhnke, 1984). Historical data was used to provide an estimate of potential yield for the locality which was then compared to actual yield. Potential yield was assessed based on crop water availability, crop management (variety, fertilizer, planting date, seeding rate), climate (temperature), weeds, insects, and diseases. The interaction of disease incidence with water stress was highly significant.

The same approach was used in rainfed and irrigated rice in Java using simulation models (Boling et al., 2004). Both environments were examined side by side in plots with plastic sheeting preventing lateral water movement. Drought, nutrient stress, and pest infestation or combinations thereof were set out in the experimental layout. Pests were monitored and injury to leaves and panicles assessed. The data was entered into a rice growth model to compare actual yields to potential yields in pest free conditions. Normal farmers' practices were followed including farmers' insecticide applications. Greatest yield loss occurred in the dry seasons from yellow stemborer *Scirpophaga incertulas*, brown spot *Helminthosporium oryzae*, and narrow brown spot *Cercospora oryzae*. Low yields were associated with high levels of panicle damage and losses when compared to the potential-yield estimates in the crop model (56% or 2.5 t/ha loss and 59% or 2.3 t/ha loss in the dry seasons of 1998 and 1999 crops, respectively). These high losses were due to the late plantings that occurred in each test year. Higher losses were associated with low potassium and low nitrogen plots. The pest losses were exacerbated by drought stress a fact which was corroborated by trials in Guimba, Nueva Ecija, Philippines in irrigated rice (Litsinger et al., 2005).

van den Berg and Soehardi (2000) working with rice bug organized trained 94 farmer groups in four districts in East Java to take field samples of rice bug densities from 45 hills three times per field during a crop from panicle emergence to milky stage in a stratified manner. These data were averaged and related to yield taken from each field of IR64 rice by linear regression analysis. Yields ranged from 4 to 10 t/ha over a range of 0–36 adults/m^2 per site, with most sites averaging $< 6/\text{m}^2$. This large sample size taken from a crop under farmer management showed a wide range of rice bug densities but there was no relationship to yield loss. Such exercises could be carried out by farmers organized over a region trained by farmer field schools over a number of crops to establish an historical yield potential as a measure of potential yield.

16.8.5 Compare Infestations on Susceptible and Resistant Varieties

This method was suggested by Israel and Abraham (1967) but the key is to find varieties of each which are of the same growth maturity and yield potential. With the advent of genetic engineering this method should have great promise in the future if designer cultivars of the same genotype can be fashioned each having resistance to individual pests. Losses could be readily measured for specific pests in a trial where all lines were sown in plots compared to the susceptible check. Such a method would be ideal for determining if pest combinations were additive, synergistic, or antagonistic. Bt rice (endotoxin of the bacterium *Bacillus thuringiensis,* a pathogen of lepidopterous insect pests (Cohen et al., 2000), could be a first example of the utility of this method which could be compared to the same genotype without the endotoxin.

16.8.6 Insecticide Check Method

Attempted elimination of insect pest populations by insecticides to quantify losses compared to an untreated check has been a widely used procedure. The method frequently is more practical with severe or perennial insect pest problems than with occasional pests as it depends on natural field infestations which are often not very high thus it is often difficult to generate damage functions. For example a range of deadhearts from 0 to 10% will be less useful than one 0–60%. It is important that the insecticides selected have no influence on crop growth. Unfortunately carbofuran which has been used extensively in rice in insecticide check trials due to its systemic properties and broad spectrum efficacy is phytotonic and will bias results to exaggerate losses (Venugopal and Litsinger, 1984; Moyal, 1988). The phytotonic effect is particularly evident if carbofuran is applied at or just after transplanting. Dosages that stimulated crop growth are higher than needed for control efficacy. The government of Korea even recommended carbofuran to be used as a 'growth hormone' with the effect of accelerating crop maturity up to 7–10 days to avoid seasonal cold temperatures. It is also known to be a nematicide but the explanation for its physiological properties has not been found. Soil pests were eliminated from consideration in the trials of Venugopal and Litsinger as the phytotonic effect was found not only on rice but on wheat and several weeds even in hydroponic culture.

An early example of use of the insecticide check method on rice was by Fernando (1959) in Sri Lanka with paired plots in farmers' fields (10 locations in each of 3 districts). One of the 30 m^2 plots was sprayed with endrin every two weeks. Two other examples are given. Another study was carried out in India in 54 m^2 field plots each with 15 different varieties and planted in a season of high gall midge *Orseolia oryzae* incidence (Prakasa Rao, 1989). Diazinon, which is not phytotonic, protected one of the plots. The method was used to evaluate the insect resistance mechanism of rice varieties. Those varieties showing least difference to insecticide protection were considered to be the most resistant. Catling et al. (1987) used the insecticide check method over several years and carbofuran applications were later replaced by diazinon. Insecticides gave only a 60% reduction in stem damage and 45% reduction in whiteheads which did not result in a significant difference in yield. Another problem was that sprays of chlorpyrifos caused resurgence of brown planthopper further confounding the results.

16.8.6.1 Growth-stage Partitioned Yield Loss

It is difficult to find selective insecticides that are specific for one pest group, thus another way of determining the key pests is to quantify losses by growth stages. The insecticide check method was used to measure losses from all insect pests in each of the three major rice growth stages: vegetative, reproductive (maximum tillering to panicle initiation), and ripening (Yoshida, 1981). In a typical 110-day variety, the reproductive stage would begin about 40 days after transplanting (d.a.t.) and end about 30 days later.

Aside from transplanted rice using wetbeds the method was carried out in a wide variety of rice environments and cultural practices such as direct seeded pregerminated rice as well as rainfed wetland and dryland environments including slash and burn culture. The method was perfected through a series of ancillary experiments. The first was to find plant-growth-neutral insecticides (Litsinger et al., 1980; Venugopal and Litsinger, 1984). The second tested the effect of plot size on insect pest infestations in adjacent treatments of insecticide treated and untreated side by side (Litsinger et al., 1987a). Plots need to be large enough where natural rates of arthropod colonization occur and the effect of a neighboring plot being treated would not influence pest and natural enemy buildup. A 50 m^2 plot was found to be too small but plots > 100 m^2 acted similarly with 1000 m^2 plots which were assumed to be identical with natural field sizes. Yield cuts at first followed IRRI's recommended 10 m^2 size established for research stations (Gomez, 1977). But when the same yield cuts were taken from on-farm trials, the coefficient of variability (CV) was often unacceptably high ($>10\%$). Larger yield cuts of 5 samples of 5 m^2 (25 m^2total) were found to provide acceptable CVs. In the randomized complete block design replications were farms with the number ranging from 4 to 8 per crop.

A further refinement was to prevent insecticide drift to unsprayed plots by having workers follow the spray man downwind with a mosquito-cloth mesh spread across a 1– × 6– × 3–m wood frame. Although dosages were at the high range of manufacturers' recommendations and frequencies of weekly or 10-day intervals, insecticide applications of broad spectrum materials (applied at recommended spray volumes), insect pest control was not as high as desired (Litsinger et al., 2005). This shows the limitation of insecticides as an IPM tool as farmers would achieve much lower levels of efficacy than were achieved in our trials. Highest efficacy occurred against leaffolders (*Cnaphalocrocis medinalis* and *Marasmia* spp.) averaging 83% control based on damaged leaves, followed by defoliators (green semi-looper *Naranga aenescens* and green hairy caterpillar *Rivula atimeta*) at 71% control also based on damaged leaves and stemborers at 67% control based on deadhearts and whiteheads. But the greatest disappointment came with whorl maggot with only 55% control. As a result in later trials the 0.75 kg a.i./ha monocrotophos sprays were replaced by seedling root soak (seedlings immersed in isofenphos or carbosulfan solution for 12 h). Efficacies increased but still did not rise above 80% control in most trials.

Three other growth stage partitioned yield loss trials were encountered in the literature that deserve comment regarding experimental technique. Kushwaha and Kapoor (1986) conducted an experiment in two consecutive wet seasons under high whitebacked planthopper *Sogatella furcifera* infestations and Pandya et al. (1989) against chronic pests over two crops. In both series of experiments, plot sizes were small (20 m^2) and carbofuran G was applied. An additional 3–4 treatments provided control in only each growth stage rather than omitting control from single growth stages to estimate loss by stage. In the trials of Litsinger et al. (1987a, 2005), loss in each of the growth stages was summed and adjusted upwards or downwards proportionally so that the total of the three stages equaled the total yield loss (complete control treatment less the untreated check). The use of carbofuran in Kushwaha and Kapoor (1986) and Pandya et al. (1989) biased the data but it would have been interesting to verify if the losses per growth stage added up in both sets of treatments. For example from protecting only the vegetative stage, one estimates the losses in the other two stages combined. There is no doubt that interactions occurred between growth stages as insecticides applied in the reproductive stage would not kill stemborer larvae already in the crop that would continue feeding into the ripening stage (Litsinger et al., 2006c). This is a limitation of the insecticide partitioned growth stage method. Pabbage (1989) undertook a trial in Sulawesi, Indonesia on dryland rice and omitted insecticide protection in four growth stages. Unfortunately he used carbofuran thus the losses may be overestimated. He also did not apportion the yield loss by growth stage thus the total loss was calculated to be 26% but when losses from the four growth stages were added it was double (59%) on a 2.4 t/ha crop.

The Philippine yield loss data was used to evaluate action thresholds which were tested empirically in farmers' fields. The insect pest infestation and yield loss were both scored against benchmark infestation levels and associated loss in each growth stage. The method was developed in order to evaluate action thresholds for each pest individually. The benchmark levels were based on the results of Smith et al. (1988). The benchmark justifying insecticide application was based on yield loss (250 kg/ha per growth stage) for all pests as well as damage levels. Combining pest damage and yield loss into a single benchmark was necessary as yield loss could only be calculated in a given growth stage and not by pest. For whorl maggot or defoliators the damage benchmark was 15% damaged leaves in the vegetative stage. The standardized infestation levels for leaffolders were set at 15% damaged leaves in the vegetative stage but lowered to 10% in the reproductive and ripening stages due to less compensation. For stemborers it was set based on percentage deadhearts in a ratio of 10:15:5 for each of the three growth stages based on (Dyck et al., 1981; Bandong and Litsinger, 2005). Action thresholds were then scored on a per field basis. Four outcomes emerged: (1) if the threshold was not surpassed and was not justified based on both benchmarks of yield and damage, it was scored 'correct not to treat', (2) if the threshold was surpassed and was justified by both benchmarks it was scored 'correct to treat', (3) if the threshold was not surpassed but was justified it was scored 'should have treated', and (4) if the threshold was reached but was not justified it was scored 'should not have treated'. The frequencies of these four outcomes add to 100%. An important point was that the trials were conducted under the prevailing management practices of the farmers with the exception of variety selection per crop. Farmers were selected over the whole range of planting dates each season so that the results would not be biased for early or late planting. Farmers were changed each season for the most part so that a more typical range of management practices would be incorporated so the results could be extrapolated over the site.

Various threshold characters were tested over the period of the trials in an iterative approach. For example for stemborers egg mass and moth densities were compared to deadhearts. Each character was tested at two levels each season in order to improve precision. A high level and a low level of each character was tested as separate threshold treatments intermixed with five other treatments to measure yield loss in a growth-stage, partitioned yield loss trial design which also included a farmer's practice and prophylactic best recommendation treatments. The trials were carried in four irrigated rice sites (recommendation domains).

16.8.6.2 Yield Gap Studies

The insecticide check method was employed by the IRRI Constraints Program to measure the 'yield gap' (the difference between researchers' insect control efforts and those of farmers) in a number of Asian countries. Complete factorial experiments and later split-plot design tested the main factors of the farmers' practice, high input, intermediate input, and other levels as appropriate for insect control (DeDatta et al., 1978; Gomez et al., 1979). The high input treatment is equivalent to the 'complete control' treatment of our yield loss trials (Litsinger et al., 2005). The statistician determined that the ideal number of replications was 20 in a given season per site. Plot size was 20 m^2 and a yield cut was taken in the center 10 m^2. Comparisons in the main trial were normally fertilizer rates, insect control, and weed control. Insect control was the use of insecticides which varied but often included vegetative stage applications of carbofuran granules. Using carbofuran and small plot sizes were not ideal to measure yield gaps due to insects based on evidence learned later on. Often the high input treatments lodged as the plants grew too tall giving a lower yield than the untreated (DeDatta et al., 1979). Fertilizer plots were bunded but an earlier ancillary trial showed that bunded plots tended to yield more due to a concentration effect of the applied chemicals. Therefore a practice of making an opening in one side allowed water to flow to depths equal to those in the field. The opening was on the side away from the water inlet so no current entered the plot.

The farmer practice treatment began with researchers attempting to copy the farmers' method in the trials by frequently surveying them during the crop. This often ended up not being exactly the farmers' method due to delays in reporting. Yield cuts were taken from the farmers' own fields where the trial was run in addition to within the experimental plot area as a cross check. In other studies the farmers' method was contrived as an average of practices based on a survey carried out previously. This of course will be highly inaccurate as we saw from Table. 16.1 that each farmer may change his practice each cropping season and has no preconceived practice that can be elicited by surveys before the crop is grown. Farmers for the most part respond to the prevailing conditions during crop growth.

Gaps were measured as the yield difference between the researchers' best technology (highest input treatment) on the farmer's field subtracted from the same treatment on the research station. The difference would be due to non-transferable technology and environmental differences. A second gap is the yield in the farmers' treatment subtracted from the researchers' best technology on the farmers' fields. This would be due to biological and socio-economic constraints and was partitioned between the main factors tested both in percentages and in absolute terms. This differs from the yield loss experiments in that there is no untreated check, although the farmers' practice approximates it (Litsinger et al., 2005). Intermediate input level treatments were also included and an economic analysis was carried out to determine the costs and benefits of all of the treatments.

Because the objective was to represent an entire area and not specific villages, proportional sampling was used. Surveys were launched to determine socioeconomic constraints from a minimum sample of 100 farmers. Surveys were carried out to determine how farmers perceive the most important constraints being tested. If farmers did not see a particular factor as a constraint one would not expect them to take action to overcome it. Researchers also recognized psychological constraints which would occur if farmers did not believe the new varieties and concomitant management practices would actually result in higher production and benefit.

16.8.7 Damage Simulation Methods

Damage simulation (surrogate damage) is one of the most controversial of the crop loss assessment methods (Poston et al., 1983). In this instance surrogate damage is imposed on the plant in the absence of natural pest populations. The primary advantage of this method stems from the ability to precisely control the degree of injury and to assess crop losses, even when economic pest populations are lacking. The method often allows the researcher more latitude in investigating the biology of the plant/crop response to insect injury. Most criticism of this approach stems from questions regarding fidelity of surrogate to actual insect injury. Therefore much biological data must be gathered and substantial equivalency information acquired before employing this technique.

A case in point is the use of injected herbicide to simulate stemborer deadhearts. The herbicide did cause deadheart symptoms but also affected plant growth in other ways and the results when various damage levels were regressed with yield showed it did not relate as well as cutting tillers carried out with scissors and to predictions based on crop modeling (Rubia et al., 1990a).

There have been various mechanical methods to simulate deadhearts. A number of other workers also resorted to scissors. Dang (1986) simulated *Maliarpha* damage produced two types: the first was to completely cut off the tillers at their base while the second was to approximate how *Maliarpha* damages tillers by making a cut half way across. Results were similar using both methods. Htun (1976) used a needle to cut the base of tillers to induce deadhearts. Feijen (1979) pulled the terminal leaf out of the stem.

Damage simulation for defoliators such as armyworm was is most often carried out by scissors but Bowling (1978) mechanized it with a rotary power mower with the height of the cutting blade adjusted to removed 25 and 50% of the above ground portion of the plants during the seedling and tillering stages.

16.8.8 Artificial Infestation

Augmentation of numbers rather than waiting for a wide range of naturally occurring pest densities to conduct the study may be preferred with chronic and occasional pests. Creating artificial populations is another technique that has been used frequently when precise control of numbers has been desired. This procedure usually involves rearing or collecting the pest and artificially infesting small plots. The pest may be restrained with cages or other barriers or unrestrained depending on the mobility of the damaging stage.

Small plots (4 m^2) made by concrete bunds in the screenhouse with plants sown in soil were infested with yellow stemborer egg masses at 5, 7, 9, and 11 w.a.t. (Soejitno, 1977). Similar trials were conducted in the Philippines with caseworm *Nymphula depunctalis* (Heinrichs and Viajante, 1987). Both studies were conducted without restraining cages which then allowed more natural sunlight.

More common is to infest caged plants in the field. The cages are left in the field for various periods of time, from one week after infestation (Bandong and Litsinger, 2005) to over the entire crop period to harvest (Heinrichs and Viajante, 1987). As cages affect the microclimate and reduce solar radiation their use will affect the quality of the results. In a study on deepwater rice, after infestation of yellow stemborer 6–8 weeks after transplanting (w.a.t.) tanks were caged to harvest (Catling et al., 1987). Viajante and Heinrichs (1987) made the observation that where cages were not used yield loss was always less than the caged condition. Thus plant shading by cages caused the plants to be stressed which combined with insect damage accentuated losses and reduced the plants' ability to compensate. Kenmore et al. (1984) reported the role solar radiation plays in manifestation of damage as hopperburn from brown planthopper occurred more on cloudy days; when the sun was shining the crop could outgrow the damage. Delpachitra and Wickramasinghe (1986) working with rice bug placed clear plastic cylindrical cages on single panicles that allowed natural solar radiation beginning at flowering after having protected the plots with insecticides until flowering. Six rice bug nymphs were placed in each cage which was checked daily to replace any that had died.

Dang (1986) infested 10 blackhead stage egg masses of *Maliarpha* on 10 random hills each in the field (an egg mass has ca. 50 eggs) in three growth stages: at early vegetative stage 20 d.a.t., maximum tillering 55 d.a.t., and pre-flowering 75 d.a.t. No caging was used thus the egg masses could have fallen prey to numerous predators to reduce populations between treatments to bias results. In the Philippines a more rigorous system involving three steps to prevent natural enemies from biasing results (Bandong and Litsinger, 2005). The trial was timed at the beginning of the planting season when natural infestation rates of stemborers and their natural enemies were low as determined by experience in the site. Moths were netted from the field and held overnight on potted rice plants. As one of the major egg parasitoids is phoretic an attempt was made to remove it from the moth by removing the anal tuft covering before oviposition occurred. As the method was not perfect, all egg masses were held in petri dishes until the blackhead stage when parasitized egg masses could be distinguished and discarded. Plots were infested weekly during the growth of the crop. During each infestation, leaf sections bearing blackhead stage egg masses were fastened to plants in the field with paper clips. Three egg masses were placed per 1-m^2plot distributed equi-distantly for each treatment except the uninfested check. Before the plots were infested, predators were removed by a motorized suction machine. As a third method, each plot was protected for 1 week with a cage with nylon mesh (0.5 mm) top and siding to exclude predators until the first instar larva entered a plant to escape predators. Using this method, near uniform densities of stemborer larvae were produced under near natural field conditions. Caging for only one week minimized the effect of shading on crop growth.

16.8.9 Crop Modeling

Crop modeling takes a dramatically different approach. Mechanistic crop growth models have been used to simulate the effects of pest damage on crop growth and yield by linking the damage effects of pest population levels to physiological rate and state variables of these models (Pinnschmidt et al., 1995). Such a model considers all of the main processes of rice growth. The daily accumulation of biomass is simulated by a growth rate which is proportional to an intrinsic rate of growth, the daily solar radiation, and the light intercepted by the canopy. The intrinsic rate of growth embeds the efficiency of several processes: gross photosynthesis, respiration, and transportation of photosynthates and synthesis of complex molecules. The biomass is then distributed to different rice organs (leaves, stems, roots, and panicles) according to partitioning coefficients that vary over time, depending on the development stage of the crop. Tillering depends on the amount of biomass partitioned daily into leaves and stems.

Empirical pest levels can be introduced into the crop simulation, but some cases represent true pest-crop models, where pest development is driven by crop variables and vice versa. For example a simulation model for the population dynamics of rice leaffolders interacting with rice was designed to improve the understanding of its role as an element of the rice ecosystem and to detect crucial knowledge gaps in view of a holistic assessment of its pest status (Graf et al., 1992). Pests are linked to crop models in physiological coupling points, and in some cases, pest effects could be measured quantitatively and in other cases damage consideration was only qualitative. Only quantitative data are suitable for simulation. Daily leaf consumption rates of leaffolders can be directly used for formalizing and parameterizing pest damage effects in crop simulations. Plant age, leaffolder larval age, varietal resistance, and temperature might affect feeding activities and have to be appropriately considered. The leaffolder model represents a synthesis of experimental results on biology and behavior. Based on the metabolic pool approach, leaffolder feeding and hence leaf mass losses were described with a generalized functional response model which is source and sink driven. An age structured submodel for the population dynamics was incorporated into the model for rice growth and development.

In another study the effect of stemborer deadhearts was simulated by subtracting the number of deadhearts from the number of vegetative tillers (Chander et al., 2002).

The removal of vegetative tillers was numerically linked to a corresponding loss in dry matter of leaves and stems. Stemborer incidence during the vegetative stage is an input of the number of deadhearts per day per unit area. The effect of whiteheads on crop yield can be simulated by reducing panicle weight in proportion to the whitehead fraction. The models were used to simulate the effect of stemborer damage by detillering 5, 15, 30, and 60% of vegetative, panicle initiation, and ripening stages on yield. Computer modeling combined with a few well chosen experiments permits more effective testing of hypotheses compared with field experiments (Rubia and Penning de Vries, 1990a). In both studies the effect of damage simulation was compared to experimental results.

Yield loss resulting from single as well as multiple pest scenarios can be simulated for any chronological pattern of pest occurrence and for any crop condition (Pinnschmidt et al., 1995). But in many cases parameterization of the pest damage mechanisms was done based on educated guesses, due to a lack of quantitative data. The simulation of pest effects with pest-coupled crop models requires knowledge of the mechanisms of pest damage. If direct observations of damage mechanisms are difficult, researchers can use indirect methods. Thus measurements of honeydew production are used to measure brown planthopper feeding rates while damage effects of stemborers are studied by artificial tiller removal. Quantitative estimates of pest effects can be obtained by characterizing the pathways of pest-crop interactions through observation and identifying the physiological crop processes affected by the pest (Pinnschmidt et al., 1995). The feeding habits of brown planthopper and the causes of hopperburn were thus studied as well as the damage activities of leaffolders and crop physiological process affected by sheath blight *Rhizoctonia solani*. Although qualitative data cannot be directly used by crop models, they do give important information about the physiological basis for simulating pest damage effects.

The basic task of yield studies is to estimate the rate at which a given amount of pest damage causes a crop to lose yield at each instant during the growing season. Because of their flexibility, pest-coupled models become the ideal tool for developing control tactics and strategies and thus improving decision making in IPM. They provide means to incorporate the crop and its growing conditions as a component of yield loss predictions and to estimate pest-free and pest-affected yields under variable conditions. By including economic values such as yield, price per unit of yield, control costs, and benefit from control in the consideration, damage thresholds can be suggested at which actions to control specific pests are economically justifiable. Least-loss strategies thus can be developed and pesticide application schemes optimized. An additional advantage of pest-coupled crop models over conventional methods consists of the fact that dynamic rather than static damage thresholds can be developed that account for the variability in the chronological patterns of pest or damage development.

16.8.10 Adding Environmental Factors to Crop Loss Assessment

Crop loss assessments for single pests have been estimated, but precise as they may be, their prediction is limited to a single pest interaction (Gangwar et al., 1986).

Crops, however, are under attack from a number of pests and other physiological stresses at any one growth stage, which estimation of yield loss should be taken into account. As we saw in Table 16.1, yields can vary widely on a given farm over years. Baumbärtner et al. (1990) felt that pest densities and yield loss should not be studied independently from other yield forming processes but should be incorporated into a comprehensive study of the production system. This objective, however, cannot be met by relying exclusively on traditional experimentation with individual factors but requires a systems approach. With this approach a production system can be achieved wherein all relevant resources, factors, and processes are evaluated simultaneously. The diversity of pests can be condensed into a small number of guilds, each functionally corresponding to one type of physiological injury mechanism. Savary et al. (2006) developed injury profiles to lump different pests and stresses into single units.

Because production levels and multiple pest infestations significantly affect control thresholds, a flexible approach to quantifying pest-induced yield losses has to consider them appropriately. Several empirical models have been developed to quantify the relationship between pest damage and yield loss (Pinnschmidt et al., 1995). But their application is limited to the specific environmental conditions, genotype, and soils. Crop growth simulation models are based on the quantitative understanding of the effect of weather, soils, plant maturity, and management on the dynamic crop growth. Crop models can enable the user to simulate the performance of crops under different regimes of climate, soil type, and cultural practices.

There has been little work in quantifying losses associated with multiple pests and complex plant stress factors. Conventional procedures provide no clues as to how to integrate single species measurements to estimate yield losses from combinations of problems (Poston et al., 1983). About the only possible choice is to assume that all yield reductions are additive (i.e., that yield reductions caused by two pests attacking one plant is the sum of the reductions when the same species each attack separate plants). By using the results from this approach, however, a pest manager could estimate plant yield reduction from multiple pests at greater than 100%. Therefore the possibility of non-additive antagonistic or synergistic interactions when dealing with multiple pests or stress factors cannot be ignored. To design a plot experiment to include all of the possible interactions is impractical. The reason so many plots are required is that entomologists typically ignore internal plant processes despite their primary role in determining experimental results. Injury is observed or induced and yield is measured.

By not building existing agronomic information into experimental designs, entomologists are forced by laws of statistics to do an amount of work equivalent to the rediscovery of these internal plant dynamics (Poston et al., 1983). This results in the impossible design of so many plots. In addition to the obvious impracticality of such an experiment, the applicability of results from one region to another would be limited. Changes in cultural practices, host varieties, stress factors, or pest complexes vary from one region to another and over time would necessitate completion of similar studies at each location periodically. A potentially more viable approach is for entomologists to begin to view the plant as a set of interacting components

(Poston et al., 1983). This viewpoint involves separating the injury-crop response question into three steps: (1) the researcher must decide which plant component or process is affected by the insect injury, e.g., an insect defoliator may remove leaf tissue and thus affect plant photosynthesis and water balance. (2) The response of the affected components or processes must be determined over a range of damage levels. In some cases such as insect defoliation, the change in the anatomy of the plant resulting from the defoliation may be used as an index of the magnitude of the damage. (3) The impact of the changes in affected components on yield must be quantified.

As an illustration, if two different stemborers show from past experience that the crop response was not additive, in step 1 we might determine that the main effect of larval tunneling is to upset the water balance (Poston et al., 1983). Step 2 would be to quantify the impact of injury on plant water use. Finding a non-linear antagonistic or synergistic relationship would account for the non-additivity of crop response to damage. Step 3 would entail determination of the influence of plant water use on yield. This would allow an indirect estimate of the impact of both pests on yield. By delving into plant physiology we have in effect found common grounds for additive responses. The total amount of tunneling is indeed the sum of each species' contribution. Thus plant response could be studied as a function of total tissue damage. Cumbersome factorial experiments may be replaced with a series of single factor experiments each corresponding to one of the steps above with a consequent large reduction in required field work.

Most estimates of yield loss are based on estimates from empirical methods and statistical comparisons between yields obtained at experimental farms and farmers' fields (Gangwar et al., 1986). One of the most important criticisms of the methods used is the assumption of the empiricity of crop loss assessment. A survey procedure was developed by Savary et al. (1994) to incorporate environmental factors inherent in the cropping system into the crop loss assessment. This method was followed in two large studies. The first occurred in C. Luzon in the Philippines on double-cropped irrigated rice (Savary et al., 1994) and the second in India in a rice-wheat rotational system (Savary et al., 1997). Two analytical approaches were used, the emphasis shifting from yield determining variables that are mostly qualitative in nature to quantitative and predominantly yield-reducing variables. The first approach was intended to characterize relationships among cluster and correspondence analyses while the second approach was aimed at generating yield loss estimates using combinations of principal components and step-wise multiple regressions.

For example, in the rice-wheat system the research team collected data for three consecutive years in 251 fields. Seven patterns of cropping practices were distinguished reflecting a wide variation in production systems especially in terms of use of inorganic fertilizers, manure, and degree of water control. Six types of disease profiles, four insect injury profiles, and four weed infestation patterns were identified. Correspondence analysis based on patterns of cropping practices and injury profiles yielded a path of increasing attainable yield associated with varying levels of intensification and combinations of injuries. The use of principal component analysis with multiple regression generated estimates of yield reductions due to rice diseases, insect pests, and weeds.

16.9 Analytical Methods

16.9.1 Direct Measurement

16.9.1.1 Simple Regression

Using data from the insecticide check method, damage functions derived from regression models showed that the relationship of pest populations and yield loss caused by them is usually linear except for the extreme upper and lower levels (Smith et al., 1988). In general when pest populations are very low, the effect on yield is minimal. At higher regions of the curve the effect of additional pests on yield loss tapers off. For each pest, the curve may change between locations. Non-linearity implies that other factors need to be considered in addition to the level of insect pest damage such as age of crop when infested.

Accuracy of sampling is influenced by the sampling method (Gomez and Bernardo, 1974). When hills were counted for stemborer damage this was less accurate than a per m^2 method as there was great variation between hills in tiller number and height. They found distribution of infested hills also influenced yield. Thus yield reduction may vary depending on whether incidence is spread widely or concentrated in a few hills. Also infested hills had more tillers showing the compensation effect had taken place. Larger sampling units were needed in the wet season than the dry season to produce the same statistical precision. They concluded that the presence of other insect pests and diseases should be considered because they could affect the yield loss estimate.

The use of absolute yield as the dependent variable in relating stemborer incidence is appropriate only if the yield loss estimate is for farms planting the same variety under the similar conditions (Gomez and Bernardo, 1974). They recognized that yield loss estimates vary greatly by growing conditions of season, variety, time of planting, and management. Damage functions can only be meaningfully made by samples taken under similar environmental conditions which effectively means taken from the same field and not mixing fields even of the same variety. Sample size has to be large >2 m^2.

Gomez and Bernardo (1974) found a linear relation between percent yield loss and percent whiteheads for most of the curve from 2 to 4 percent (the top range) although an exponential equation was the best overall fit. Thus percent yield loss varied with the yield, 2 percent deadhearts and 2 percent whiteheads caused 4.4 percent loss in fields yielding 3 t/ha whereas the same damage level caused 6.4% loss in a 4 t/ha crop, indicating that little compensation occurred. Ishikura (1967) found non-linear relationships between stemborer infestation rates and yield in numerous studies in Japan. In one of the earliest reports, Wyatt (1957) in Malaysia simulated varying degrees of stemborer incidence by removing 10–70% of the tillers at random from each hill 3 weeks before flowering. He showed that for each 1% increase in stemborer deadhearts before maximum tillering that 1.3% loss occurred. In Indonesia small plots in the screen house infested with yellow stemborer egg masses at 5, 7, 9, and 11 w.a.t. all produced linear regression relationships between damaged tillers and yield when yields were taken per hill (Soejitno, 1977). Barr et al. (1975) report a similar exercise in India where a loss of 0.3% was predicted for every 1% increase in deadhearts before maximum tillering and 0.6% loss at heading. Summarizing field data in a number of states from 1965 to 1992, Muralidharan and Pasalu (2005) found that for every 1% increase in deadhearts, whiteheads, or both, losses were predicted to be 2.5, 4.0, and 6.4% yield loss, respectively. In terms of grain production loss over ecosystems, 1% deadhearts, or whiteheads, or both phases would be 108, 174 and 278 kg/ha, respectively. Van Haltern (1979) found a linear relationship of each increase of 1% whiteheads resulted 1.2% loss with *S. innotata*. All of these damage functions differed because the growing conditions and management were different. Researchers think that these damage functions for each pest species are immutable but there is no right or wrong damage function but infinite numbers of damage functions due to the many interacting factors. Because of this variability in damage functions it follows that economic thresholds will also vary accordingly.

Damage caused by *Maliarpha* is manifested as percentage empty grains. The formula using percentage of empty grains was proposed for the assessment of loss and was found to be related to larval tunnel length in a linear fashion (Dang et al., 1983). The proportion of empty grains can be affected by many factors including crop management, diseases, soil, and adverse conditions and calamities such as drought and cold. In another study the principal parameter that can be used for assessment of the level of *Maliarpha* damage is percent tiller infestation and the relationship was non-linear, indicating that proportionally greater yield losses occurred as damage levels increased (Dang, 1986).

Whereas non-linear relations are the norm due to compensation there are notable exceptions. van Dinther (1971) selected 200 plants one week before harvest and by dissecting the tillers he formed five categories separating the panicles damaged by: (1) young *Rupela* larvae, (2) older *Rupela* larvae, (3) young *Diatraea* larvae, (4) older *Diatraea* larvae, and (5) uninfested. His data was graphed to show highly linear relationships between a wide range of damage levels and yield loss (van Dinther, 1971) (Fig. 16.2). Damage of *Rupela* was much less than *Diatraea* for equal infestation levels. *Rupela* develops within one internode and the nodal septum is not destroyed thus does not cause deadhearts or whiteheads in the same manner as *Maliarpha* in Africa.

Reddy (1967) reported with gall midge in India that yield was linearly correlated with percentage of damaged tillers that for every 1% of damage there is a loss of 0.5% yield. Williams et al. (1999) working with African gall midge *Orseolia oryzivora*, after excluding plots with infestation levels > 30%, found a linear regression relating a 2.9% loss per 1% increase in infested tillers.

Van Haltern (1979) monitored 35 sites on the Maros experiment station in Sulawesi, Indonesia and recorded the mean number of rice bugs per m^2 daily over the ripening stage for 21 days. At harvest time he sampled 10 panicles per m^2 where he monitored the feeding sheaths by a staining method to determine percentage of damaged grains which he plotted a linear regression with rice bug density expressed in rice bug-days. A rice bug day is the mean number of bugs multiplied by the number of days of observation which was 21. He then assumed that the percentage

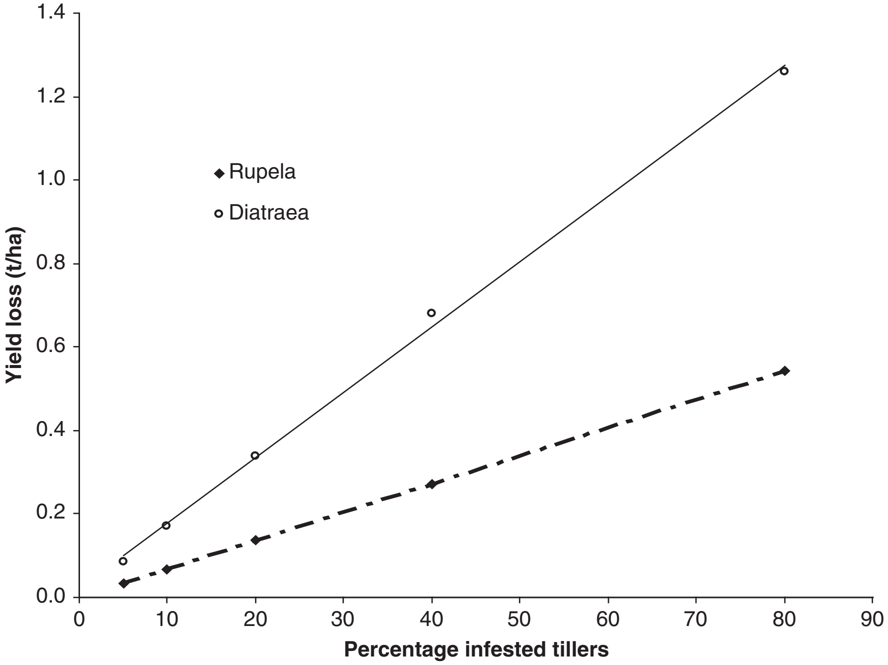

Fig. 16.2 Relationship between stemborer infestation rates and yield loss from two rice stemborers *Rupela albinella* and *Diatraea saccharalis* in Surinam. Data modified from van Dinther (1971) and show linear relationships and damage from *Diatraea* cause more loss than that from *Rupela*

of fed upon grains was equivalent to percentage yield loss in the analysis such that 5% damage will occur per 15 bug days/m^{2}which undoubtedly produced a bias as compensation documented by Litsinger et al. (1998) and later van den Berg and Soehardi (2000) was not taken into consideration.

16.9.1.2 Damage Functions

The economic injury level (EIL) concept has been generally accepted by entomologists as the backbone of progressive concepts in insect control, namely IPM. The concept serves as the economic foundation in decision-making processes. In sharp contrast to their theoretical importance, EILs have often been the weakest component in management programs (Poston et al., 1983). In fact very few firm research-based EILs have been established. Many in use are static and do not reflect changes in prices or other factors. This weakness has persisted for several reasons. Most of the IPM research effort has been devoted to pest ecology and especially to development of appropriate management tactics rather than the determination of explicit EILs. When attempts have been made they have been found to be notoriously difficult to measure. Also weaknesses in application of the EIL concept have become more obvious as specialists assume management tasks of greater complexity, e.g., multiple pests in a single crop or one pest in several crops. In these complex situations the EIL, at least in practice, becomes conceptually fatigued. Although the EIL was a major breakthrough when first proposed, it is now clear that some revision, re-interpretation, or expansion of the concept is needed if further progress is to be made. Many of the problems with current research stem from a lack of consideration for plant physiology. To correct this an improved research methodology is proposed which breaks the pest-host interaction into three separate types termed susceptive, tolerant, and over compensatory (Poston et al., 1983; Pedigo et al., 1986).

Susceptive is a linear relation, ie., every increment in damage results in a given incremental loss in yield (Fig. 16.3A). In many cases the responses may be linear over the range of damage increments tested. Many plant species compensate or tolerate substantial insect damage. If the range of damage increments in these studies is increased, the tolerance or compensation response may be exhibited. Consequently many of the damage functions reported probably are not susceptive responses. For practical purposes they may be considered susceptive because the range of damage increments tested encompasses values needed for EIL determinations. In the tolerant plant response to insect damage, probably the most common is sigmoidal (Fig. 16.3B). With this situation the plant will tolerate or compensate for some quantity of injury without reducing marketable yield until a critical point is reached. At this point the plant's ability to tolerate injury is exceeded and yield is reduced. After this stage yield is reduced with each additional increment of injury until a lower plateau is reached (the point after which additional injury does not cause a yield reduction). This lower level may reflect the plant's priority for energy allocation to reproductive parts or plant yield that was generated and stored before the insect attack. The overcompensatory relationship probably is the least documented plant response to injury (Fig. 16.3C). It differs from the tolerant response only at lower damage levels where the plant is stimulated to increase its marketable yield. This may result from the induction of tillering or other morphological or physiological changes in the plant. At higher damage levels the overcompensatory response is similar to the tolerant response.

16.9.1.3 Multiple-Regression

The rice crop is affected by a large number of abiotic and biotic constraints each of which alone or in combination will influence crop growth and thus yield loss. Confounding the determination of single pest relationships with yield is that there are normally several pests attacking the crop in any growth stage. In response to this, multiple decision thresholds have been developed which incorporate several pests that occur in a particular growth stage to be developed (Palis et al., 1990). However the rice crop and consequent losses which form the basis of developing thresholds are under the influence of not only insects, but as has been mentioned also from other abiotic and biotic stresses.

Savary et al. (1994) has attempted to take many of these into account with his crop loss assessment method that takes large samples of fields and monitors each frequently trying to quantify as many important variables as practical. They found

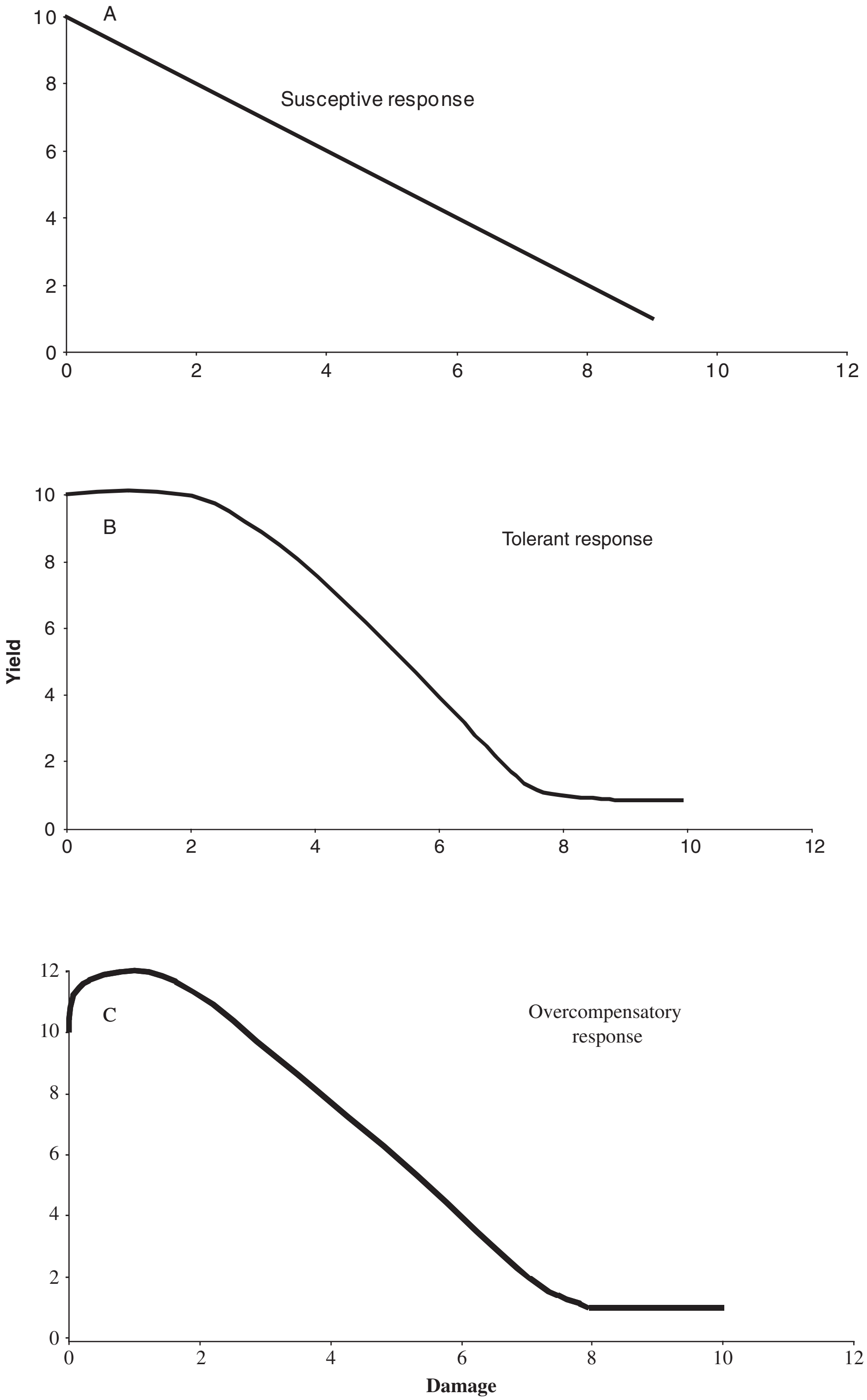

Fig. 16.3 Representation of the most common three (**A–C**) generalized damage functions that relate insect pest damage to yield (data adapted from Poston et al., 1983)

low yields were the result of combinations of many of these factors that alone were subeconomic but in combination became economic (Savary et al., 1994; Willocquet et al., 2000). It is no wonder that rice yields are so variable even within a farm community as the crop can be affected by literally >30 stresses each season, any one of which or of the multitude of combinations can affect yield. This number becomes even larger if we measure incidence over crop growth stages. The combinations are enormous and defy measurement. We know that a certain abundance of stemborer deadhearts has a different yield loss effect in each growth stage.

Multiple regression, as an analytical tool has been used to relate a wide set of biotic and abiotic variables to yield. Israel and Abraham (1967) worked out a multiple regression equation to incorporate loss at early growth and late growth for stemborers and then for all pests. They admitted that the equation does not take into account any possible relation between plant vigor and level of incidence in the field.

Williams et al. (1999) working on African gall midge recognized that variables such as topography, water level, fertilizer use in the nursery, and plant spacing had significant partial regression coefficients as well. Other stresses were also prevalent such as nutrient deficiencies, iron toxicity, and drought at ripening. They concluded that translation of injury to yield is dependent on the plant's physiological status (food reserves), genetics, crop stage, and environmental influences.

Gangwar et al. (1986) stated that various methods were available for estimating yield loss in rice in multiple pest situations. Surveillance in farmers' fields and the utilization of multiple regression analysis can be a useful tool for synoptic assessment of the contributions made by different pest variables on yield and in identifying the key pests. Such an exercise is particularly important in determining the threshold levels for pathogens and weeds. They assessed yield loss from surveillance data of rice yield and incidence of various pests in farmers' fields by multiple regression, with a view to obtaining a simple yet reliable tool which may be applicable in farmers' fields. Insects were evaluated in 1 m^2 areas as deadhearts, number of cut or folded leaves, or number of insects in net sweeps for hoppers or rice bug. Data were also taken on diseases where fungicide was applied to measure loss. Traditional and modern varieties were aggregated separately. In regression models yellow stemborer was the only insect to be found to cause significant loss in both traditional and modern varieties, however, all pests produced significant correlation coefficients. Yellow stemborer alone explained 69% of yield variation in modern varieties and 62% in traditional varieties. But a combination of pests explained variations in yield better than did any individual pest.

Seth et al. (1969, 1970) and Singh et al. (1972) from the Institute of Agricultural Research Statistics in Delhi undertook a large scale study in several states with the objective of estimating the incidence of pest populations and relating the level of incidence to yield and yield loss. They noted that relating incidence with yield (damage function) is difficult because yield is affected by a number of abiotic and biotic factors aside from pests such as variety, fertility, cultural, and manurial practices. Thus if yield loss studies are done in controlled conditions on experimental stations to derive the damage functions these effects will be missing and the results are not extrapolatable.

In the multi-year studies, each district within a state was divided into nine zones, and six villages were selected randomly from each zone, and within each village four fields were selected for observations and field trials. In two fields they were paired with another two fields of similar variety, manuring schedule, topography, soil type, and cultural practices. Three activities were carried out in the test fields:

1. Avoidable yield was measured by spraying one field of the pairs with insecticide in the seedbed, at 30 d.a.t., and again at heading.
2. In each field four plots of 1 m^2 each were selected to monitor stemborer and fungal diseases and yield,
3. Five plants were for tiller counts, and
4. Yield cut was only 4 m^2.

Estimates of damage functions were determined from our data in the Philippines using multiple regression for rice whorl maggot, leaffolders, stemborers, and white-backed planthopper but only the first two were significant over ten crops and five years of data (Smith et al., 1988).

16.10 Physiological Basis of Yield Loss and Compensation

The leaf blade is the most important photosynthesizing plant part. Any detrimental effect of leaf removal is directly related to loss of photosynthetic tissue and will generally retard plant growth. Tall, traditional rices have a different mechanism for compensation than for the semi-dwarf modern types. With tall varieties it was a common practice for the farmers to lop the tops off of > 40-day old, leafy seedlings before transplanting to stimulate tillering. An additional practice with traditional varieties was to remove the tops of vegetative stage plants to provide quality livestock feed and stimulate tillering without loss of yield. Plants growing in rich bottomland which produce luxuriant vegetative growth that would lead to lodging or cause mutual shading of lower lying leaves were most selected for this practice. Longer culms of traditional rices can accumulate more assimilate which later can be translocated to the grain as a mechanism of compensation. But taller plants have a higher proportion of non-photosynthetic tissue and a major disadvantage is their proneness to lodging.

In a number of tall varieties, yields actually increased up to 30% even with as high as 25–50% leaf removal at 40–55 d.a.t. (Kupkanchanakul and Vergara, 1991). Under good cultural conditions in the wet season, removal of $1/2$, 2/3, or all of the foliage of traditional rices can increase yield 32, 28, and 9%, respectively, when this is done before tillering (Taylor, 1972). Furthermore he reported defoliation of rice may have a rejuvenating effect and result in faster growth and more grains if there were enough time for recovery before flowers were initiated. Recovery was most for the longer maturing varieties and least for the shorter maturing ones. In plots where 30 cm of the leaf blades were removed from the tips at 34 d.a.t., rice yield increased 45% in a traditional variety yielding 2.1 t/ha (Rawat et al., 1980b).

Plant physiological studies showed pruning may actually increase the net assimilation rate (Kupkanchanakul and Vergara, 1991). If part of the green tissue is removed, the photosynthetic rate of the remaining green tissue increases to compensate for the loss. In some cases, however, removal of leaves will reduce yield, the balance (plus or minus) depending on the rate of crop regrowth. Leaf regrowth after cutting is associated with residual leaf area, current photosynthesis, and the utilization of accumulated carbohydrates in the stubble or roots. Starch content in the stem and leaf sheath is reduced as a result of defoliation since most of the reserve is consumed to make up for compensatory growth of the new leaf. Tillering can be inhibited, promoted, or unaffected by pruning. The controversial effects of cutting on tiller production can be traced to the photosynthate status of the rice plant. Readily available carbohydrate will be used primarily for the renewal of foliage and later for tiller growth. Removal of leaf blades retards growth of tiller buds as well as the accumulation of dry weight. Tiller formation can be promoted by herbage removal through suppression of apical dominance. Removal of growth apices stimulates tillering where new shoots arise from axillary buds. Over-vegetative growth leads to the death of young or developing tillers through heavy shading (Yoshida, 1981). Leaf pruning at later growth stages when most tillers have been initiated and are well developed, will not likely reduce tillering much. It may certainly prevent the death of tillers.

Increased grain yield resulting from pruning could be associated with an increase in panicle number per unit area. Apart from that, the growth of small and more erect leaves is enhanced. Rice plants with erect leaves intercept solar energy more efficiently, thus increasing grain production. Grain yield is reduced if leaves are removed at the reproductive stage. The yield component that is most greatly affected is the number of spikelets per panicle. This component decreases progressively with late cutting. Lower numbers of spikelets indicate an inadequate supply of assimilates from a small leaf area. Decreased grain yield as a result of flag leaf removal was also reported (Kupkanchanakul and Vergara, 1991). Varieties of a very long duration are least prone to grain loss from vegetative pruning. Leaf removal can reduce fertility percentage and grain weight. These yield components could be affected due to cutting by changes in light distribution and translocation of photosynthate during flowering and ripening. Critical stages of leaf removal that will adversely affect fertility percentage and grain weight occur between reduction division stage and grain filling.

Herbage removal may increase or decrease grain yield depending on such factors as varietal characteristics (leaf length, growth duration), growth stage at cutting, percentage and intensity of herbage removal, cultural practices, soil fertility, and environment (Kupkanchanakul and Vergara, 1991). Last cutting should be imposed not later than 30 days before panicle initiation so as not to limit leaf area for photosynthetic activity at flowering. Leaf cutting in deepwater rice reduced the rate of dry matter production but plant recovery was rapid and dry matter weight was the same as the control at harvest. The relative growth rate dropped severely after cutting due to low photosynthesis resulting from less active leaf area, causing negative net assimilation. Later relative growth rate in the cut plot increased and was similar to that of the control within 3–4 weeks, indicating that normal growth can be achieved with in 4 weeks of cutting.

Leaf cutting was reported to delay flowering from 1 to 37 days depending on the cultivar (Kupkanchanakul and Vergara, 1991). Although top growth removal produced variable responses in above-ground parts, root growth was always depressed. Removal of more than 50% of the plant's top stopped root growth within 24 hours and no new root growth occurred for 6–18 days afterward. Nitrogen application increases nitrogen uptake by the plant, and leaf area which results in increased net fixed energy and finally higher biomass production. Increasing total biomass production through increased nitrogen uptake also increases respiration losses and lodging susceptibility proportionally especially in tall traditional varieties. These negative effects can be overcome by herbage removal.

Compensation is the process by which plants respond positively to the effects of injury by insects and the decrease the negative effect of insect injury on yield (Bardner and Fletcher, 1974; Pedigo, 1991). It is also known that modern rices, as opposed to traditional rices, have a higher yield potential from their high tillering habit and actually possess a higher compensatory ability against a wide array of stresses, although as we have seen, traditional rices have great latitudes for compensation but more mechanisms are involved in the semi-dwarfs. They also can tolerate pruning although to a lesser degree and make up for their short stature by producing more tillers, thus they can store more reserve photosynthate to reallocate to injured plant parts or to fill more grains. They also have larger physiological sinks from greater spikelet densities. Tillers of modern rices grow to fill in open spaces in fields which ability traditional varieties lack. Thus if tillers are killed by stemborer larvae then new tillers can form or fewer will naturally die after maximum tillering. Many tillers die naturally from competition between their neighbors for light, space, and nutrients (Yoshida, 1981). Modern rices have a high capacity to compensate from stemborer injury particularly at the vegetative stage (Rubia et al., 1990a).

Compensation is possible via production of new tillers and by increasing the number of productive tillers and grain weight (Rubia et al., 1996). Defoliation lets in more solar radiation to the lower canopy, or stimulates nutrients to be allocated to grain filling vs. vegetative growth. El-Abdallah and Metwally (1984) observed a heavier 1000-grain weight at 10% deadhearts and at 2 and 6% whiteheads from *Chilo agamemnon* damaged rice relative to uninfested controls. In healthy plants an increase in grain weight may be due to increased translocation of photosynthetic products between tillers during grain filling (Rubia et al., 1996). Some insect pest damage can even increase grain quality via higher protein content.

Computer simulations predicted that up to 20% deadhearts can be tolerated without significant yield loss in the vegetative stage (Rubia and Penning de Vries, 1990a). Damage that prevents grain filling causes almost a proportionate yield reduction. While high use of nitrogen can increase compensation, shading would have an opposite effect. In use of detillering as an artificial simulation method, removal of tillers decreased shading, thus producing a bias. A corrective factor was developed which is needed to be used to agree with natural stemborer damage of a tiller slowly withering.

Results are not always straightforward as field studies by Akinsola (1984) showed there were instances where hills containing tillers bored by *Maliarpha* produced higher yields (overcompensation) than unattacked hills. The relationship between tiller damage and yield loss is multifaceted as stemborer effects on yield vary with pest population density, time of damage, and growing conditions (Rubia et al., 1990a). Some of the discrepancies can be explained by intra-plant and inter-plant effects. Within a plant there is compensation between tillers, and between plants there is compensation of uninfested neighboring plants which grow better alongside an infested plant. Environmental influences, however, determine how much compensation can occur at a given time.

One of the earliest reports of compensation comes from work on stemborers Ishikura (1967). He reported that generally there were more grains per panicle in the healthy tillers of an infested plant than in the uninfested plant although there were far fewer grains in the surviving infested tillers. Apparently infested plants made up for loss from injury by increasing the number of grains on the tillers that escaped infestation. Dang et al. (1983) likewise reported that sometimes there were greater numbers of grains per panicle in *Maliarpha* infested than uninfested crops.

In some crops even a low infestation can increase yield. Compensation virtually enters into all aspects of rice crop physiology. In most annual crops, the individual plants are in competition with each other. Competition tends to accentuate differences in yield between attacked and unattacked plants in an attacked crop. Unattacked or slightly injured plants yield more than do individual plants in an unattacked crop, filling the space of plants which have been killed, or where growth is badly affected. These features are well illustrated by rice where competition is intense. An isolated plant can yield more than 25 times more than a plant sown at normal field densities. There is a considerable capacity for compensatory growth by young plants should any of their neighbors be killed (Judenko, 1973). Cereals also show competition between organs of the same plant, for at normal spacing not all the shoots which are produced can survive to produce ears. The rice plant normally produces a large sink of grains via many tillers and leaves. More often than not the environmental conditions cannot sustain the anticipated high level of photosynthesis resulting in empty grains. It is not unusual for modern rices to average 15% unfilled grains (Yoshida, 1981).

According to Bardner and Fletcher (1974) compensation involves one or more of the following three processes:

1. Attacked plants or organs are competing with others for space in which to absorb water, plant nutrients, or light. This is commonly seen in cereals that have a relatively constant yield for a wide range of sowing rates. Where injury occurs early in the life of the crop, the surviving plants (especially those that are uninjured) grow larger and have more panicle-bearing shoots than normal. Surviving plants also produce heavier ears than normal.
2. Attacked organs can still provide what is needed. This can happen if the source of water, plant nutrients, and photosynthetic products is larger than the sink.

3. Harvested organs are attacked, but many are superfluous. This is the reverse of (2) and occurs when the sink is larger than the source and is common in crops of indefinite growth. Pruning that stimulates yield is another example.

An important caveat applies to reports documenting increases in photosynthetic activity following defoliation. Many experiments have been interpreted too broadly (Trumble et al., 1993). Although the tissues remaining after partial defoliation may increase photosynthetic activity, the increase may not be adequate to replace the productivity of the leaf area lost.

In natural systems, plant species that can tolerate or compensate (e.g., recover equivalent yield or fitness) for herbivore feeding have obvious selective advantages that lead to genotype maintenance (Trumble et al., 1993). Scientists often cite an optimal strategy for enhancing fitness. Historically one of the most significant problems delaying an understanding of compensatory processes has been the erroneous assumption of linearity between plant growth (usually assumed to be equal to yield) and leaf area based simply on the presumption that carbohydrate production increases proportionately with leaf area. During the 1960–1970s this generally accepted presumption greatly inhibited the understanding of compensatory responses.

Because differences in growth versus yield can be dramatic, with arthropod damage to foliage greatly stimulating one at the expense of the other, conclusions were often apparently contradictory (Trumble et al., 1993). In addition the relative importance of growth versus yield is substantial when comparing evolutionary or ecological fitness with agricultural suitability, but these concepts were often considered equivalent. Fortunately the pursuit of this hypothesized linear relationship between leaf area and yield led to a body of knowledge that allowed researchers to recognize the limitations of this assumption and stimulated investigation into a variety of important mechanisms affecting plant compensation. Probably the foremost reason for the lack of a consistent linear relationship between carbohydrate production and growth or yield is the complexity and variability of the plant resource-allocation infrastructure. The exact mechanisms associated with the partitioning and allocation of photo-assimilates in plants are poorly understood at best. Plants such as monocots with a limited number of sinks and extensive vascular systems may not show such restricted allocation (Trumble et al., 1993). Other factors can impact the complexity of plant responses. Variability in environments creates a mosaic of possible outcomes from herbivory which is further complicated by changes in plant physiology and concomitant compensatory events that vary with vegetative or reproductive stages.

Endogenous factors affecting plant compensation are defined as those mechanisms that are primarily influenced by allocation or reallocation of resources within the plant (Trumble et al., 1993). These include regrowth patterns, photosynthetic activity, senescence, leaf morphology, and canopy architecture. Variable distribution of resources can result in major changes in the form of plant compensatory responses and is strongly influenced by source-sink relationships. Sink-limited plants are characterized by lack of yield reduction following leaf loss. In such plants carbohydrates may be stored in structures other than leaves; up to 40% of the stem weight may be sucrose.

Judging the degree of sink limitation is often difficult because of variable importance of other compensatory factors, including hormonal balance effects on translocation or assimilate release by senescing tissues (Trumble et al., 1993). In contrast source-limited plants usually suffer marked growth or yield reductions following a decrease in leaf area. Many common crop plants are source-limited, and the literature provides numerous examples of yield loss due to arthropod removal of leaf area. The relative effects of sink or source limitation on yield in agricultural crops are likely to vary with cultivar, growing conditions, and stress. This variability represents a major challenge for plant breeders attempting to utilize plant compensation for arthropod resistance.

An increase in net photosynthesis activity may occur following arthropod damage because leaves often function below maximum capacity particularly in monsoon season crops (Trumble et al., 1993). Less leaf area may improve water availability for the remaining leaves thereby improving water status resulting in stomata remaining open longer in dry periods. Similarly an increased availability of nitrogen due to either reduced leaf area or a feeding-induced (premature) senescence could enhance protein synthesis. Defoliation during the critical stage of grain set frequently results in reduced yields.

Exogenous factors that impact compensatory responses are not directly under the physiological control of the plant (Trumble et al., 1993). These include such environmental factors as nutrient availability, intensity and timing of defoliation, and herbivore distribution. Predicting plant compensation responses for arthropod damage is complicated by variance in nutrient availability which can affect not only growth but also the allocation of resources within the plant. Nutrient pulses which occur in both natural and agricultural systems variably affect leaf- and root-relative growth rates and allocation of reproductive structures. The relative level of optimal versus substandard nutrient availability as well as accessibility of growth related nutrients (N, P, S) versus other nutrients (K etc.) will influence biomass allocation (Trumble et al., 1983). Thus because nutrient availability to the roots changes relative sink strengths, and sink strength relates directly to compensation through resource allocation, the nutritional status of the root medium plays a significant role in compensatory responses.

Intensity of defoliation includes both degree of leaf loss and number of successive episodes of defoliation (Trumble et al., 1983). Although plants generally compensate less for multiple defoliations due to chronic herbivory than for episodes of single defoliations, some plants can effectively compensate for more than one partial defoliation.

The relationship between timing of arthropod damage and plant phenological state is critical to understanding compensation responses. Bardner and Fletcher (1974) reported that the relationship between injury and yield varies with growth stage at the time of injury resulted in the following generalized pattern for annual plants:

1) Plants are intolerant of damage and compensate little immediately following germination,
2) As vegetative growth proceeds, plants become increasingly tolerant,

3) At the onset of flower production, plants become less able to compensate (specifically those species with short flowering periods), and
4) As reproductive structures ripen, plants again become tolerant to arthropod defoliation.

The injury to the rice plant as well as the loss in yield caused by stemborers is complicated by diverse factors (Ishikura, 1967). The recovery of the infested plant from injury caused by the first stemborer generation is remarkable and is affected by plant characteristics, soil fertility, and climate.

Water and temperature stress can significantly impact plant compensatory capacity, mostly through alteration of allocation and reallocation of resources and stomatal closure effects on gas exchange and photosynthetic capacity (Trumble et al., 1983). Most of the physiological changes due to water and temperature stress that influence plant compensation are similar. The rate of leaf photosynthesis at light intensities is proportional to the leaf nitrogen content (Rubia and Penning de Vries, 1990a). In the case of low nitrogen supply there was always little compensation so that the yield reduction is approximately proportional to the incidence level. These results suggest that applying fertilizers will suppress yield reduction caused by stemborer.

Results show that rice may compensate for stemborer injury by increase the rate of photosynthesis of leaves adjacent to the stemborer killed leaves (Rubia et al., 1996). There are at least three mechanisms that could explain this increase:

1) Partial defoliation can cause increase in photosynthesis in the remaining leaves, allowing for an improved supply of cytokinins to the remaining leaves by removal of sinks and leading to an increase of carboxylation enzymes,
2) An increase in assimilate demand by previously existing or new sinks (e.g., replacement tissue) can increase photosynthesis in the remaining leaves, and
3) There may be translocation of nitrogen from dying leaves to healthy leaves to increase nitrogen concentration in the leaf blades.

At the vegetative stage, rice plants actively produce tillers, and some tillers including leaves of those tillers may be lost without reducing grain yield because the number of productive tillers is determined at the maximum tillering stage. Simulated damage was made by removing tillers with scissors showed that the vegetative damage could tolerate a 30% loss through this physiological mechanism (Rubia et al., 1990a). There was no effect on the total number of panicles formed if the rate of productive tiller formation is as fast as the rate of tiller loss due to stemborers.

The rate of induction of new tillers, spikelets, and grains depends on the rate of production of carbohydrates. The amount of carbohydrates required to initiate a tiller determines the maximum number of tillers that the crop can support in the prevailing environment and this amount increases with plant age. Spikelet and grain formation rates are proportional to the rate of carbohydrate production and independent of the number of tillers until the maximum number of spikelets per tiller or the maximum grain weight is reached (Rubia and Penning de Vries, 1990a).

Reproductive stage infestation leads to greater yield reduction, and physical factors such as low solar radiation can especially aggravate the effect of stemborer on yield (Rubia et al., 1996). Rice plants can compensate for stemborer injury by translocating assimilates from injured to healthy tillers. There appears to be less active translocation at the reproductive stage and less photosynthetic activity in the primary tillers, roots, and cut stems. That implies the later the injury the slower the plants can compensate by translocating assimilates from injured to healthy tillers.

The results by Rubia-Sanchez et al. (1999) suggest that primary tillers, not infested by brown planthopper, translocate nutrients and assimilates to the main shoot as a compensatory mechanism. Brown planthopper sucking on the main shoot reduced height, leaf area, average photosynthetic rate of the two upper leaves, leaf and stem nitrogen content, and shoot dry weight. Brown planthopper-susceptible cultivars with few tillers may not be able to compensate sufficiently for injury at the vegetative stage. Thus cultivars with high photosynthetic capacity and faster translocation ability may suffer less. Photosynthesis and transfer of nutrients and assimilates from tiller to tiller is an important aspect in plant compensation from brown planthopper.

Evidence of compensation also occurred with studies on the rice bug which was based on the fact that over 95% of stylet sheaths (left on the plant after feeding) were located on filled grains (Litsinger et al., 1998). This observation goes contrary to the belief that rice bug feeding at the milky stage causes empty grains. Rice bug feeding does cause empty grains but the evidence points to the cause of unfilled grains as being indirect. After the rice bug stops feeding the plant apparently redistributes photosynthates to the fed-upon grain at the expense of a younger spikelet which goes unfilled.

16.10.1 Field Distribution of Damage

The distribution of insect infestations on and between plants affects the ability of a crop to make compensatory growth in response to injury (Bardner and Fletcher, 1974). Compensation is less effective if killed or injured plants are aggregated such as hopperburn, a caseworm attack and stemborers. Colonization of planthoppers is in patches and once they kill a plant they disperse to neighboring living ones and after these in turn are killed keep migrating in an ever concentrated ring outwards causing a growing patch of damage. The cause of aggregation for caseworms is wind blown or water driven larvae in their floating cases and for stemborers by short larval dispersal from egg masses. Sometimes the edges of a field are most heavily infested due to dispersal and host seeking behavior. Small insects such as hoppers can be windborne for many miles and fall out on the windward side of barriers such as wind breaks or hills. In agricultural systems, plant spacing is such that small losses to the canopy can be readily filled but if larger areas are damaged adjacent plants cannot easily compensate.

Arthropods that feed in aggregated or clumped dispersion patterns are likely to cause such damage at lower population levels than those with random or systematic dispersion. Bardner and Fletcher (1974) discuss several mechanisms responsible for aggregated dispersions including edge effects, obstruction effects, plant density, and plant heterogeneity. Other potential mechanisms include protection or self defense, mating behaviors, feeding strategies, pesticide application, and oviposition patterns. The feeding site preferences of arthropods can impact the compensatory responses of plants.

Judenko (1973) proposed in his analytical method of crop loss assessment that undamaged plants can yield more than normal if neighboring plants or tillers were damaged (case B in Fig. 1.3 in Litsinger, 1991). An unattacked plant adjacent to an attacked plant could better compensate in the same way border plants grow better in the absence of a 360° complement of competing neighbors. Damaged plants are stunted and compete less for nutrients and sunlight. Whereas a damaged plant located next to an undamaged plant would have less ability to compensate (case C). In case A all plants are damaged and there is no compensation and the same if all plants were undamaged.

This result was corroborated in the simulation of Rubia-Sanchez et al. (1999) where with random distribution of damaged hills there was less compensation than if there were aggregated areas or clumps of damaged areas. In some instances hills with one whitehead, yield was more than hills without whiteheads. This may have been that the whiteheads were in secondary or tillers that contributed little to yield.

16.10.2 Within-Plant Distribution of Feeding Insects

Rice stemborer moths and larvae prefer the most vigorous tillers in which to oviposit and penetrate. Ishikura (1967) pointed out that both striped stemborer generations prefer stouter and more vigorous stems, which potentially are more productive. The same conclusion was noted with *Maliarpha* where infested tillers produce the heaviest panicles due to the behavior of the females to oviposit on the most vigorous plants and first instar larvae which enter internodes of the thickest tillers (Delucchi et al., 1996). Rice leaffolders feeding on the leaf sheaths cause greater damage than on leaf blades (Graf et al., 1992).

16.10.3 Crop Age

Numerous trials have shown that a young rice crop can tolerate damage more than an older crop. Van Haltern (1979) examined effects of removing the top 25 and 50% of leaves by scissors to Pelita rice in plants of varying weekly age from 1 to 11 w.a.t.. The results showed only 12% loss from 25% leaf removal from 1 to 6 w.a.t. with greatest loss increasing from 7 to 9 w.a.t. which lessened at 10–11 w.a.t. (Fig. 16.4). Similarly with 50% leaf removal there was negligible loss from 1 to 6 w.a.t. but greatest loss from 7 to 9 w.a.t. Van Haltern (1979) followed up this trial conducted on small plots with a larger field experiment. Removing the leaf area from 50 to 100% (to ground level) at 2 w.a.t. showed 9 and 15% loss in yield respectively with no significant difference between cutting heights on Pelita cultivar.

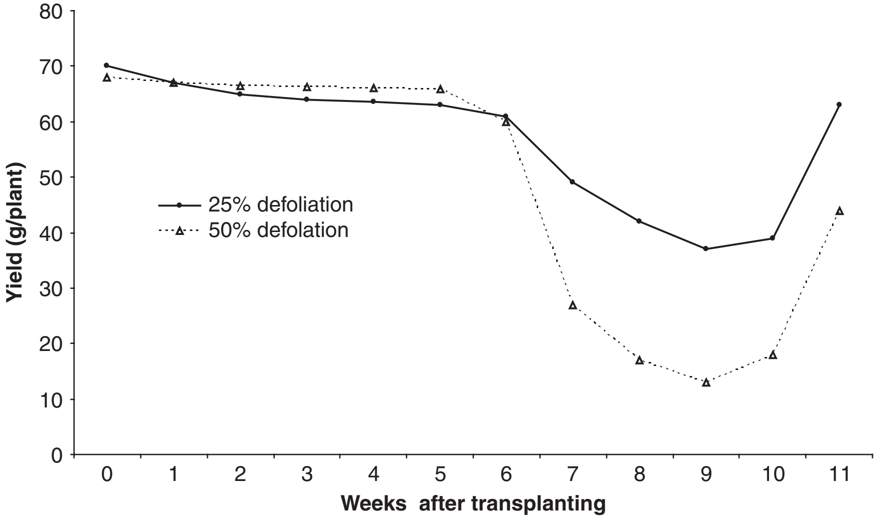

Fig. 16.4 Average grain yield per plant after artificial defoliation with scissors of the top quarter (25%) and the top half (50%) of the leaf blades from plants aged 1–11 weeks after transplanting. Plants at zero weeks after transplanted equal the uncut control. One single defoliation at the specified week after transplanting on Pelita rice in the field, Maros Research Station, Sulawesi, Indonesia, 1974 (adapted from Van Haltern, 1979)

It has been generally assumed that any reduction in leaf area would result in loss caused by armyworms. Navas (1976) in dryland rice concluded from studies in Panama that plants could withstand extensive leaf removal by artificial methods or by natural populations of armyworm particularly in the vegetative stage. Bowling (1978) removed 25 and 50% of leaf tips at the seedling stage (simulating armyworm damage) which reduced yield only 3 and 8% and similarly at the tillering stage only 5 and 12%. Although yields were reduced in all treatments the scale of loss was not as great as expected. He concluded that rice plants were able to recover from extensive leaf removal in the early vegetative stages of growth. In addition leaf removal did reduce yields proportionally.

Defoliation damage although has been found to be greatest at the flag leaf stage where losses at times can be lower than expected. Tripathi and Purohit (1971) found that when leaves were cut in half or fully removed at panicle initiation on Basmati rice, yields were only reduced by 14 (top half removed) or 19% (fully removed). Likewise the number of grains per panicle was reduced 5 and 13%, respectively, and sterility was 9 and 18%.

For pests such as gall midge and stemborers causing damage to tillers, there is a somewhat different relationship. Greatest correlation of gall midge to yield loss occurred from sampling at 7 w.a.t. and not a younger or older crop (Williams et al., 1999). Ishikura (1967) reported from studies in Japan that the second generation striped stemborer attacked the main stem and primary tillers VI, VII, and VIII. Most infested stems were main stems and tillers branching from lower nodes which potentially bear more grains. The more frequent injury to the main stem and to tillers from the lower nodes seemed to have been caused by extended exposure to the attack and not by the preference of the larvae for larger stems and tillers. Of the infested tillers, 9–56% tolerated the injury and survived. The date of heading was almost the same in both infested and uninfested plants and even in surviving infested tillers. The average number of grains per panicle was 5 and 14% more in infested plants than in healthy plants in two experiments in 1936 and 9% more in infested than healthy plants in 1937.

An experiment in Malaysia (Wyatt, 1957) in which researchers placed stemborer larvae on potted plants of various ages demonstrated their effect on yield. The infestation rate was 1 larva per 2 tillers, approximately equal to the level at that time in peninsular Malaysia. The experiment showed that although the size of the loss depended on the age of the plant when infested, infested plants of all ages suffered some loss. Loss was greatest on 50–65 day old plants (31–58%).

Infestations at 7 and 9 w.a.t. appeared to be more severe (steeper slope in linear regression) than at 5 w.a.t. which Soejitno (1977) attributed to compensation by the formation of new tillers. He attributed the greater damage to loss in plant vigor. Bandong and Litsinger (2005) hypothesized a different mechanism and found rice is most susceptible to yellow stemborer during periods of elongation which occurs at maximum tillering (to give the most deadhearts) and at panicle exsersion (to give the most whiteheads), in between these two periods stems toughen due to silica and lignin making penetration by the first instar stemborer larva less successful. A similar result also has been recorded for *Maliarpha* (Delucchi et al., 1996) who reported there was only one sensitive period which is at booting development beginning 42–65 d.a.t. (beginning 3 weeks from the end of tillering). Before this period larval mortality is high and the plant can compensate. After this period the severity of damage is negligible.

In deepwater rice culture defoliation from hispa at the maximum tillering stage produces higher losses than when it occurs at tiller elongation as the rising water prevents compensation from increased tillering that would be expected in normal rice culture (Islam, 1989).

Heong (1990) reported an exponential increase in the per capita leaf area consumption with leaffolder larval age but a decrease with host-plant age. The same relationship emerged from modeling. Rice appears to be sensitive to leaffolder damage only during booting to heading. During the same period the plant is also most attractive to immigrating moths and more so if the crop is highly fertilized (de Kraker et al., 2000). Despite the high attraction between booting and heading, the crop is highly tolerant of leaf removal during this time.

16.10.4 *Effect of Cultivar*

Genetic resistance to insect pests is well established in rice (Heinrichs, 1994). Tolerant varieties have also been identified. However there are also a number of reports of susceptible and non-tolerant rice cultivars that at times do not suffer significant losses from high levels of insect pest damage. Litsinger et al. (1987a) showed a

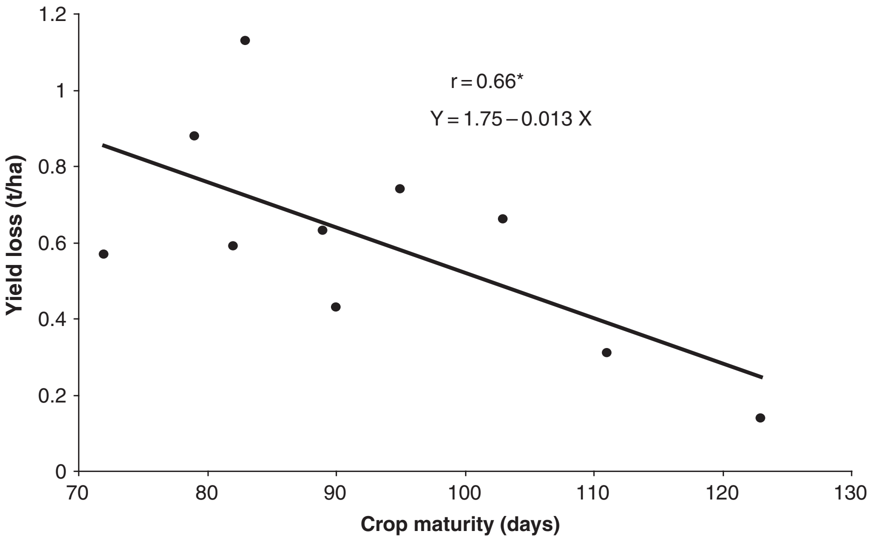

Fig. 16.5 Relationship of yield loss to crop maturity across ten sites in transplanted irrigated and rainfed rice environments in the Philippines, 1976–1986 (after Litsinger et al., 1987a)

linear relation between declining yield loss with increased plant maturity of cultivars (Fig. 16.5). This is a generalized relationship that has nothing to do with genetic resistance and the only factor is longer maturity. There are exceptions to this, however, as Rubia-Sanchez et al. (1997) showed that IR64 compensated more than Cisandane for damage even though Cisandane was longer maturing. Litsinger (1993) compared a medium and early maturity variety using the insecticide check method where there was significant yield loss in the early maturing variety but not the longer maturing one.

The apparent tolerance of yellow stemborer by deepwater rice varieties is consistent with their being a primitive group of cultivated rices (Taylor, 1988). With the loss of main stems and basal tillers there was usually a compensatory increase in nodal tillers (Catling et al., 1987). Vigorous nodal tillering must help compensate the plant for early stem losses (from stemborer, drought, rats, and flooding). Nodal tillers account for more than 30% of the total stem population in some Bangladesh fields attacked by yellow stemborer.

16.10.5 Evidence for Compensation

A number of studies have pointed to different expressions of compensation.

16.10.5.1 High Pest Counts and Low Loss

Modern rices have been known to tolerate high levels of insect pest damage which instances are often quoted (Litsinger et al., 2005) and used as justification for reducing insecticide usage in rice (Heong, 1998) essentially by raising action threshold levels. Miyashita (1985) showed that a crop in Japan with even 67% damaged leaves from leaffolder did not result in significant yield loss. Research has shown that up to 30% stemborer deadhearts and 10% whiteheads (Rubia et al., 1996) and 3 whiteheads/hill (Litsinger, 1993) can be tolerated by modern rices without yield loss. In another study, rice fields with high nitrogen can tolerate up to 60% deadhearts and 20% whiteheads without a significant effect on yield (Rubia and Penning de Vries, 1990a). Swarna a 145 day modern variety common in Chhattisgarh, India can tolerate up to 25% silver shoots from gall midge without significant yield loss (RK Sahu personnel communication).

16.10.5.2 Slope of Regression of Yield Loss with Yield

Rubia-Sanchez et al. (1997) took the yields on a per-hill basis in fields of varying white stemborer *Scirpophaga innotata* infestation rates. When a regression relating damage to yield the slope was flat, they suspected compensation was responsible for this outcome. As a result they commented it would be difficult to generalize yield reduction as a result of white stemborer damage unless conditions affecting plant vigor were known. Stemborers causing deadhearts before tiller number is fixed will have very little effect. The compensatory mechanism from gall midge, rice whorl maggot, and stemborers to injury is for the plant to produce more tillers.

In a multi-crop study in the Philippines across four sites found crop compensation in five of the eight wet and dry season crops (Fig. 16.6). A crop in this case refers to a seasonal average over a number of years. Compensation was measured as an insignificant slope when yield loss was regressed with yield over crops. One notes that higher yielding crops had relatively lower losses, i.e., more vigorous crops tolerated more damage. In addition high compensation was observed in Guimba and Calauan sites in both wet and dry season crops where pest incidence was generally low and nitrogen inputs high. In Zaragoza under high pest pressure, high compensation occurred during the dry season, whereas in the wet season, the crop could not outgrow damage. In Koronadal pest incidence was high and compensation was not recorded in any crop probably as nitrogen levels were too low.

16.10.5.3 Role of Solar Radiation in Crop Compensation

Among the abiotic physical factors affecting rice yield, solar radiation is one of the most important. Low yields in the monsoon season are attributed to lack of adequate irradiance. Irradiance becomes a limiting factor during seasons of short day lengths. This is seen in the average solar radiation measured at the IRRI Experimental Farm over a 11 year period (Fig. 16.7). The authors noted that there was considerable variation year to year based on cloud cover due to monsoon weather and the fact that IRRI sits next to the 1100 m Mt. Makiling volcano that creates its own weather. The wet season crop begins in June or July and as can be seen will mature during increasingly lower irradiance which is a combination of cloud cover and short day

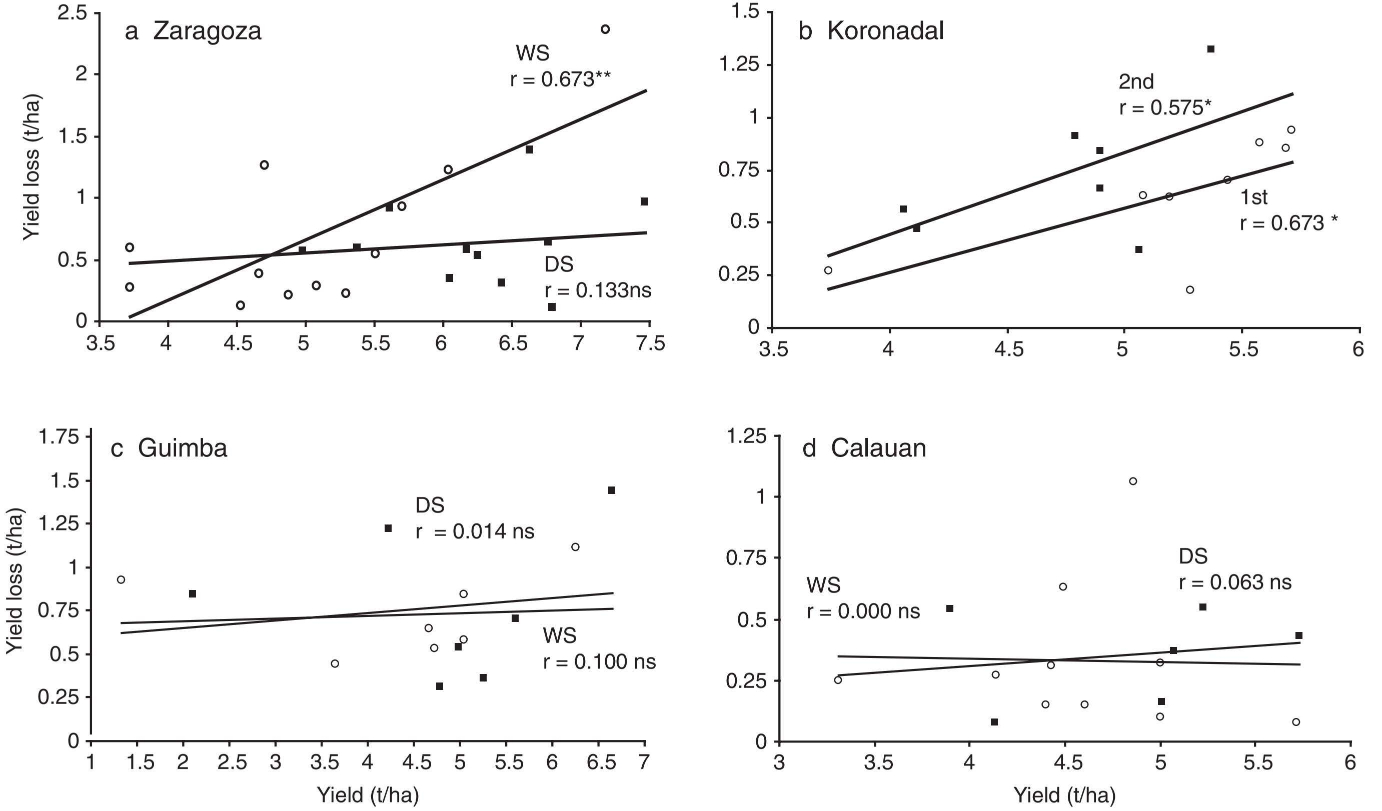

Fig. 16.6 Relationship between yield and insect pest-caused yield loss in four sites showing compensatory capacity in those crops with significant slopes in the regression equation: for WS or first (o wet season) and DS or second (■ dry season) crops (**a**) Zaragoza, (**b**) Koronadal, (**c**) Guimba, and (**d**) Calauan, Philippines. (after Litsinger et al., 2005)

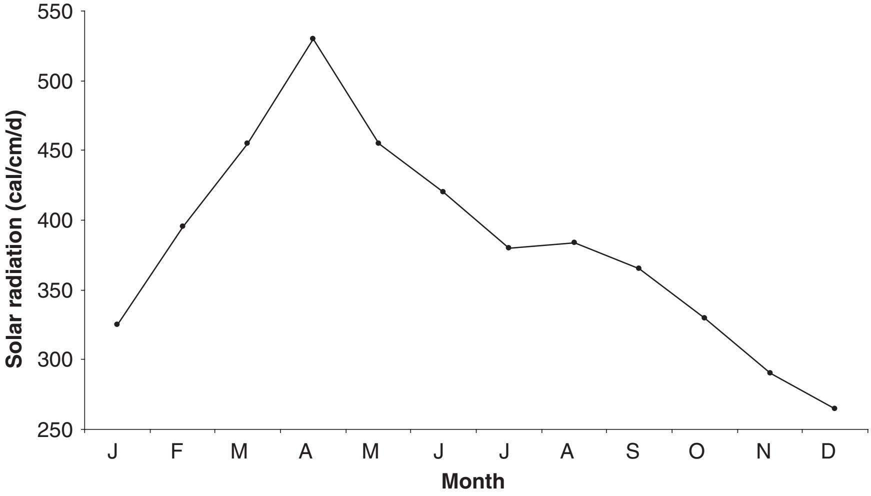

Fig. 16.7 Monthly solar radiation on the IRRI Farm over an eleven year period, Los Baños, Philippines, 1966–1976 (after Evans and DeDatta, 1979)

lengths. However, the dry season crop is cultivated during periods of the highest irradiance levels due to longer day lengths and cloudless weather.

Evans and DeDatta (1979) related incidence of solar radiation to yields taken from the top ten cultivars in production trials during an 11-year span over varying periods of crop growth. Irradiance influenced yield components in the order in which they were determined, the earliest being number of panicles/m^2, followed in turn by spikelets/m^2, and grains/m^2. The correlations were highest for crops grown under high irradiance, and were lowest for crops grown during the wet season, probably because of pests. Regardless of whether irradiance was progressively rising or falling, high irradiance at any stage after panicle initiation was associated with higher yields in both traditional and modern varieties. Yields of all varieties were most significantly correlated with irradiance (over 20- or 30-day intervals) during both the reproductive and the ripening stages, but the most important period was 20–30 days before maturity, depending on the cultivar. With Peta variety the correlation was high even for irradiance during only the last 20 days before maturity, whereas it was relatively low for irradiance at that stages for TN1 and Milfor 6 and highest when irradiance during the 15 days before flowering was also included in the correlation. Responsiveness to irradiance was also greater at higher levels of nitrogen fertilization. High irradiance at any time after panicle initiation could contribute to higher yield even when preceded or followed by a period of lower irradiance. But high early irradiance may have encouraged tillering to an extent that was disadvantageous under conditions of rapidly falling irradiance.

Kenmore et al. (1984) noted that hopperburn in fields with heavy infestations of brown planthopper happened on cloudy days in the wet season. They noted that solar radiation can vary as much as 30% from planting either a month earlier or later. During the monsoon season, solar radiation in most years is a limiting factor to yield and the crop is often under stress as photosynthesis cannot keep up with physiological demands. Brown planthoppers remove phloem sap which is necessary to manufacture carbohydrates which are basic material for growth, and shading reduces the supply of sap creating a deficit in plant needs. Kenmore et al. (1984) hypothesized that hopperburn is due to the accumulation of ammonia as a by product of plant metabolism.

16.10.5.4 Crop Management to Enhance Compensation

Some of the earliest work to enhance compensation by crop management came from Japan. Ishikura (1967) summarized research where it was noted that an increase in the application of nitrogen fertilizer increased the compensatory ability of rice plants to striped stemborer injury. This practice was used by farmers before the synthetic pesticide era, although the mechanism of how plants recovered from damage was unclear. Ishikura (1967) concluded that this practice could be used for the management of stemborers, but that the right concentration and timing of applications should be determined in order to avoid the positive effect of nitrogen on stemborer population dynamics.

Rubia-Sanchez et al. (1997) noted that the relationship between white stemborer whiteheads and yield was location specific, most likely due to variation in farmers' practices and environmental conditions and concluded that insufficient knowledge of the various factors influencing the relationship may lead to an overestimation of damage. Since tillering is strongly influenced by nitrogen supply, plant recovery to stemborer injury may be enhanced by fertilizer application. Topdressing with nitrogen aiding plants to recover from stemborer injury has been a recommended practice in India (Rubia et al., 1996). Applications of nitrogen in later growth stages favor compensation from leaffolder and stemborer damage by delaying leaf senescence (Peng et al., 1996), however this application also prolongs pest attack. Litsinger (1993) showed that increasing nitrogen rates over a range of 0–90 kg/ha led to progressively less yield loss from combined damage from whorl maggot and defoliators.

16.10.6 Yield Loss Paradox

We have discussed how high pest populations can result in low yield losses via crop compensation. Data from some trials, however, show evidence for the opposite phenomenon where low pest numbers are associated with high losses. Baumbärtner et al. (1990) in Madagascar, for example, recorded high losses with the insecticide check method using phosphamidon when sub-economic insect pest numbers were detected. In the Philippines the numerous insecticide check trials also produced 11 crops where high losses were recorded while sampling revealed below average insect pest numbers (Table 16.2). Such trials occurred in virtually all sites and either wet or dry seasons. The paradox has been discussed by Litsinger et al. (2006b,c)

Table 16.2 High yield losses unexplained by insect pest counts in insecticide check trials in rainfed and irrigated rice culture, Philippines,1976–1989[1]

Province	Town	Year	month	Cultivar	Yield(t/ha)		Yield loss (%)
					Complete protection	Untreated	
Rainfed wetland culture							
Pangasinan	Manaoag	1976	Nov	IR36	3.82	2.28	40
		1978	Aug	IR36	3.65	2.14	41
		1978	Oct	IR36	2.23	1.44	35
lloilo	Oton	1978	Aug	IR36	5.01	3.57	29
Cagayan	Solana	1980	Oct	Wagwag	1.27	0.45	35
Irrigated wetland culture							
Laguna	Calauan	1988	WS	C1	4.86	3.8	22
N. Ecija	Guimba	1984	WS	IR58	1.33	0.41	69
N. Ecija	Zaragoza	1979	WS	IR36	7.18	4.81	33
		1988	DS	IR64	6.63	5.25	21
		1989	DS	IR64	7.47	6.57	13
S. Cotabato	Koronadal	1986	2nd	IR62	5.37	4.15	25
		1987	1st	IR62	5.69	4.84	15

[1] Data from Litsinger et al. (2005).

in instances where high yield gains from insecticide protection occurred on crops where sampling showed insect pest infestations to be below action threshold levels. The very large yield gain in the 1979 wet season in Zaragoza is explained by the 1978 wet season crop which was destroyed by a typhoon near harvest. It in effect became a green manure crop for succeeding crops. The effect was only modest in the 1979 dry season, however, as perhaps the organic matter had not decomposed sufficiently. The 1984 wet season crop in Guimba was severely affected by the combined action of drought and stemborer whiteheads (14%) which together accentuated yield loss. All the other trials in Table 16.2 had modest insect pest infestations.

An explanation, of course, is that the insecticides used in the experiments stimulated rice growth thus giving false high yields in the complete control plots compared to the untreated checks. Being aware of the potential problem we had tested the range of insecticides commonly used in greenhouse trials for exactly this source of error in the insecticide check method. We only found carbofuran that had phytotonic effects (Venugopal and Litsinger, 1984). Carbofuran was used through 1978, but not thereafter in our yield loss trials. But if this were true, then all trials would have been similarly affected, and in half of the crops there was no significant yield gain (Litsinger, 1984). There may be an environmental interaction which varies field to field from unknown factors so we cannot fully discount this effect.

However there is another possible explanation. The effects of several pests attacking at once has been pursued which show heightened losses in field trials (Table 16.3). In these trials sub-economic insect pest densities of rice whorl maggot, defoliators, and yellow stemborer were artificially infested onto caged plants as single and combinations of species. Only yellow stemborer resulted in loss when

Table 16.3 Yield of IR36 based on single and multiple artificial infestations by three insect pesets, IRRI field, Philippines,1982 wet season

Pest	Yield (g/m^2)
Caseworm (1)	514a
Whorl maggot (2)	514a
Yellow stemborer (3)	458b
1+2	426bc
1+3	413c
2+3	419c
1+2+3	402c

[1] Average of four replicates. In a column, means followed by a common letter are not significantly different ($p \leq 0.05$) by LSD test. (IRRI Annual Report for 1982, p.204).

caged without other species but each combination increased yield loss significantly. Synergistic losses have been documented from nematodes (Noling, 1987) where higher than anticipated losses occurred from the simultaneous attack of two pests where the results were more than additive. Andow and Hidaka (1998) compared the effects of simulated defoliation on organic and inorganic rice farms and concluded that insect pests and diseases may have affected yield loss independently in natural farming, but in conventional paddies, multiple pest injury may have interacted synergistically compounding yield loss. They concluded the reason for this result remains uncertain but it could be to rice physiology or competition. Conventional rice has thinner cell walls which makes it more susceptible to rice blast. Removal of leaf tissue might have resulted in a greater susceptibility to infection in conventional rice by altering cell wall thickness or another physiological defense. In addition, biomass was greater in conventional rice so the surrounding hills might have competitively suppressed the clipped hills more in conventional rice causing them to be more susceptible to infection. This level of complexity is likely to occur in many crops and cropping systems.

Multiple stresses acting on a single growth stage influencing the yield loss relationship may provide the most important insight into explaining the yield loss paradox. It is hypothesized that there is a synergistic effect of the occurrence of multiple pests/stresses on yield loss documented by Table 16.3 and the results of Savary et al. (1994) and as elaborated by Litsinger (1991). Thus, when occurring in combination with other pests and/or stresses, even a low stemborer population can become magnified synergistically as a significant yield loss, much more so than would be expected if stemborers were the only stress present. Thus, when stemborer numbers are even partially controlled, the plant's physiological compensatory abilities are released to partially overcome not only stemborer damage but that from other stresses, producing a concomitant *synergistic yield gain*. This mechanism is offered to explain the yield paradox and is the opposite of synergistic yield losses described above.

Litsinger et al. (2006b, c) postulated that if synergistic losses can occur, the corollary can also occur. If one stress is lessened then a synergistic yield gain can occur from release of compensatory ability for any source of stress. The stresses as described previously can be from any cause, biotic and abiotic, not just insect pests.

Therefore the following interpretation of the above observations can be made. High tillering rice crops can tolerate high levels of insect damage, especially those that are growing vigorously due to good management, under good growing conditions such as sufficient water and solar radiation, and free of significant environmental stresses. There is a large body of research results that has been reviewed herein that supports this hypothesis. However researchers have used this data to assume that this happens in all crops thus concluding that insecticide control measures would be rarely needed. Evidence presented earlier where we showed that even the same farmer can experience dramatic swings in yield mostly from factors that are not under his control supports the reality that these ideal conditions are not the norm.

The crop's ability to compensate becomes increasingly less as the number and intensity of stresses increase, particularly for stresses that affect different physiological processes which are more likely to cause synergistic effects. Those, such as several species of defoliators, reduce photosynthetic surface area and their effect is additive while those such as either whorl maggot or stemborers combined with defoliators not only reduce photosynthetic area but block the movement of water and nutrient flows in vascular tissue.

Crops are low yielding as they suffer from multiple stresses due to suboptimal environmental conditions and perhaps from poor management, either under the farmer's control or not. As these stresses become lessened from corrective actions such as the applied insecticide in the insecticide check method, the resulting yield gain becomes accentuated or synergistic. Thus the control exerted against insect pests relieves one stress which in turn frees up physiological capacity that can compensate from stresses due to other causes. From the example of wheat in Montana, controlling fungal diseases allowed the crop to overcome some of the negative effects from drought stress as well (Nissen and Juhnke, 1984). This would explain the observed high yield gains from controlling low incidence of insect pests as the crop then compensated for other stresses. The greater the stress load the greater the yield gain when stresses are released.

If this hypothesis is true, then the yield losses measured by the insecticide check method are not strictly due to insect pests and the conclusions from using this method of crop loss assessment needs to be reassessed. Due to the ability of modern rices to tolerate stresses and the high response to favorable management or weather, losses measured by the insecticide check method are therefore combined with losses due to other stresses. The conclusion therefore is that the oft used insecticide check method is not applicable for measuring losses from insect pests per se and the effects should be termed *yield gain* from insecticide use. A given infestation level of an insect pest therefore can cause very different loss levels depending on the type and severity other stresses, management practices, and the prevailing physical environment at the time.

16.10.7 Tolerance as A Mechanism of Plant Resistance

The tolerant plant response to insect damage is probably the most common of damage function relationships and is sigmoidal (Fig. 16.3B) (Poston et al., 1983; Pedigo et al., 1986). In this situation the plant will compensate for some quantity of injury without reducing marketable yield until a critical point is reached. At this point the plant's ability to tolerate injury is exceeded and yield is reduced. After this stage yield is reduced with each additional increment of injury until a lower plateau is reached (the point after which additional injury does not cause a yield reduction). This lower level may reflect the plant's priority for energy allocation to reproductive parts or plant yield that was generated and stored before the insect attack.

Tolerance is a basis of resistance in which the plant possesses an ability to grow and reproduce or to repair injury to a marked degree despite supporting a pest population approximately equal to that damaging a susceptible host. The basic triad of resistance mechanisms: (1) non preference, (2) antibiosis, and (3) tolerance usually have been found to result from independent genetic characters which are interrelated in their effects. The expression of genetic factors resulting in these three mechanisms is frequently modified by various ecological conditions and by other genes.

Painter (1958) emphasized, that in most cases of resistance, preference, antibiosis, and tolerance work in combination even though the contribution made by one might be very much greater than that of the other two. Beck (1965) underscored the presence of the complex nature of resistance mechanisms and emphasized the importance of interactions between insect behavior and chemicals produced by the plant. The main mechanism of tolerance is compensation. Conditions for plant growth also affect the compensation of the plant or crop to insect attack. The relationship between sowing dates and the ability of crops to tolerate infestations is often significant but plant nutrition is also important because crops grown in nutrient deficient soil grow more slowly and remain vulnerable to attack longer. Crops of rice in potassium deficient soil are damaged more by stemborers than those with infestations of a similar size on well fertilized land by balanced nutrients (Litsinger, 1994). Tolerance of injury also depends greatly on the pattern or growth of the crop or plant. Often tolerance can only be effective if sufficient time elapses between the infliction of injury and the end of the yield-forming process. This is why longer maturing rices can tolerate more damage (Litsinger et al., 1987a).

Two examples of tolerance can be cited from work on the brown planthopper with traditional varieties Triveni and Utri Rajapan (Dang et al., 1982). Seedling screening and survival and population growth studies on 30-day-old plants indicated similar degrees of susceptibility on TN1 and Triveni cultivars. Studies in the screen house and field indicated that at both the vegetative and ripening stages Triveni possessed tolerance to insect damage expressed as the ability to survive and produce a higher percentage of productive tillers than TN1 at a similar insect population. Yield reduction caused by brown planthopper was 40% on Triveni infested with 400 insects on 35-, 50- or 75-day-old plants, whereas almost 100% on TN1 at the same ages. Photosynthetic activity of seedling stage Triveni was less affected than TN1 when severely damaged by feeding.

Feeding activity on IR26 measured as the area of honeydew spots was significantly higher than that on Utri Rajapan (Panda and Heinrichs, 1983). It was also observed that brown planthopper feeds primarily on the outer leaf sheaths of Utri Rajapan while on the main shoot of IR26. Hopperburn symptoms developed more slowly in plants where only the leaf sheaths were exposed in contrast to those where the main shoot was exposed. The higher feeding activity and the feeding on the main shoot of IR26 are two possible reasons for the greater plant damage.

A study on gall midge was carried out with 15 different varieties and planted in a season of high infestation using the insecticide check method (Prakasa Rao, 1989). Some varieties had no yield loss despite high infestations and were termed tolerant. In Nigeria, the cultivar Cisandane was compared by the farmers to their normal variety and on average Cisandane yielded 26% higher but African gall midge damage levels were only slightly less than the farmers' cultivars thus tolerance was suspected (Williams et al., 1999).

16.11 Measurements of Crop Loss

This section is presented to focus on more examples of crop loss results from the various methods described. In reporting losses caused by insect pests, the data presented is only meant to illustrate of the potential of each pest or pest group to cause damage. The data are in no means to be taken as annual averages for a mentioned country. Also presented are a number of references that can be used to source more information on yield loss. Teng and Revilla (1996) make the point that although many crop loss assessment methods have been developed their use has not always resulted in more accurate or extensive loss estimates and that a gap exists.

16.11.1 Chronic vs. Epidemic Pests

The terminology for chronic and epidemic pest classifications commonly found in the literature is comprised of temporal and density (severity) components. A pest is an insect that causes economic damage. Chronic pests are those that are commonly present on a crop and occur each season. Occasional pests only occur in economic densities from time to time. A chronic or occasional pest can cause various degrees of damage that range from non-economic to highly economic. Occasional pests which cause severe damage are termed epidemic pests.

Some areas experience high losses from chronic pests each year which approach epidemic loss proportions. Some examples are gall midge and rice hispa in endemic areas mentioned below. White stemborer can also attain this ranking within its limited distribution as can yellow stemborer in deep water rice. Fortunately these areas are limited in size. We only found one reference that stated that farmers ceased growing rice because of annual high losses. Barr et al. (1975) cited an example in India where the damage to the first rice crop was so great from stemborers that farmers were hesitant to plant a second in irrigated conditions. But such reports are rare mainly due to the high value farmers give to rice as a food. Losses nationwide from chronic pests normally outstrip the losses from occasional epidemics as the former occur every year in most rice growing regions, and often farmers do not notice the subtle symptoms which they believe are what a 'normal' rice crop looks like (Barr et al., 1975).

Quelling chronic losses should be important to policy makers interested in increasing rice production in a region or country. If an intensive extension program, focused on improved insect pest control, could increase yields by 5%, that would be a significant boost in food supplies for a nation. Epidemic pests normally affect only a small number of farms in a country and generally are not important to national production but severely affect individual farmers. Thus epidemic pests garner the greatest headlines, some warranted but most not in terms of threatening national food supplies. In 1983 a headline in a Kuala Lumpur newspaper stated that the Department of Agriculture reported that the current rice crop was threatened by a pest menace that could cause complete loss (Kenmore, 1987). A follow-up study showed that only 8% of the area discussed was infested by tungro where only 2% was severely damaged. Production loss was estimated to be less than 1% in Malaysia. As our yield data show that each crop there are farmers who harvest meager yields from many different causes.

Similar reports on brown planthopper were repeated in Indonesia, Sri Lanka, and the Philippines over the same period but fortunately were rare occurrences. This is termed the ‘political pest outbreak panic threshold’. With knowledge that indiscriminant insecticide usage spurs such outbreaks has led to more ecologically sound management practices that can temper them (Heinrichs et al., 1982; Gallagher et al., 1994). At the time of this writing there was only one recent report of an outbreak in Asia and that was from brown planthopper and grassy stunt in the Mekong Delta of Vietnam (KL Heong personal communication). In this area, triple rice cropping is practiced and farmers use insecticides indiscriminately that led to resurgence of brown planthopper and possible breakdown of resistant rices. Reports of this nature are often exaggerated in terms of the threat to rice production in the region, still many farmers no doubt suffer high losses as a result.

16.11.2 Losses by Growth Stage

Yield losses have been determined for the major rice growth stages in a number of studies. Losses in the seedbed have been the least studied but some data is available in the Philippines. However 26 trials conducted by IRRI researchers from 1978 to 1982 (Table 16.4) show that in none of trials was seedbed loss significantly different from the complete protection treatment in the partitioned growth stage insecticide check method (Reissig et al., 1981). As a result a separate treatment to protect the seedbed was discontinued from future trials order to economize on research costs. But the percentage of Filipino farmers applying insecticide to the seedbed as determined from surveys averaged 39% in Koronadal, South Cotabato and 71% in Zaragoza, Nueva Ecija (Litsinger et al., 2008). In Guimba (also in Nueva Ecija) 95% of farmers surveyed applied insecticides to the seedbed and two thirds of these were prophylactic in nature (Fajardo et al., 2000). One wonders why so many Filipino farmers applied insecticide to their seedbeds. Recommendations to control insect pests in the seedbed that would have justification would be to control green leafhoppers *Nephotettix* spp. to prevent tungro disease transmission or white

Table 16.4 Insecticide check method of determining yield loss in the rice seedbed stage of 26 trials on farmers' fields. Data presented here incude only the full protection (insect pest-free over the entire crop) and omitting protection in the seedbed, irrigated and rainfed locations in the philippines with modern and and traditional varieties, 1978–82

Town	Province	Culture	Variety	Season	Year	Yield (t/ha)[1]		
						Complete protection	No Seedbed protection	Untreated
Talavera	Nueva Ecija	Irrigated	IR42	WS	1979	6.7a	7.3a	6.2a
			IR36	DS	1980	4.6a	4.6a	3.9b
			IR54	WS	1981	5.53a	5.52a	5.00a
Cabanatuan	Nueva Ecija	Irrigated	IR36	DS	1979	6.26a	6.01a	5.73b
			IR36	DS	1980	6.05a	6.01a	5.70b
			IR36	WS	1980	3.72a	3.78a	3.77a
			IR36	WS	1981	7.18a	7.08a	4.81b
Santa Maria	Laguna	Irrigated	IR42	WS	1982	4.40a	4.40a	4.28b
			IR46	DS	1982	5.73a	5.19a	5.26a
Victoria	Laguna	Irrigated	IR22	WS	1981	4.84a	5.10a	3.69b
			IR54	WS	1981	4.27a	4.55a	3.66b
Managoag	Pangasinan	Rainfed	IR36	WS	1978	3.65a	3.33ab	2.14b
			IR36	WS	1978	3.70a	3.27ab	2.63b
			Wagwag	WS	1978	2.94a	2.89a	2.14b
			IR36	WS	1979	5.63a	5.54a	4.27b
			IR36	WS	1979	3.53a	3.56a	2.85b
			Wagwag	WS	1979	1.27a	1.22a	0.82b
			IR36	WS	1980	2.59a	2.58a	2.52b
			IR36	WS	1980	4.23a	4.23a	3.76b
			IR36	WS	1980	2.77a	3.83a	2.45b
			Wagwag	WS	1980	2.22a	2.26a	1.73b
Solana	Cagayan	Rainfed	IR36	WS	1980	1.57a	0.96a	0.94a
			IR52	WS	1981	3.6a	3.4a	3.1a
			Wagwag	WS	1981	3.18a	3.43a	3.44a
			IR52	WS	1982	1.84a	1.81a	1.69a
			Wagwag	WS	1982	1.06a	1.16a	0.92a

[1] Yield loss trials were conducted on 4–8 farmers' fields (replications) per crop. Treatements were unreplicated on each field, plot sizes were 100 m^2 and yield cuts were 25 m^2. In a row, means followed by a common letter, are not significantly different ($P \leq 0.05$). Complete protection consisted of 9–11 insecticide applications including weekly sprays in the seedbed beginning 1 week after sowing and every 10 days on the main crop.

stemborer during an outbreak. Otherwise research has shown that farmers who apply insecticides to seedbeds waste capital and effort.

Yield losses on the main crop based on the insecticide check method in four irrigated double-cropped locations in Philippine rice bowls (Litsinger et al., 2005) were significant and were almost equally distributed for each of the three crop growth stages of rice (0.23 t/ha in the vegetative stage, 0.24 t/ha in the reproductive stage, and 0.15 t/ha in the ripening stage).

Another research group from IRRI conducted similar partitioned growth stage insecticide check trials nearby to Zaragoza in the same irrigation system from 1979 to 1981. Although this represented a different research team (supervised by

Table 16.5 Comparison of yield loss results using the partitioned growth stage yield loss method between nearby sites by two different research teams using the same methodology on irrigated, double-cropped rice, Nueva Ecija Province, Philippines,1978–1991[1]

Site	Crops (no.)	Years	Yield(t/ha)[2]		Yield loss		Yield loss (%) by rice growth stage		
			Complete protection	Untreated	t/ha	%	Vegetative	Reproductive	Ripening
Zaragoza	22	1978–91	5.6 ± 1.0	4.9 ± 0.8	0.67	11.5	4.2	4.6	2.4
Talavera	5	1979–81	5.9 ± 0.9	5.0 ± 1.0	0.89	15.3	2.8	6.8	5.7

[1] All trials were conducted on farmers' fields growing modern pest-resistant IRRI varieties.

[2] Means ± standard error.

Table 16.6 Comparison of the yield loss in insect resistant and susceptible varieties, Masapang and Victoria, Laguna, Philippines, 1979–1981[1]

Variety[2]		Yield (t/ha)		Yield loss	
		Protected	Unprotected	t/ha	%
IR 22	Susceptible	4.75a	3.78b	0.98	20.5
IR36, IR54	Resistant	4.39a	3.41b	0.98	22.1

[1] Total of 4 crops grown in farmers' fields using the insecticide check yield loss method. In a row means followed by a common letter are not significantly different ($P < 0.01$)by LSD test.

[2] Susceptibility ratings are in relation to epidemic insect pests, brown planthopper and green leafhopper.

E.A. Heinrichs) and different site and even shorter span of years, the results were almost identical, with total loss equal to 12–15% and greatest loss in the reproductive stage (Table 16.5). The two Philippine data sets described above were all performed using the latest insect resistant varieties (highly resistant to brown planthopper and green leafhopper and with moderate resistance to stemborers). This results suggest that at least in some sites that yield loss figures can be gathered after only a few years of effort in a location.

A similar set of trials in Laguna province also under the direction of E.A. Heinrichs compared an insect susceptible variety IR22 to resistant varieties using the insecticide check method. Even when brown planthopper populations averaged 8 per hill and one crop had 23% of hills infected with tungro, there was no significant difference in yield loss between varietal types (Table 16.6). Losses from chronic pests were identical at nearly 1 t/ha per crop representing 20% reduction in yield. Thus both pest susceptible and resistant varietal types suffered equally from chronic pests which in the case of these trials were mainly stemborers. The Laguna trials were planted at the end of the planting seasons to encourage epidemic pests so are not averages for the Laguna farmer.

16.11.3 Damage Functions and EIL and Decision Thresholds

As seen from the data presented, reliable correlations of insect pest densities to yield (damage functions) are seen to be difficult to achieve in rice, especially when natural infestations are employed on plot levels versus on a per hill level or when artificial infestation is used (Litsinger et al., 1987a; Litsinger, 1991). Most of the problem is that the range in pest infestation is too narrow for relationships to emerge such as would occur if the damage range were from 0 to 3 on the scale in Figure 16.3B, the most common model. Damage functions, however, are an integral part of EIL determination. Traditionally the EIL is viewed as having five primary determinants: (1) control costs, (2) crop market value, (3) proportionate injury per individual pest, (4) crop response to injury vs. yield, and (5) the insecticide kill coefficient (Poston et al., 1983; Pedigo et al., 1986). Although the mathematical relationship of these variables to the EIL is quite straightforward, it is difficult to estimate values for the pest injury potential and the resulting crop response (to calculate damage functions). The difficulty arises because these variables are not simple constants but rather complex biological processes, ie., mechanisms that operate through space and time.

The intractability of the pest intensity-yield loss function is most apparent when attempts are made to estimate the potential damage from a single density estimate in the field (Poston et al., 1983). The pest density measured at a point in time relates most directly to the increment of damage inflicted at that time. At a later time, the pest population and consequently the corresponding damage increment will probably be different. To compare losses with control costs, accurate assessments of this loss from injury detection until harvest must be made. Thus the ability of a single pest density measurement to serve as an estimate of overall damage potential is dependent in part on the ability to reliably predict changes in the pest population through time. This problem may not arise in instances in which the population dynamics of the pest is simple (e.g., limited mortality within discrete generations) or when an accurate model exists that predicts changes in more complex populations (e.g., overlapping generations with variable mortality). Unfortunately these constitute only a minority of the cases with which pest managers must deal. In multiple-cropped tropical rice it is normal for generations to be overlapping particularly where planting is staggered (Perfect and Cook, 1994).

The way economic thresholds have been developed in Asia has been first to determine damage functions based on artificial infestation trials in the greenhouse (e.g., Dyck et al., 1981) or from taking samples from hills of rice in the field that display a wide range of damage (e.g.,Gomez and Bernardo, 1974). Economic thresholds were developed based on this data and initially researchers were surprised at the variability in the resulting figures (Way et al., 1991). For example for economic thresholds for stemborers in the Philippines, Dyck et al. (1981) came up with 10% deadhearts while Liu (1977) in China and Kulshrestha (1976) arrived at 5% deadhearts. Another way was to use large yield loss datasets such as that of Litsinger et al. (1987a) where individual fields or crops and not hills became the points on the regression curves (Waibel, 1987; Smith et al., 1988). This data is much more expensive and logistically challenging to derive and most national programs cannot conduct such investigations.

Some researchers recognized that there could be different damage functions by crop growth stage. Again with stemborers Israel and Abraham (1967) report that for each 1% increase in deadhearts was a 0.3% loss in the vegetative stage but 0.6% in the reproductive stage. Rubia and Penning de Vries (1990a) noted that stemborer threshold values can be 50% deadhearts in the early vegetative stage but 10% deadhearts in reproductive stage.

Rubia and Penning de Vries (1990a) opined that thresholds with low nitrogen should be lower. Indeed Litsinger (1993) showed that yield loss declined with increasing rates of nitrogen, with longer maturing varieties, and higher seeding rates. Rubia and Penning de Vries (1990b) also questioned how to measure a damage function for a single pest when some 3–4 chronic insect pests occurred in each growth stage and a greater number of fungal and bacterial chronic diseases. Indeed that is a major dilemma.

Thus the concept of action thresholds has evolved where researchers take their best estimate based on values from local research and then test them in the field to fine tune them. This was the approach used by Bandong and Litsinger (1988), Litsinger et al. (2006a–c) for chronic pests (whorl maggot, defoliators, leaffolders, and stemborers) in the Philippines. As a result of these evaluations, the best performing characters (> 90% correct decisions) for whorl maggot were 1–2 eggs/hill and 15–30% damaged leaves, for defoliators were 10% damaged leaves, for leaffolders as 15% damaged leaves, and for stemborers was 5–25% deadhearts depending on the growth stage. Despite the wide range of growing conditions, the resulting action threshold levels were surprisingly similar across sites. Although the accuracy of the action thresholds to predict growth stages with 250 kg/ha losses and significant pest damage was over 90%, the outcome was that the insecticide response applied by knapsack sprayers (even when performed by researchers) resulted in poor kill ratios and consequently low yield gains. Motorized sprayers should have given better control but very few farmers can afford them, besides most farmers are satisfied with the performance of insecticides applied with knapsack sprayers. The conclusion therefore became that farmers are best to use insecticides only if the crop is heavily infested and the crop otherwise has low capacity to compensate.

16.11.4 Yield Gaps

The impact of insect pests on rice yields was noted to be highly significant in the yield gap field trials which were basically insecticide check experiments conducted in a number of Asian countries from the mid to late 1970s as part of IRRI's Constraints Program. Yield gaps were measurements of the potential yield derived from better insecticide control technology compared to the farmers' current practice which often is not much different from an untreated check.

16.11.4.1 Philippines

Data from four locations showed losses from insect pests averaged 0.5 t/ha (10% below potential) in the wet season and 0.8 t/ha (14%) in the dry season (Table 16.7). Even though the method biased losses upwards due the use of carbofuran insecticide in the high input treatment (complete control), the figures are similar to those calculated by Litsinger et al. (2005) for similar irrigated rice locations. During the period when yield gaps were measured in the Philippines, inputs were subsidized by a government program and farmers' insecticide application frequency consequently was higher than normal (crop means of 1–7 times with averages of 3–5). Despite the high farmer insecticide frequency, the insect control gaps were on par with gaps measured from better fertilizer management. Farmers were better managers of weeds as that contribution to the yield gap was minimal. The average costs for the high input treatments were three times the average farmers' input over the four sites, and by spending the extra $122 they would have an increased profit of only $4 (Herdt et al., 1984). The high input treatment is equivalent to a prophylactic

Table 16.7 Yield gap as determined from the difference between high input and farmers' input levels for insect control, weed control, and fertilizer usage in four provinces, Phillippines, 1973–1979[1]

Province	Fields (no.)	Yield (t/ha)			Contribution (t/ha) of yield gap			
		Farmers' inputs	High inputs	Gap	Insecticide	Fertilizer	Weed control	Other
	Wet season							
Laguna	57	3.6	5.3	1.6	0.8	0.6	0.3	0
Nueva Ecija	78	3.9	4.8	0.9	0.5	0.4	0.1	0
Camarines Sur	47	3.9	4.7	0.8	0.1	0.2	0.1	0.4
Iloilo	38	3.8	5.2	1.3	0.5	0.7	0.3	0
All sites	*220*	*3.8*	*5.0*	*1.1*	*0.5*	*0.5*	*0.3*	*0.1*
	Dry season							
Laguna	57	4.4	6.5	2.1	1.0	0.4	0.2	0.5
Nueva Ecija	60	5.0	6.9	1.9	0.7	1.0	0.2	0
Camarines Sur	40	4.3	6.8	2.5	1.5	1.1	0.2	0
Iloilo	32	4.1	5.3	1.2	0.3	1.1	0.2	0
All sites	*189*	*4.5*	*6.3*	*1.9*	*0.8*	*0.9*	*0.2*	*0.1*

[1] Source: Herdt et al. (1984), cross tabulations sometimes do not add up due to rounding errors.

approach to insect control and the low returns therefore support an IPM approach to insect pest management.

Greatest seasonal variation came in Camarines Sur, a site in S. Luzon, where in the wet season no yield gap from insect control was measured, whereas in the dry season it rose to 19%. In terms of the proportions of the yield gap that measured fertilizer and weed control in addition to insect control, the latter made up 13% and 73% of the wet and dry seasons over five seasons. The only insect pest mentioned was whorl maggot but other chronic insect pests such as stemborers must have played a role. There was no entomologist in the team.

In Laguna a surprisingly large yield gap was attributed to insect pests, and was equivalent to 15% lower than the yield potential in both the wet and dry seasons equal to 0.8 and 1.0 t/ha, respectively (Table 16.7). Tungro was more prevalent in Laguna during this period and probably the control of its vector, the green leafhopper, by carbofuran, a systemic insecticide, contributed to most of the yield difference. Insect control made up 48 and 50% of the yield gap in both seasons respectively.

In Nueva Ecija yield gaps were calculated to be 10% in both growing seasons and the proportion of the yield gap attributed to poor insect control was 55% in the wet season and 37% in the dry season. A tungro outbreak occurred in the 1976 wet season that made up a large part of the yield gap. The farmers' fertilizer level was high but with little yield effect due to poor timing. Rat damage occurred in the 1977 dry season. C. Luzon is typhoon prone and wet season yields are often severely depressed. The 1978 wet season crop was a total loss from a super typhoon giving great economic hardship to farm communities.

The Iloilo site included both rainfed and irrigated areas and poor insecticide usage played a prominent role in the measured yield gaps which represented 38% and 25% in the wet and dry seasons. Direct seeding became popular in Iloilo which was the dominant crop establishment method due to chronic labor shortage. Yield loss from insect pests was estimated to be 10% in the wet season and 6% in the dry season. The major insect pests were stemborers, both yellow and white, as well as leaffolders. White stemborer was prominent in the rainfed culture which occurred away from the seashore towards the mountains while irrigated rice occupied a strip running along the shoreline in lower lying areas. This is one of the few wetland areas where both stemborer species exist side by side. Another large part of the gap was unreliable water supply and low and ill-timed fertilizer applications.

16.11.4.2 Indonesia

The constraints trials in Subang, W. Java, were preceded by a large baseline survey of farmers that showed modern rices were adopted extensively (Nataatmadja et al., 1979). Although farmers preferred the Pelita cultivar due to its better taste, it was susceptible to brown planthopper so farmers were forced to sow IR26, IR30, and IR36 as each became available. Due to labor shortages to transplant, farmers often transplanted seedlings > 30 days old which limited tiller production. For insecticides farmers followed their own timing and did not follow the government BIMAS program's recommended prophylactic prescriptions. It was realized that variation in the farmers' practice was so large that it would be difficult to select a typical farmer, thus from a baseline survey in 1974, they established an average farmer's practice which was followed in the factorial trials. As a result no plot accurately represented farmers' practices, and thus the associated yield.

In 1976, the first wet season, brown planthopper appeared toward the end of the season causing extensive damage. In the farmers' practice plots outside of the experimental plots, farmers had sprayed diazinon at 14 and 42 d.a.t. and when brown planthopper came they sprayed carbaryl at 3-day intervals beginning 56 d.a.t. followed by carbofuran G paddy water broadcast at 70 and 84 d.a.t. All the insecticide usage was in vain as the planthopper was not controlled, and to the contrary, usage undoubtedly caused insecticide-induced resurgence. Farmers applied inputs over 2.5 times the value of the high input treatment but harvested lower levels (2.5 t/ha). Indonesian farmers lying outside of the monsoon climate can apply high levels of nitrogen (> 100 kg/ha) with low risk of lodging. Therefore nitrogen was applied at higher rates than was common in the Philippines. The government BIMAS program suggested rates that were even higher (150 kg N/ha). In some sites there was a significant interaction between fertilizer and insecticide. It is well documented that brown planthopper numbers increase with higher use of nitrogen (Litsinger, 1994). Farmers typically applied carbofuran G and diazinon EC on their farms which were the insecticides available in government outlets. At the time of the trials all rice insecticides had to be procured from government stores. As inputs were highly subsidized farmers could afford the high insecticide and fertilizer usage. The total yield gap in the 1976 wet season was an astounding 4.6 t/ha with the highest contribution from insect control (1.7 t/ha) and with fertilizer much less (0.2 t/ha). Farmers were close to the optimum fertilizer level but did not apply basally. Their first application was > 20 d.a.t. for nitrogen and phosphorous. Farmers did not apply at the recommended higher fertilizer rate due to an aversion to debt, lack of capital, and believing the suggested rate of 150 kg N/ha was too high. Those using higher rates were in a better financial position and could better afford the risk of a large loss should the crop fail. The lack of technical proficiency was suggested as a constraint by the results. An additional constraint would also be the unavailability of insecticides in the government outlets.

The Constraints Program also gathered data in Yogyakarta. Due to brown planthopper and grassy stunt, the insect yield gap was relatively large, 0.8 t/ha in 1977 dry season (Widodo et al., 1979). Three years of research showed the highest gap was from fertilizer but higher levels only made the crop more susceptible to brown planthopper. Lack of adequate technical knowledge was the most serious socio-economic constraint. The epidemic encouraged farmers to adopt resistant varieties. The average yield gap from 1974 to 1977 for insect control was only 0.1 and 0.2 t/ha below the measured potential in the wet and dry seasons, respectively. The gaps for weed control were highest at 0.3 and 0.4 t/ha followed by fertilizer at 0.3 and 1.0 t/ha in the wet and dry seasons, respectively.

16.11.4.3 Thailand

In the baseline surveys, 24% of farmers said they had a serious insect pest problem, while 35% used no insecticide, mainly because they did not know how, were unfamiliar with the technology, and said insecticides were too costly (Adulavidhaya et al., 1979). As insecticide usage by farmers was low, insects were not included in the factorial experiment. Fertilizer was the largest yield gap, 0.5 t/ha below the potential. Technical constraints were inadequate water, low temperatures, and rats. The identified socio-economic constraints were lack of capital to purchase inputs, lack of technical knowledge, and unstable prices of inputs and rice. Fertilizer was only profitable on farms with good water control. Excess water was also a problem as field water levels ranged up to 39 cm deep. There was no systematic relationship between water depth and input usage apparently because none of the farmers believed that the prevailing conditions were so bad as to discourage usage.

16.11.4.4 Sri Lanka

According to Jogaratnam et al. (1979) insect control resulted in a gap of only < 0.2 t/ha over the two year study. A survey showed 80% of farmers were not familiar with insecticide or herbicide usage. Some 40% indicated there was no insect damage and for those that did, 90% did not follow the recommended practices. However 70% said yields were less than expected, primarily due to water problems, insect damage, fertilizer shortage, delayed planting, and rat and bird damage. Some 50% reported insecticides were not available on time and 7% stated heavy rains affected efficacy. Hand weeding was most preferred, but 25% did no weed control, only 3% weeded more than once, 90% used family labor, and 60% said they had no need for credit.

The yield gap studies revealed that recommended practices were too costly for farmers and were not often economical. Farmers also did not have sufficient training to know how to use inputs optimally for their rice crops thus in the first decades after modern rices farmers' yields were much below the potential of the varieties.

16.11.5 Losses From all Pest Groups

Crop loss data presented by Cramer (1967) showed that insect pests registered the highest losses with weeds lowest and diseases intermediate. This deserves some comment. Farmers have developed more effective practices in controlling weeds thus the losses provided by Cramer measured the difference between the farmers' practice and improved weed management. As farmers generally control weeds well this gap is small. It is well known however that if the farmer did not conduct weed control, losses would be almost 100% in most areas. Diseases are mostly controlled by varietal resistance as if a highly susceptible variety is grown total crop loss can be expected. This is why when new varieties are developed they have to be tested throughout the whole country before being released as if local strains exist that can develop well on the new rice then loss can be extreme. Thus losses from rice diseases are low as they are mainly controlled by genetic resistance. Losses are highest from insect pests as resistance levels are only against epidemic pests and farmers generally do not exert many cultural practices to minimize insect pests. In addition Cramer's data came from insecticide trials which are often done on late plantings when pest populations are highest thus do not represent the average insect pest situation.

Experts determined that in Indonesia that rats were the most important rice pests followed by stemborers, bacterial leaf blight, and brown planthopper (Geddes, 1992). A similar study in five countries in south Asia ranked rice pests as blast, yellow stemborer, bacterial leaf blight and brown planthopper (Geddes and Iles, 1991). A few studies combined both insect and disease pests in loss estimates. Losses of 44% in the wet season and 21% in the dry season were reported in India by Tandon (1973). More commonly, rather imprecise estimates based on the appearance of the rice crop were made for large areas. One estimate for all of India was 20% from insect pests and diseases (Reddy, 1967). While in Thailand an estimate of 15% representing 1 million t/year was given by Wongsiri and Kovitvadhi (1967). In the studies of Seth et al. (1969, 1970) in India, they found an overall 10.5% yield loss for long duration varieties and 14.4% for medium duration varieties. Avoidable yield loss was a meager 0.08 t/ha for the wet season and 0.2 t/ha for the dry season. Multiple regression found significant correlation of yield loss with blast in the reproductive and ripening stages, and false smut.

16.11.6 Losses from Insect Pests by Rice Environment

Average losses due to insects from potential rice production by Cramer (1967) calculated from extensive insecticide trials was 28% as a worldwide average with 34% occurring in Asia. These data are mainly from irrigated wetland rice environments. It was the highest loss of any of the commodities listed by FAO with the next highest being sugarcane at 20% followed by groundnuts at 18%. Although these figures are considered high others have found no good evidence to the contrary. Ahrens et al. (1982) in a similar study later on again using insecticide evaluation trials came up with 24% loss from a 12-year dataset. Pathak and Dhaliwal (1981) estimated losses of 35–44% in tropical rice while Way (1976) gave 35% for India and 16–30% for the Philippines.

A series of experiments conducted in farmers' fields by IRRI in collaboration with the Philippine Bureau of Plant Industry revealed that plots protected with insecticides yielded an average of 1 t/ha more than untreated (20–25% loss) (Pathak and Dyck, 1973). Experiments on the IRRI farm from 1964 to 1971 showed protected trials yielded 5.8 t/ha and only 3.1 t/ha in the untreated checks on highly susceptible varieties with high nitrogen application (Pathak and Dyck, 1973). An insecticide check trial in Zamboanga del Sur province in S. Mindanao in the 1984 dry season using plant growth neutral insecticides registered a 14% loss of 0.66 t/ha on a 4.7 t/ha crop (Pulmano, 1985).

A more recent effort was conducted in the Philippines as part of the National IPM program where in 50% of the 105 crops studied there was no significant yield loss between a complete insect control trial using insecticides (6–9 applications) compared to the untreated (Kenmore, 1987). The work of other IPM training programs in Asia reported similar results in India, Malaysia, and Indonesia. Another study in the Philippines over a 13-year period (1979–1991) in four sites representing 68 crops, Litsinger et al. (2005), estimated losses in irrigated rice from chronic insect pests on modern insect pest resistant rices. Losses were estimated to be a mean of 0.62 t/ha or 12.7% per crop. Upon inspection of the data on a per crop basis 68% of crops registered significant yield loss with the lowest being in Calauan in Laguna of only 23% of crops and the highest in Koronadal with 91%. But if this were broken down by growth stages, the stage with the highest losses was the reproductive stage in three of four sites. Calauan, with least total loss, had significant losses in the vegetative stage in only 15% of the crops and no significant losses in the other stages. Calauan farmers prefer longer maturing rices and being near to IRRI farmers were better managers thus there could have been more yield compensation as a result. Guimba in C. Luzon had high whitehead counts in most years which is the probable reason for the relatively high losses in the ripening stage. The electric pump for the irrigation system often had interrupted service leading to drought stress explaining the high total losses even though pest populations were more similar to those in Calauan.

Both Zaragoza (C. Luzon) and Koronadal (Mindanao) had above average pest densities both as a result of asynchronous cropping. Koronadal registered the highest number of crops with significant total losses but when partitioned by growth stage were lower than expected. This could have come from the high variability in yield loss data from averaging the results from two irrigation systems, the communal system which averaged 2.5 rice crops per year compared to a synchronous site with two rice crops per year. Mean yields per crop for the untreated check ranged between 3.9 and 4.9 t/ha in the four sites, which is a proxy for the farmers' yields as the trials were grown under farmer management. When the yield loss data were analyzed by including the cost of one insecticide application, less than half of the fields could economically justify applying a single insecticide applications to recover the losses (Litsinger, 1984).

In Sulawesi, Indonesia Van Haltern (1979) used carbofuran root zone application (0.5–1.0 kg ai/ha) to record an average yield loss of 34% on some trials from 1973 to 1977 on three research stations. Some published losses based on the insecticide check method in Japan from Mochida (1974) estimated 50% loss in the Kyushu National Agricultural Experiment Station from 1962 to 1971 due mostly to planthoppers and leafhoppers and vectored virus diseases.

In India where experts estimated that in three districts that 4–14% loss occurred depending on the district, growing season, and growth duration of rice varieties (Singh et al., 1972). Losses ranged from short (4–7%), medium (11–14%), and long (4–13%) season varieties. In the states of Tamil Nadu and Uttar Pradesh a mean 8% loss was measured in 1962–1966 (range 0–16% over the five year period) (Barr et al., 1975). In 1951 in Bangladesh 6% loss to insects was estimated (Alam, 1961).

Studies in Sri Lanka reported 10–20% loss annually (Barr et al., 1975), and in insecticide check plots in 77% of farmers' fields there was no significant yield response from 5 to 6 applications (Kenmore, 1987). Fernando, (1967) reported loss from all pests to range from 3 to 53% with an average of 34% depending on location.

Fewer studies on losses in rainfed wetland environments were found in the literature. The problem is that often authors do not state the rice cultural type in their reports. The most extensive were reported from three sites in the Philippines with both traditional and modern rices (Litsinger et al., 1987a). Two sites (Iloilo and Pangasinan) were classified as being favorable environments where flooding and drought stress were minimal and the other site (Solana in Cagayan Valley) is classified as unfavorable. Even in favorable environments yields were well below those from irrigated wetlands. Losses in traditional cultivars ranged from 18 to 25% in two sites and those from modern rices were similar, ranging from 11 to 22% per crop. Rainfed wetland rice sites registered lower pest densities as it is cropped only once a year, but received high loss figures percentage wise probably because of the additional stresses experienced from drought, low solar radiation, and low nutrient management. Losses were measured by the insecticide check method where perhaps the results were more synergistic yield gains than direct measurements of recovery from insect pest damage alone. Muralidharan and Pasalu (2005) found that stemborer deadheart damage had an 8–10 fold greater effect on yield in rainfed wetlands than in irrigated rice.

Deepwater rice which represents some 8% of rice area worldwide has been studied in Thailand and Bangladesh by Catling et al. (1987) where losses ranged from 27 to 34% but their yield loss figures have been challenged by Taylor (1988). In response Catling and Islam (1999), however, remain firm in their conclusions.

There have been some trials in Asia which measured losses on dryland rice culture all using the insecticide check method. Dryland rice has unique insect pest complexes and is generally suffers more stresses than wetland rice (Litsinger et al., 1987b). As a starter, dryland rice areas are entirely rainfed and rice among the major cereals has the lowest tolerance for drought. In Thailand, Katanyukul and Chandartat (1981) found losses were only 5% (range 1–13%) from 1976 to 1979. In Tanauan, Batangas province, Philippines, on favorable soils and diversified agriculture where the soil was frequently tilled with animal drawn moldboard plows losses from five years on a traditional variety averaged 5% from 1976 to 1980 (Litsinger et al., 1987b). Higher losses of 10% were recorded on an improved cultivar over three years 1978–1980 (Litsinger et al., 1987b). Losses were higher (19%) in another favorable dryland area in Tupi, S. Cotabato in Mindanao where farmers used modern cultivars 1987–1991 (Litsinger unpublished data). In Claveria, N. Mindanao on acidic soils with surrounding grasslands after deforestation, losses averaged 29% from 1985 to 1990 (Litsinger unpublished data). Elsewhere in other frontier sites high losses were recorded (Litsinger et al., 1987b). In Pangantucan, Bukidnon province also in Mindanao losses were 23% from a trial in 1980 and Dumarao, Capiz province on Panay Island, Visayas loss was 56% in 1979. Losses were highest 46% in a slash and burn area in a dipterocarp forest in Siniloan, Laguna where yields averaged $<$ 1 t/ha (Litsinger unpublished data).

Litsinger (1993) developed a hypothesis to explain the wide variation in dryland rice losses in the Philippines which represent sites along a continuum of habitats beginning in recently cleared slash and burn forest such as Siniloan with the highest losses due to pest concentration on small fields, to moderate damage levels in grassland areas from older deforested areas such as in Claveria where grasslands replaced the forests and acted as a reservoir for key pests to very favorable areas such as Batangas and Tupi with very low losses due to the fact that most area was farmed and fields were frequently tilled limiting soil pests.

Dryland rice is the most important culture in Latin America and losses measured in Minas Gerais, Brazil, averaged 29% over three years (1977–1979) (range 24–35%) from mostly soil pests and spittlebug as determined from insecticide check method using carbofuran (Litsinger et al., 1987b). The lesser corn stalk borer attacks seedlings from underground webbed nests and can cause the farmers to replant. Pest populations are high because of the extensive forage grasses grown for livestock which act as a reservoir alternate host.

Cramer (1967) estimated losses in rice in Africa as 14% from insects which represents a wide range of rice environments. Agyen-Sampong (1988) reported losses from different countries such as Ivory Coast 25% or 1 t/ha loss. Losses were 25% in Senegal and 30% in Ghana where crop protection in farmers' fields gave yield increases of 3.3 and 5.7 t/ha. Moyal (1988) reported on trials in the first and second crops of irrigated rice in the savannah region of the Ivory Coast with losses of 29% and 20%, respectively, on 4.7 t/ha and 4.6 t/ha crops. Dryland rice in Ivory Coast registered losses of 15% averaged over two years 1977–1980 (Litsinger et al., 1987b). The main pests were stemborers and soil pests.

Catling et al. (1978) along with Litsinger et al. (1987a) were the only two studies found where insect pest losses were carried out in studies representing the major rice cultures for a country over a period of time. This observation agrees with Teng and Revilla (1996) who state that most yield loss datasets from a given location are normally less than three years. Catling et al. (1978) measured losses with the insecticide check method in four seasonal/cultural rice ecosystems in Bangladesh from 1974 to 1976. A mean 9% loss was calculated for the four classes. *Boro* is the dry season (winter) crop of irrigated wetland rice and averaged 4% loss in four sites. *Aus* (direct seeded pre-monsoon season) rainfed wetland rice averaged 6% loss in two sites. A*man* represents the main wet season crops of rainfed or irrigated transplanted rice which averaged 16% loss. Unfortunately the data were not segregated out for irrigated versus rainfed and deepwater rice was not included. Previous data on losses from Bangladesh as reported by Catling et al. (1978) on the basis of a review ranged from 4 to 15% and at times rising to 20% in some years. In neither of the two studies there was an attempt to apportion losses relative to national rice production statistics probably because the number of research sites were so few.

16.11.7 Losses from Individual Insect Pests

Most of the published information for this section comes from reports of high populations and infestations thus the literature paints a more severe picture of insect pest losses than is the norm. These reports, however, do show the potential harm of each pest or guild. Coverage of all pest groups also is not complete and the focus of this review is on wetland rice. Dryland rice has a large contingent of soil pests that cannot survive wetland flooding thus this rice culture has a larger fauna than wetland rice but is less well known particularly in Asia where its area is decreasing (Litsinger et al., 1987b).

16.11.7.1 Rice Whorl Maggot

Studies to measure the effect of rice whorl maggot *Hydrellia philippina* (an ephydrid fly) on yield has led to conflicting reports. Ferino (1968) recorded losses of $> 40\%$ from damage in the Philippines based on insecticide trials. While Shepard et al. (1990) found that even at 60–100% damaged leaves no significant loss was recorded. Viajante and Heinrichs (1986) reported similar results. Litsinger et al. (2006a) proposed a theory that could explain the contradictory findings. The trials that found rice whorl maggot not to cause yield loss were conducted on the IRRI Experimental Farm where seedlings are raised in communal beds of soft mud, the consistency of pea soup. When the seedlings are pulled there is little root damage and consequently transplanting shock is minimal. In farmers' seedbeds, however, in less prepared soil there is considerable root damage from pulling. The combined stress of transplanting shock and other early season insect pests can produce multiple stress and consequent high loss (Litsinger, 1993). In most locations the whorl maggot is usually one of a number of early season insect pests such as defoliators that form a complex.

16.11.7.2 Defoliators

Yield loss from the green hairy caterpillar *Rivula atimeta* was highest when rice was infested at a younger age and that a density of one moth per m^2 resulted in a loss of 7% (Viajante and Heinrichs, 1987). In the Philippines aside from whorl maggot two other insect pests normally occur with the green hairy caterpillar, namely the green semi-looper *Naranga aenescens* and rice caseworm *Nymphula depunctalis*.

Litsinger et al. (2005) recorded losses from this complex of 0.23 t/ha or (5%) in the vegetative stage. Losses from caseworm averaged 0.5 t/ha or 10% loss occurred when 30% of leaves were cut or 25% of the leaf area was removed (Heinrichs and Viajante, 1987). Losses can be patchy as the larvae which float on water are often windswept or taken by irrigation water currents to one side of the field where they become concentrated and larvae can kill off portions of the field. Even though compensation can occur from most damage, patches of killed rice lead to gaps in the field and thus high losses. Van Haltern (1979) reported losses in Sulawesi of 5–10% from this early season insect pest complex.

16.11.7.3 Armyworms

Armyworms (*Spodoptera* and *Mythimna*) as their name suggests can become highly abundant and devastating. Some species are migratory and can descend on an area in great numbers. They can attack a young crop or one near harvest. The common name of one species *Mythimna separata* is the ear-cutting caterpillar. Barr et al. (1975) also reported a 1967 outbreak in Malaysia affecting 10,000 ha and in India where in some fields yielded only 0.4 t/ha. Like caseworms, damage can be highly concentrated. Several outbreak years occurred in Bangladesh between 1939 and 1973 and in 1969 where 0.5 million ha were infested, with 50,000 ha severely damaged (Catling and Islam, 1999). An outbreak in 1966 in Ghana from a related species caused half of the fields became devastated as if grazed by cattle (Barr et al., 1975).

16.11.7.4 Rice Stemborers

Among all insect guilds, stemborers have been credited with being the most influential regarding contributing to annual losses (Barr et al., 1975; Litsinger et al., 2006c). Among the 20 or so species, the yellow stemborer is the most highly adapted to wetland rice in monsoon Asia while its cousin the white stemborer which is also monophagous on *Oryza* spp. is adapted to the Intertropical Convergent Zone wetland rice as well as dryland rice. Both co-evolved with rice throughout its origin and domestication and dispersed to different rice environments created by farmers clearing new rice lands. The former is adapted to an aquatic environment while the latter can withstand long periods of drought. While both species can enter diapause, yellow stemborer only does so in sub-tropical environments. Both are more adapted to narrow stemmed modern rices due to their narrower girth than *Chilo* species, the next most prevalent stemborer taxonomic group. Yellow and white rice stemborers can be considered together as the insect pest group which causes probably the greatest losses to mankind according to Catling and Islam (1999) due to their pervasiveness on the world's most important food crop, ability to attack throughout the life of the crop, dispersive abilities, and the nature of the injury which disrupts transport of nutrients and water throughout the plant. Yellow stemborer in deepwater rice can attain densities of 50 larvae and pupae/m^2 or ca. 0.5 million immatures/ha (Catling and Islam, 1999). Stemborers as a group were relatively more important on single crop long maturing rices that were prevalent before the shorter duration modern semi-dwarfs. Stemborer larvae are tissue consumers. Their damage is assumed to reduce the weights of green leaves, stems, and reproductive organs proportional to the fraction of tillers affected (Rubia and Penning de Vries, 1990b). Although damage becomes evident as deadhearts and whiteheads significant loss is inflicted by larvae that feed within the stem without severing the growing plant parts (tiller or panicle) to produce field symptoms. Two species of stemborers do not cause this visible damage (*Maliarpha* and *Rupela*) but are known to reduce yields through lessened plant vigor, production of fewer tillers, and many unfilled and partially filled grains. Bandong and Litsinger (2005) showed rice is especially susceptible during two growth periods, both involving elongation of the tillers (for deadhearts) or panicles (whiteheads). Plants are more resistant during non-elongation periods due to the deposition of silica and lignin hindering first instar larvae from boring into the plant. As stemborers are difficult to control with insecticides and for which only resistant varieties have not been developed (with the exception of Bt rice), rice crops therefore have never reached their full yield potential, and thus the amount of loss caused has not been fully appreciated.

Barr et al. (1975) reported losses in a number of Asian countries. In India and Indonesia losses ranged from 3 to 95% in given locations and years. These are data from the years prior to modern rices that rivaled the more recent epidemics of brown planthopper and green leafhopper in the same countries, thus Asia was no stranger to suffering high losses from insect pests. In 1970 in Pakistan after an outbreak fields were harvested for fodder or turned over to grazing animals because there were essentially no filled grains. In Bangladesh 30–70% loss occurred in epidemic years in some fields and 3–20% in normal years. In Malaysia there were reports of 4–5% loss in 1965 and a 33% loss in over 24,000 ha in an epidemic in N. Krian in 1955–1956. In the Philippines a normal year averages 7% loss but in Calamba in 1953, it rose to 48% loss (Cendaña and Calora, 1967). In 1989–1990 the white stemborer caused losses of more than 250,000 tons of rice in W. Java (Oka, 1979). Van der Goot (1925) reported high chronic losses in the early part of the 20th century in Java due to white stemborer. In 1903, 26,000 ha were severely affected and in 1912 28,000 ha suffered 50% loss. White stemborer is so damaging because of its synchronized emergence after the long aestivation period that overwhelms resident natural enemies. In addition traditional tall long duration of varieties sustained over five borer generations per crop. Highest losses occurred if the timing of larval eclosion of the last generation occurred at panicle exsertion.

Agyen-Sampong (1988) reported the following yield losses from Africa: (1) Egypt *Chilo agamennon* caused 10% loss in 1978 and (2) Ivory Coast five years of trials measured 50–70% infested tillers resulting in 13% loss from *M. separatella*. Soto and Siddiqi (1978) report that in the Ivory Coast a 33% increase in yield can come from insecticides directed at stemborers and in Sierra Leone similar insecticide protection would bring a 50% increase.

16.11.7.5 Gall Midge

Silver shoots or onion leaves produced by gall midge *Orseolia oryzae* larvae are the equivalent of deadhearts as only on rare occasions will a panicle will form on the tiller. The silver shoot is actually a transformation of the leaf sheath into a gall

(Reddy, 1967). As a result of its damage the crop responds by actively tillering which depletes its vigor and thus yield. Most of the new tillers will not form productive panicles. Reddy (1967) reported numerous instances of yield loss throughout its range in Asia and from its cousin in Africa. A 30% loss was documented in Bihar, India in 1917 where it first attracted attention to its importance. In the 1930s it was recorded causing 12% loss in West Bengal and 35% in Raipur Madyah Pradesh. In 1954 it caused 60% loss in Bangalore and 15% in Cuttack, Orissa. In Fukien province China losses of 30–40% occurred from 1939 to 1942 and in Vietnam in 1922 ranged from 50 to 100%. In N. Thailand losses of 50% per annum were common. In Cameroon, 75% of the crop was destroyed in 1954.

16.11.7.6 Rice Hispa

Both the adult and larva of the hispa beetle *Dicladispa armigera* defoliate rice. It is aquatic loving as all stages have a high moisture requirement (Catling and Islam, 1999) and populations can become very abundant even in flooded deepwater rice as well as irrigated rice and in Bangladesh losses of 10–65% of the 60,000 ha infested annually occurred (Barr et al., 1975). Adults can live over a month and are highly dispersive and may pass the off season in marshy areas. In India as well certain hot spots report high annual losses (Barr et al., 1975), up to 50% in some 10,000 ha were attacked annually in Bihar and 39–65% damaged leaves have been reported in other Indian states including 215,000 ha affected in 1985 in Assam and W. Bengal (Catling and Islam, 1999). In areas of Burma up to 50% damaged leaves are known (Barr et al., 1975).

16.11.7.7 Leaffolders

There are 4–5 leaffolder species that attack rice. Their damage is associated with damaging the flag leaf and the penultimate leaf in the grain filling period (Barrion et al., 1991). India in some areas losses of 50% in early 1970s occurred (Kushwaha and Singh, 1984), but normally damage ranged from 5 to 12% damaged leaves, but in the 1983 wet season levels rose to 60–70% damaged leaves and reached 20–29% elsewhere. Heavy rainfall was the cited as the cause but it is known that insecticide resurgence can also be the cause (Qadeer et al., 1988; Panda and Shi, 1989). Damage is higher on later transplanted crops.

16.11.7.8 Planthoppers

The brown and whitebacked planthoppers are examples of epidemic pests and have caused serious yield losses from hopperburn over millennia as well as in recent times particularly after modern rices became widespread (Litsinger, 1991; Gallagher et al., 1994). High populations have mostly been associated with resurgence or secondary pest outbreak phenomena or from farmers growing highly susceptible varieties. In earlier years, before synthetic insecticides, insecticide-induced resurgence could have been caused by whale oil and kerosene. Other causes could have been flooding that washed away natural enemies (Litsinger et al., 1986) or long distance immigration rapidly inundating an area to overwhelm local natural enemy populations (Kisimoto and Rosenberg, 1994). Outbreaks have been recorded since AD 18 in Korea and AD 697 in Japan and in Java during the 1930s and 40s, but planthoppers came to prominence in the early 1970s after the introduction of modern rices in virtually all major rice producing S. and SE Asian countries (Mochida et al., 1977). The scale of these outbreaks was large and in many instances created shock waves in governments that tried as best they could to contain them. In Indonesia in 1976–1977, some 30% of 450,000 ha was lost having an estimated value of over $100 million (Oka, 1979). This was enough rice to feed 3 million people for a year. In 1986 an outbreak in Java affected more than 50,000 ha which led President Soeharto to ban 57 insecticides and replace the minister of agriculture. In 1973 a serious outbreak of brown planthopper in Laguna, Philippines caused a loss of 150,000 tons ($20 million) from grassy stunt (Sanchez, 1983). A report from the Tanjong Karang Irrigation scheme in Malaysia registered 1,600 ha of total loss to brown planthopper in the 20,000 ha system in 1997 with losses valued at up to $4.2 million for the dry season crop and $0.2 million in the wet season (Lim et al., 1980). In severely infested areas, losses ranged from 53 to 75% while in less infested areas losses were 12–25% when high numbers began 30–45 d.a.t compared to only 3–5% when high populations occurred near harvest. Epidemic losses have occurred in most Asian countries even into the ‘90s where losses of $30 million occurred in Thailand and Vietnam (Holt et al., 1996). In India losses ranged from 1 to 33% (Jayaraj et al., 1974). In 1991 rice losses in China totaled more than $400 million from brown planthopper (Holt et al., 1996). Whitebacked planthopper was involved in the complete failure of the 1966 wet season crop in two states in India (Barr et al., 1975). In 1979 an epidemic of whitebacked planthopper in Kedah and Perlis states badly damaged 7,000 ha and only through a national campaign that included aerial insecticide application was a larger area saved in the Muda Irrigation Scheme (Ooi et al., 1978).

16.11.7.9 Leafhoppers

Several species of *Nephotettix* green leafhoppers are important pests of rice, usually through a role as vectors of tungro and other rice diseases. Some reports of direct damage have come in the past, e.g., in Bangladesh 50–80% (Alam, 1967) and in 1956 causing 20–50% loss at heading (Barr et al., 1975). Along with brown planthoppers, green leafhoppers have reached large epidemics in most Asian countries over the same period. Azzam and Chancellor (2002) list nine major epidemics that affected > 4000 ha each since 1980, while Sogawa (1976) enumerated earlier epidemics.

16.11.7.10 Rice Seed Bug

The rice seed bug *Leptocorisa* spp., as a relatively large insect, is highly mobile and can seek out isolated fields such as dryland rice or late planted wetland crops. It builds up during the wet season on wetland rice and alternate weed hosts and concentrates on late plantings particularly in areas of staggered plantings. Its habit of aestivating in the dry season mean that it is more abundant near wooded areas rather than in open plains. An understanding of the damage it does was not appreciated until recently when it was shown that rice bugs prefer to feed on pre-flowering spikelets in free-choice tests (Morrill, 1997). Epidemics are reported from most rice growing countries in Asia with losses ranging from 10 to 40% to some fields with almost complete losses in some occasions (Srivastava and Saxena, 1967). In Indonesia losses as high as 50% and even 100% are reported from rice seed bugs (Van Haltern, 1979). A paper in Dutch dated 1878 discusses failed crops in Java due to this pest (Koningsberger, 1878). In Malaysia losses ranged from 10 to 36% but include *Nezara* spp. stink bugs (Soon, 1971). Rice bug numbers can rise to 275 per 10 net sweeps. In 1924 in one area the losses were so high that farmers had to purchase rice six weeks after harvest (Barnes and South, 1925). Historically in the Philippines high losses have been recorded particularly if a farmer plants out of step with his neighbors where losses can be $> 70\%$ (Uichanco, 1921). Farmers in Tarlac province said that rice bugs were worse than locusts. The only pest that was worse was stemborers, however. In Sri Lanka, Delpachitra and Wickramasinghe (1986) artificially infested six rice bugs per panicle beginning at flowering which resulted in 100% unfilled grains compared to a caged untreated check with 20%. 100-grain weight was reduced 45%. Only one rice bug density was tested in their trial which if extrapolated to 25 hills of 10 panicles each would give an outrageous density of 1,500 rice bugs/m^2 density. Such a trial therefore shows the potential but the density was much beyond what would be even feasible in nature. In India loss was 10% over 3 million ha in 1952 (Pruthi, 1953).

16.11.8 Losses from Multiple Pests and Stresses

Bardner and Fletcher (1974) underscore a major conclusion from this chapter when they stated that damage functions are highly dynamic as a multitude of biotic and abiotic factors control the relationship between insect infestation and crop injury. These factors can be divided into two groups: (1) those that are relatively constant for any specific pest-crop relationship and (2) those that are variable. Constant factors are the growth patterns of the particular cultivar, the nature of the injuries, and their characteristic distribution on and between plants. Variable factors include the time of attack in relation to plant growth, the intensity of injuries, the duration of the attack, and the environmental factors affecting plant and crop growth. Of the constant factors, the nature of the injuries and their distribution have been much studied but researchers have been slow to make use of the ideas and results of crop physiologists.

The effects of insects on plant and crop growth and yield are often complex, but the number of ways in which plants can be injured is limited as are the general responses of the plant or crop to injury (Bardner and Fletcher, 1974). Knowledge of the physiology of growth and yield in unattacked crops can provide a useful insight into the probable nature of the relationships between attacks and their effects on growth and yield. The variable factors affect the quantitative relationships between infestation and yield, their effect being especially important on the often delicate balance between the rate at which injuries are inflicted and the capacity of the plant or crop to compensate for them. Farmers traditionally manipulate such factors as planting dates, sowing rates, and other cultural conditions to minimize the effects of possible pest infestation based on trial and error. On the other hand, uncontrollable variations in the time of attack, soil conditions, and weather often make it difficult to define economic injury levels and to forecast the effects of an attack on yield though, where it is possible to establish quantitative relationships between measurements of infestation and yield, these usually conform to some part of the generalized response curve or damage function.

The occurrence of two different injuries, simultaneously or in sequence may modify the damage function and their effect is not always additive but can be antagonistic or synergistic. In the rice-wheat cropping system in India, an estimate of absolute yield losses of all pest stresses taken together was 1.4 t/ha but if added individually that total came to 1.8 t/ha (Savary et al., 1997), thus there is evidence of antagonism between factors rather than being purely additive. In terms of relative losses the total was 29% and if added individually was 37%. Highest individual pest loss was stemborer deadhearts at 0.5 t/ha and 9% relative loss followed by weeds below the canopy, brown spot, sheath blight, weeds above the canopy, neck blast, and sheath rot.

An earlier study by Savary et al. (1994) in C. Luzon, Philippines found that weeds above and below the canopy and stemborers were the main contributors to low irrigated rice yields. Stemborer was the only insect group to be associated with high yield loss in the study that measured over 30 crop production variables. Late planting was associated with low fertilizer applications and poor weed control. Surprisingly sheath blight was associated with high yields.

In Madagascar a multiple regression rice production function indicated that regional differences were important, as was quality of irrigation and optimum planting densities at appropriate dates of transplanting (Baumbärtner et al., 1990). Weed control and insecticides contributed positively to yield only when applied in fields with high yield potential. Although the data were limited, fertilization had a positive effect on compensation. In early plantings the relationship between high planting density and yield was positive, but neutral for average planting time and negative for late planting.

Multiple regression studies in India estimated that overall loss at 11% for long duration varieties and 14% for medium duration varieties (Seth et al., 1970). Avoidable loss was only 0.1 t/ha for the wet season and 0.2 t/ha for the dry season. Deadhearts were low, <3% as was whiteheads 5%, with neck blast registering 3–6% incidence.

16.12 Feedback to IPM

16.12.1 Usefulness of Yield Loss Data

Cohen et al. (1998) reviewed the rice crop loss assessment literature over a period of three decades for diseases and insect pests to determine the representativeness of existing data so as to evaluate how it could be extrapolated regionwide. The study focused on five criteria: (1) rice production in tropical Asia, (2) main objective was to measure yield loss, (3) descriptions of experimental and sampling designs provided, (4) techniques used for measuring loss described, and (5) quantitative information on loss provided. Reports were compiled according to rice ecosystem.

Among all of the literature reports, a subset was assembled of studies that were: (1) conducted over more than one year, (2) in more than one location, (3), and the plot size was field level. The main result was that surprisingly few reports met these three criteria. Most were in irrigated rice conducted in one location, in one season, and in plots $< 100\ \mathrm{m}^2$. The conclusion of the study team was that it is was difficult to extrapolate such results for even the irrigated rice ecosystem in Asia. The results presented herein would confirm this same conclusion. Given the strict criteria imposed the team such a conclusion is not surprising. For example the main objective of our extensive studies (Litsinger et al., 1987a, 2005) was to use yield loss data to develop improved insect pest control data not to estimate annual production loss for the Philippines as clearly the number of research sites were too few to allow meaningful extrapolation to a national scale. It would be very costly to set up teams to carry out field experiments in all major rice growing areas of a country. To undertake trials on farmers' fields it requires that local people be hired to continuously monitor the studies (Zandstra et al., 1981). Therefore it is not surprising that no studies could be found that would meet this criteria as networks of satellite stations would need to be established to achieve such an objective. It is difficult enough for national programs just to compile data on production let alone yield loss. Yield data is often compiled by interviewing the farmers to record their estimated yield rather than tediously taking yield cuts due to the time and cost involved. In addition it is known that farmers often underestimate their yield when reporting it to a government officer (Litsinger et al., 2008). The reason for under-reporting is for farmers to seem poorer than they are to avoid taxes or to attract government aid.

16.12.2 Rice IPM Program Development

The severe losses from rice pests that threatened food production in Asia in the early 1970s prompted aid organizations to support more effective IPM program development. Smith and Calvert (1978) on contract with USAID outlined four proposals for creation of a new research entity to meet that goal:

1. A developed country-based international plant protection center,
2. US consortium of universities,
3. FAO posting experts in national programs, and
4. Foreign based international plant protection center

A number of international plant protection centers were eventually established in developed countries such as US, France, and UK but their impact was limited to small research projects as the only local linkages were weak research systems. A US consortium of universities did materialize 15 years later (IPM-CRSP), but this was after rice IPM programs were in full swing in many countries. The IPM-CRSP which focused on other crops than rice had more success due to the more lengthy relationships with national programs by lasting over a decade in each country. The role of FAO was not only in posting experts in national programs but also functioning as a facilitating unit based in Asia called the Inter-country Program for Integrated Pest Control in Rice in South and Southeast Asia and now called the FAO Program for Community IPM in Asia (www.communityipm.org and www.farmerfieldschool.info). This was very effective in extending IPM programs. There never was a foreign based international plant protection center, but IRRI, a commodity based center, filled the role in developing many of the appropriate technologies and elucidating the ecological underpinnings of IPM. It provided the strong local research presence needed. IRRI's strengths were in assembling large research teams to undertake action research on key problems. These teams were in turn backed by ample funding and effective support services. Therefore option four above proved to be the most effective mechanism in IPM development.

Mounting a research program to study arthropod ecology including natural enemies is difficult for national programs that lack adequate taxonomic and scientific literature support. IRRI was successful as it had an international rice germplasm bank, an excellent library and bibliographic services, a strong arthropod taxonomic unit with a reference collection of authoritatively identified species, adequate greenhouse and laboratory facilities, ability to hire large numbers of field workers among other needed inputs, and a budget to allow annual travel to international scientific meetings and to national programs. This basic unit in turn attracted scholars, post-docs, and visiting scientists to undertake further indepth studies.

It was soon realized that IPM needs to be seen in the light of Integrated Crop Management due to the potential of modern rices to compensate from insect pest damage and other stresses. The first principle of IPM for irrigated rice advocated in farmer field school training programs is to grow a good crop (Matteson, 2000). The rationale behind this conviction has been to bolster modern rices with greater capacity for pest tolerance. Interpretation of the 'pest pressure-crop tolerance paradox' (Litsinger et al., 2006c) further supports this approach. In Madagascar, farmers were recommended to enhance the quality of agronomic management and to limit insecticide application in their fields that have high yield potential (Baumbärtner et al., 1990). Litsinger et al. (2006c) however recommended to target insecticide use more to crops under multiple stress to get the synergistic yield gain.

Rubia et al. (1996) concluded that enhancing the crop's compensatory attributes may be a better strategy than insecticide application. Litsinger et al. (2005) tested this hypothesis by comparing treatments where 25 kg N/ha (the equivalent cost of one insecticide application) was applied in lieu of insecticide when an action threshold was triggered. The outcome was mixed. There was a significant benefit recorded in the wet season to stemborers and to both whorl maggot and defoliators in the dry season. But there were no significant yield gains with leaffolders in any season. In order for the added nutrients to take their full effect the growing conditions such as solar radiation should not be limiting and of course this is highly variable in the wet season.

Crop management then becomes a two pronged strategy. The first thrust is for the farmer to undertake steps in crop husbandry to increase the crop's inherent yield potential commensurate with the magnitude of the complex of stresses present in the given season and expected weather. This can be best done by aping the practices of the highest yielding farmers in a given season.

The relationship of IPM vis-à-vis crop management practices is complex due to two opposing forces:

(1) On the one hand, the great capacity of high tillering and longer maturing rices that bolster compensation from damage is counterbalanced by
(2) The synergistic effect of multiple stresses in reducing yield, with each pest being just one stress (Litsinger et al., 2006c).

The observation of Viajante and Heinrichs (1987) illustrates this point where they studied the effect of artificial infestation of a defoliator on yield loss in the field with and without wooden frame screen cages. They noticed consistent lower yield losses from the same pest density levels when the plants were not caged over a series of trials. Our interpretation is that solar radiation allowed the crop to compensate from the damage more when no cages were used. On the other hand when cages were used the crop suffered from two stresses – from the defoliator and lack of sunlight. We predict that if they had caged the uninfested check but not the infested treatment that the yield loss would also have been low as both crops would have suffered from a stress. While if they had caged the infested crop but not the uninfested crop that the greatest degree of yield loss would have been measured as the difference between plants which had optimal compensation versus those suffering from two stresses.

It would be a mistake, however, to conclude that because rice can tolerate such high levels of injury that there is no need to apply corrective measures in all rice fields. The compensatory potential is only in effect when the crop is growing under optimal conditions and from farmer surveys we learned this is not happening in two thirds of the farms in any season. Compensation is dependent on several crucial factors, some of which are not under the farmer's influence:

1) Whether the variety is high tillering or not,
2) Maturity class of variety (long maturity allows more compensation),
3) How well the crop is agronomically managed,
4) The weather (cloudy weather lowers the yield potential especially during ripening), and
5) The number and severity of stresses affecting the crop in any growth stage (Litsinger et al., 2006c).

The results of the synergistic yield gain hypothesis have implications for IPM. To obtain optimal yield, the farmer does not have to directly control all of the stresses acting on the crop and would have the choice of correcting those that are least costly or less technically difficult. Research will have to determine which stresses relieve the most compensating capacity in the various stress combinations. It is estimated that half the yield potential of modern rices is based on the degree of management that is given to the crop. This is not true of traditional rices. Being tall, traditional rices have large capacities to store photosynthate that can be used in compensation (Kupkanchanakul and Vergara, 1991) but this is less effective than modern rices that use this mechanism as well as greater tillering ability.

Knowing what stresses are prevalent in the field, the farmer would have options in deploying control measures. As in Montana the deleterious effects of drought could be overcome from farmers adopting disease resistant wheat (Nissen and Juhnke, 1984). But a better tactic may be to improve the crop's ability to compensate by apply more fertilizer or weeding more rather than trying to kill the insect pest with environmentally destabilizing, hazardous insecticides which as applied by farmers have low kill ratios. Thus statements that research has shown that rice crops can tolerate much leaffolder defoliation and insecticide use does not increase yields, therefore insecticide control is unnecessary (Heong, 1998; Teng and Revilla, 1996) becomes conditional. The statement would be more true if the crop were not under stresses but not as true if it were as results (Litsinger et al., 2005) have shown that insecticides, even with their faults often result in significant although marginal yield increases.

On the other hand modern rices to date have not been given sufficient credit for having remarkable compensatory abilities. It is important to note that traditional low tillering rices do not have such an ability. We argue that the compensatory abilities of high yielding varieties are at least as important (if not more important) than genetic insect pest resistance. Luckily modern varieties contain both features where the former has greater importance against chronic pests while genetic resistance targets epidemic pests. We concluded that national rice production is more negatively affected by chronically economically significant insect pests.

In a related matter, if the synergistic yield gain hypothesis were correct, we predict the genetically engineered Bt rice, by effectively controlling lepidopterous insect pests such as stemborers, leaffolders, and defoliators (IRRI, 1996) should result in higher than anticipated yield gains by removing losses caused by not only from key chronic insect pests but also from other stresses. The benefit would perhaps be higher than the yield gain recorded from the insecticide-check method due to the greater killing ability of the bacterium's endotoxin than insecticide sprayed via knapsacks. Thus instead of the crop compensating just from insect pest damage, the effect may be compensation from other stresses as predicted. This hypothesis could be tested in rice environments with Bt rice and the parental non-engineered genotype both protected and unprotected by insecticide producing four treatments. The largest yield gain should come from the comparison of the protected Bt rice vs. unprotected genotype, more so than the yield gain from the protected genotype vs. the unprotected genotype (the conventional insecticide-check comparison). The field results should vary, however, depending on the balance of lepidopterous and non-lepidopterous pests attacking the particular crop.

In addition insect pest crop loss assessment in the light of the findings presented in this review needs to be rethought. Clearly results of trials that measure losses are highly site and time specific, so much so that such results would have little extrapolative value as concluded by Cohen et al. (1998). Also the much used insecticide check method that we believe measures yield gain rather than yield loss needs to be replaced by methods such as genetically designed cultivars or crop modeling where more variables can be included in the assessment as expressed by Baumbärtner et al. (1990) and Pinnschmidt et al. (1995).

16.13 Why Insects are Pests – Breaking of Some Myths

Ecological studies initiated in the 1980s resulted in a clearer understanding of why some rice insects are pests and has led to more effective strategies for their control. This has meant that a number of previously held beliefs to explain pest outbreaks have not stood the test of scientific inquiry. These impressions have been repeated so often that they have come to be taken truths when in fact experimental evidence was lacking. These we term myths and as such they will take a long time to replace with more scientifically sound results. Some of the results of scientific inquiry have several interpretations thus not all researchers agree on the following conclusions. But even while disagreeing these researchers cannot show research data to back up their beliefs.

One of the most prevalent myths is that traditional varieties are more pest resistant than modern rices. Researchers noted correctly that when modern rices were adopted that a number of new pests emerged and many pests became highly abundant (Litsinger, 2008). It was first believed that modern rices such as IR8 were intrinsically more pest susceptible than traditional rices and outbreaks resulted from the wide scale planting of a single susceptible variety. But studies showed that it was not true that modern rices lacked pest resistance as IR8 was resistant to green leafhopper (Heinrichs et al., 1985). Most traditional varieties were later found to be highly susceptible to all common rice insect pests in side by side comparisons and very few have been resistant donors. Outbreaks were shown by research trials to be mainly the result of multiple rice cropping and the use of insecticides (Loevinsohn et al., 1993). As traditional rices were only grown as an annual crop it gave the impression of being resistant due to the lengthy dry season fallow not genetic resistance. The other half of the myth states that the new pest resistant modern rices by being planted uniformly over broad areas increased risk of development of highly virulent insect biotypes such as happened with maize in the US in 1971 with southern corn leaf blight. This indeed did happen at the beginning of the Green Revolution (Gallagher et al., 1994) when few new varieties were available such as IR36 being the most wide scale example which is still widely planted in Asia. It was only natural that farmers wanted to plant the best variety available. Nowadays many local modern rices have been developed by national programs and farmers sow a wider range of varieties. In addition farmers regularly change varieties as measure to prevent such problems.

Initially researchers concluded that systems of modern irrigated culture resulted in lessened arthropod biodiversity compared to natural ecosystems thus had less complex food chains and fewer linkage redundancies and were therefore more susceptible to perturbations. Recent studies in community ecology have indicated that floodwater and canopy invertebrate densities in irrigated rice planted to modern rices equaled those of several natural ecosystems in biodiversity parameters (Schoenly et al., 1998) indicating a rich fauna of beneficial arthropods and are not as tenuous as previously believed and can withstand moderate insecticide usage.

In addition some people concluded that if insect pests were not controlled on modern rices, the damage could become so great that yields would be less than those of traditional varieties. This led to the myth that insecticides were therefore ‘required’ for high yields. In fact this is not supported by evidence. When modern rices are grown in irrigated culture side by side with traditional ones both without insecticide or fertilizer, yields of the modern rices will be significantly higher (Litsinger, 2008). The misperception came from early trials at IRRI where highly susceptible cultivars were used and insecticide trials registered very high losses. Farmers do not plant such highly susceptible varieties and if they do will quickly change as there are many choices nowadays.

Another myth is that nitrogen fertilizer contributes to many of the pest outbreaks and thus should only be used sparingly. A corollary of this myth is that losses are greater in more vigorous growing crops (Way, 1976). It is true that nitrogen increases pest fecundity and survival leading to higher pest incidence (Litsinger, 1994) but this belief does not take into account crop compensation which enhances the crop’s ability to tolerate damage (Litsinger, 1993). The researchers that perpetrated the myth did not integrate yield data into their conclusions, as despite higher pest incidence, one finds yields are also higher and this is what matters to the farmer. Farmers in India who have adopted hybrid rices have noted higher yields despite higher pest incidence and are no longer hesitant to use recommended dosages of inorganic nitrogen along with basal farm yard manure. If nitrogen is used judiciously by splitting applications 3–4 times per crop, the effect on pest buildup is moderated.

When outbreaks first appeared, researchers attributed much of this to changes in the microclimate or weather (Litsinger, 2008). It is true that close spacing increases brown planthopper that could be attributed to the higher humidity for increased egg survival (Dyck et al., 1979), but research has shown that the primary factors spawning outbreaks have been insecticide usage, increase in rice area, and by multiple cropping (Loevinsohn et al., 1993). Climate and weather factors are only secondary factors but they can become important from time to time and be responsible for some of the outbreaks mentioned earlier. For example yellow stemborer suffers high mortality when days reach > 34°C and RH < 70%, as at > 30°C oviposition ceases, and strong winds disrupt dispersal (Catling and Islam, 1999). Similar weather events negatively affect natural enemies which then unleash rapid population increases that can lead to epidemics (Mochida et al., 1987).

The next myth is that planthopper epidemics have been caused by the stimulation of their reproductive capacities by direct exposure to low insecticide dosages. While it is true that greenhouse trials showed that exposure to sublethal dosages of insecticides does stimulate increased fecundity, the magnitude of the effect is not enough to explain the large field populations that developed within the span of a few months (Chelliah et al., 1980). Extensive research has demonstrated that killing of natural enemies by insecticides is by far the most important mechanism (Heinrichs et al., 1982).

A final myth is that new technologies such as modern rices, hybrid rices, or new pest resistant rices such as Bt rice alone will solve the world's food crisis. Indeed these technologies show the potential but as we learned from the Constraints Program at IRRI which identified yield gaps as well as the concept of economic slack where there is a considerable lag phase between researchers developing new technologies and their final adoption by farmers. It was true that farmers readily adopted modern rices but the lag occurred with developing concomitant management practices to obtain the promised high yields. In the US it took farmers two decades to learn how to management the new hybrid maize varieties (Way, 1976). Effective extension systems are needed to assist farmers in learning how to best obtain the promises of modern rice yields (Matteson et al., 1984). The message is that there are few quick and cheap solutions and there is no substitute for more in-depth studies that focus on understanding how the agroecosystem is affected by the changes and can be made more stable by sustainable farm management (Smith, 1972) as well as the development of more effective extension systems to run side by side with new technological developments.

16.14 IPM Tactics

Over the period that rice has been domesticated, a combination of cultural practices and farmer-selected pest-resistant rices and assemblages of natural enemies developed and coevolved in wetland rice, its natural habitat. Although damaged by pests, flooding, and drought traditional crops produced stable yields on which Asian civilizations have depended for at least 7,000 years (Oka, 1988). Unfortunately these traditional systems are low yielding and could not meet the food demands of human population increase. The changes brought by the Green Revolution dramatically changed the way rice is grown. In traditional rice systems most of the farmer management occurred during crop establishment, harvesting, and processing. In the intervening period between transplanting and harvest most management was limited to checking on the water levels and repairing bunds. Nutrient and pest management were almost non-existent because traditional rices did not respond to better husbandry practices.

But modern rices greatly respond to improved management practices, and rice farming now needs to be thought of as a business rather than subsistence agriculture. Before the Green Revolution, IPM had its roots in industrialized societies but soon became the philosophy of choice for managing pests in modern rices in the late 1970s. Rice IPM program development for Asia had its beginning in 1977 funded by USAID in a training course held in Manila, Philippines (BPI, 1978). But IPM is often misunderstood, especially by non-specialists, who think of IPM as a tactic rather than an approach to more sustainable pest control. In IPM jargon, tactics can be thought of as weapons, but strategies are how they are deployed. Furthermore there is a mistaken impression by some that IPM will replace all existing pest control technologies. IPM is a philosophy, a different way in which crop protection is viewed rather than a fixed set of prescriptions.

The IPM concept first began as the integration of biocontrol with chemical control against alfalfa pests in California (Stern et al., 1959), thus the term integrated control was born. It now includes all methods of control including genetic resistance, quarantine, and cultural, mechanical and physical control. IPM began in the domain of entomology but has branched into the other pest control disciplines. Now it is seen as a subset of crop management. Thus the term 'integrated' implies incorporating different control tactics together in a harmonious manner for each recommendation domain (Zandstra et al., 1981); it also advocates integration of the tactics of pest control disciplines, and finally integration into the farming system.

IPM in rice in Asia began with the integration of host plant resistance and chemical control (Pathak and Dyck, 1973). Eventually when the limits of chemical control were realized other tactics were developed. In fact, reduction of chemical control was seen as a necessary step to maintaining the sustainability of genetic resistance particularly in regard to the brown planthopper (Gallagher et al., 1994). Widespread adoption of a single variety resistant to the brown planthopper such as IR36 did not lead to less insecticide usage but rather more directed at chronic pests. Farmers followed the credo 'if a little insecticide works well then more will work better'. The result was resurgence, secondary pest outbreaks, and the evolution of new biotypes, all of which demanded a new IPM strategy (Heinrichs, 1994). Nowadays insecticides are seen in a different light where they play a much more limited role while host plant resistance, natural biocontrol, and cultural control methods form the backbone of most IPM programs. No longer are insecticides considered to be necessary (in the sense that inorganic fertilizers are necessary) to grow modern rices. Ironically it was fear of more outbreaks that led farmers to use more insecticides, which is akin to putting out a fire with kerosene.

Many farmers believe that all arthropods in a rice field are pests and if one takes a few sweeps with an insect net and shows the farmer the contents, his first instinct would be to reach for his sprayer. Only through training will farmers begin to appreciate the importance of the rich beneficial fauna that occurs naturally in their fields, and that by using insecticides indiscriminately on a prophylactic basis this fauna will be depressed robbing farmers of this wealth that Nature provides gratis. It is this fauna which keeps most pests to below economical levels in farmers' fields each season if allowed (Ooi and Shepard, 1994).

The core of IPM is a set of practices that maintain pests below economic damaging levels with husbandry of natural regulating agents and minimal or no use of pesticides. IPM demands an understanding of ecological relationships and that pesticides kill more than pests. Research in the 1980s contributed greatly to understanding the ecological basis of why insect pests had become such problems a decade earlier. This new understanding guides IPM decisions in rice today, which along with new holistic thinking on the mechanisms of compensation give pest managers new insight to develop more effective control strategies.

Before we give examples of these new strategies we review the tools or tactics that are available to pest managers. Farmers are naturally reluctant to adopt technology when they are unsure how it will fit within their farming system. Since it will be virtually impossible for the crop protection specialist to anticipate the full effect of a given technology on an individual farmer's field, a choice or menu of technologies should be on offer from which the farmer can select and with which further on-farm experimentation can be carried out. Technologies must be presented in a form that enables farmers to see how they may fit into his or her farming system. This is a major challenge for adaptive research and demands much improved knowledge of the farmer's decision process (Heong, 1999) and the ability to produce technologies to meet the needs of a range of farmer types (Litsinger et al., 2008). A strategy would also be to train farmers to gather yield loss data in order to build their indigenous technical knowledge base (Kenmore, 1987).

16.14.1 Genetic Resistance

Rice is self fertilized and farmers can harvest seed for the next crop from a standing crop. Man has selected, consciously or unconsciously, the best yielding (adapted) cultivars over the seven millennia of rice domestication. Such selection has produced strains that show high yields even under a multitude of environmental stresses utilizing the mechanisms of genetic resistance and tolerance to pests. Host plant resistance has been the basis of plant protection for centuries. It is also the main means of technology transfer, via improved seeds, to rice farmers all over the world as effective extension services are not needed for this to occur. Although much host plant resistance is of the pedigree single gene type, the recorded insect and disease outbreaks reveal its weakness when used as the sole method of plant protection. Many of the insect pests and diseases that affect modern rices were not important during the era of traditional rice culture so resistance to these organisms is not common.

Genetic resistance is especially valuable in developing countries with small farm sizes, farmers' economic constraints, and lack of technical knowledge that limit the utility of other control methods. Genetic resistance is economical for small-scale farmers as new seed does not have to be purchased each crop. Compared to chemical control, the farmer does not have to develop skills on how to use the control method as it is in the seed and works every day in the field. The large germplasm collection at IRRI and screening programs for pest resistance have allowed the identification a number of genes resistant to four diseases (blast, bacterial blight, tungro, and grassy stunt) and five insect pests (brown and whitebacked planthoppers, green leafhopper, stemborers, and gall midge) (Khush, 1982). These genes have been incorporated into modern rices with high grain quality and early to intermediate duration and are available for breeders to use in national programs throughout Asia. IR36 for example has resistance to all but whitebacked planthopper and sheath blight in the list above. The basis for resistance in the insect pests, with the exception of stemborers, is antibiosis meaning that the insects are killed in the same way as putting insecticide into the rice plant but without the non-target environmental and health problems. The basis of resistance to stemborers is morphological and non-preference but the level of resistance is rated as only moderate (Chaudhary et al., 1984).

The main breeding strategy has been the sequential release of rices with new genes if resistance breaks down. There are greater attempts to place more than one gene in a variety (pyramiding) so that resistance will be that much harder for the pest to overcome. This is the goal for Bt rice as resistance is bound to breakdown otherwise (Ho et al., 2006).

Tolerance, unlike non-preference and antibiosis which interfere with insect behavior and metabolism, provides a plant with the ability to produce satisfactory yield in the presence of pests that would cause loss in a susceptible plant. Tolerant cultivars do not depress or limit pest populations nor do they provide selection pressure that can lead to the development of insect biotypes capable of overcoming resistance. The phenomenon of tolerance is generally cumulative and a result of interacting plant growth responses. These include general vigor, inter- and intra-plant compensatory growth, wound compensation, mechanical strength of tissues and organs, and nutrient and growth regulator partitioning (Velusamy and Heinrichs, 1986). The fact that tolerance is not likely to provide a high level of insect resistance suggests that it should be used in combination with other mechanisms of resistance or IPM tactics.

Although not highly resistant, tolerant varieties have higher decision thresholds than susceptible varieties resulting in a reduction of insecticide usage and enhanced natural enemy activity (Panda and Heinrichs, 1983). Tolerant plants which support large insect populations with little damage or yield loss, have value in preventing selection of new biotypes and in maintaining beneficial natural enemy densities. Tolerance increases yield stability by providing at least a moderate level of resistance when the vertical genes, that provide a high level of resistance through non-preference and antibiosis, are rendered ineffective because of a selection for a biotype with virulent genes. When biotype selection is detected and this first line of defense provided by major genes is removed, the tolerance mechanism becomes a secondary line of defense and will continue to function while preparations can be made to release a new resistant variety.

16.14.2 Cultural Controls

Cultural control in rice is the purposeful manipulation of the agro-ecosystem to suppress insect pest densities (Litsinger, 1994). As such, farmers use crop husbandry practices that have a dual purpose of crop production and insect pest suppression. No matter how the farmer grows his crop, however, certain pests will be favored while others are disfavored. The farmer needs to determine the appropriate balance. Farmers developed these practices mostly by trial and error handed down through generations. The far majority of these practices are more effective if carried out over a large area the size of a village or an irrigation turnout (Litsinger et al., 2008). Practices that are effective on a single field basis are altering the planting method, plant density, water management, and fertilizer usage. Those that are more effective if carried out on an area wide basis are modifying crop rotation, number of crops per year, plant maturity, planting time, synchronous planting, tillage, and crop residue destruction. See Litsinger (1994) for literature citations of cultural control practices stated in the following sections.

16.14.2.1 Single Field Adoption

Transplanting is the preferred sowing method due to its better weed control, but in areas where labor is unreliable, farmers direct seed. Direct seeding and consequent dense seeding favors a number of pests including black bugs (*Scotinophara* spp.), stemborers, and planthoppers, but whorl maggot is virtually suppressed. Ponding attracts the more aquatic species such as caseworm, whorl maggot, black bugs, yellow stemborer, and hispa. Inorganic nitrogen fertilization increases almost all insect pests but particularly brown planthopper and leaffolders, but use of potassium increases the ability of the rice plant to tolerate pests. On the other hand, nitrogen increases the crop's tolerance for insect pest damage.

16.14.2.2 Community Wide Adoption

Early planting is generally an escape mechanism but the effects of planting time are highly site specific as their effect depends on cropping patterns in the surrounding several thousand hectares. A single crop of rice per year ensures the least buildup of insect pests, and rotating a non-rice crop offers pest suppression for the same reason. If double rice cropping is practiced the best suppressive results occur if the dry season crop is planted soon after the wet season one is harvested to create a long dry fallow. Planting more than two rice crops per year, particularly when fields are planted asynchronously, is risking severe insect pest and disease problems because it reduces the pest suppressive effect of a dry fallow (Loevinsohn et al., 1993). Synchronous planting and maintaining a rice free period in the dry season breaks pest cycles and is particularly effective for virus disease control (Litsinger, 2008). Plantings so that fields all mature within a few weeks of each other regardless of plant maturity is an effective method to minimize buildup of stemborers and rice bugs. Thus in order to take advantage of the benefits of synchronous planting and harvest farmers should select varieties of the same maturity class. The consequences of some fields falling out of synchrony are well known to farmers. There are some circumstances where the rice-free fallow has a greater depressing effect on natural enemies, fostering brown planthopper buildup (Litsinger et al., 2008). In such areas farmers should sow brown planthopper resistant rices if available. Tillage and crop residue destruction in the off season aid disease and stemborer control.

16.14.3 Biological and Natural Control

Rice has been domesticated for millennia engendering notable elements of stability, particularly in irrigated culture which is ecologically akin to its original marshland habitat. A rich fauna of biocontrol organisms coevolved which can rapidly colonize a ricefield, thrive in the stable conditions offered by ponded fields, and make a notable impact on most insect pests. To make the most of this natural resource, farmers need to learn to recognize the beneficial effect of the wide array of natural enemies in rice fields and undertake efforts to conserve them. Ecological costs of not doing so include disruption of food web linkages by injudicious insecticide usage that will kill off important natural enemies (Settle et al., 1996; Schoenly et al., 1996). Using food web data and arthropod time-series records from one irrigated field, Cohen et al. (1994) found that insecticides disorganized and destabilized the population and community dynamics of arthropod species in rice agro-ecosystems. One consequence is to trigger outbreaks of primary and secondary pests (Kenmore et al., 1984; Heinrichs, 1994).

Reports from Schoenly et al. (1996) and Settle et al. (1996) show a profound arthropod taxonomic richness in tropical irrigated rice fields. Food webs or the assemblages of natural enemies have been constructed for common rice pests in the Philippines (Jahn et al., 2007). These represent the sum of all the host associations for a pest species and can be presented as records for a season or over all years (Schoenly et al., 1996). Counts of macro-invertebrates alone for Philippine and Indonesian rice fields exceed 600 and 760 taxa, respectively. Significant biocontrol elements of this fauna, such as spiders and hymenopteran parasitoids in Indian irrigated fields number up to 92 and 84 taxa, respectively (Sebastian et al., 2005; Beevi and Lyla, 2000). Like other invertebrate assemblages, rice invertebrate faunas follow the usual distribution pattern of having a few very abundant taxa (> 5%), more taxa of moderate abundance (1–5%), and a large number of rare taxa (Schoenly et al., 1998).

Among the ecological conclusions that have emerged from whole-community studies of rice-invertebrate faunas under pesticide-free conditions are that detritivores and plankton feeders (springtails, midge and mosquito larvae) dominate early crop periods. Their food is the decomposing stubble and roots from the previous crop as well as algal blooms. They provide sustenance for early season generalist predators dominated by spiders. Although there are literally dozens of species of natural enemies in the field at any moment, their number steadily increases with crop age as they colonize from areas outside of each field after land preparation. But there are generally only a few groups that are the most important in a given area, including generalist predators and specialist parasitoids.

A subset of rice pests has specialized in colonizing fields early. These include rice whorl maggot, caseworm, green hairy caterpillar, green semi-looper, rice hispa, armyworms, and cutworms. As natural enemies build up over the crop, these vegetative pests flourish in the absence of effective natural enemy pressure during the first month of the crop in the field.

Spiders are perhaps the largest group of beneficial arthropods whose role in limiting brown planthopper first gave them notoriety by Kenmore et al. (1984) from field studies. Before that studies in temperate climates had concluded that spiders only preyed on nonpest detritus feeders (Yasumatsu and Torri, 1968). Their rich abundance in tropical rice was revealed by Barrion and Litsinger (1984). Katydids and crickets (Canapi et al., 1988; Rubia et al., 1990b) are effective predators particularly of eggs. *Conocephalus longipennis* katydid can for example eat an entire *Scirpophaga* spp. stemborer egg mass, hair mat and all. Aquatic hemiptera in the genera *Microvelia* and *Mesovelia* feed on plant- and leafhoppers that fall on the water surface (Nakasuji and Dyck, 1984). Aquatic predators feed on caseworm larvae (Litsinger et al., 1994).

Cyrtorhinus lividipennis is a noted mirid egg predator of plant- and leafhoppers and also feeds on small nymphs (Heong et al., 1990; Ooi and Shepard, 1994). Its mouthparts penetrate into rice culms where the eggs are inserted by hoppers. Ladybeetles (e.g. *Micraspis, Menochilus, Synharmonia*), staphylinids (e.g. *Paederus fuscipes*), and carabids (e.g. *Ophionea nigrofasciata*) are important against a wide array of pests including planthoppers, leafhoppers, leaffolders, stemborers, and early vegetative lepidopterous defoliators (van den Berg et al., 1992; Ooi and Shepard, 1994).

Of the parasitoids, the egg parasitoids are the most prominent against stemborers (Shepard and Arida, 1986; Litsinger et al., 2006d), planthoppers and leafhoppers (Chandra, 1980), rice bug (Rothschild, 1970b), rice hispa (Prakasa Rao et al., 1971), armyworms (Rothschild, 1969), black bugs (Perez et al., 1989), and gall midge (Hidaka et al., 1988).

Pathogens also play a role in natural pest suppression (Rombach et al., 1994). Epizootics of entomopathogens have been noted for many rice insect pests. Example the fungus *Nomuraea rileyi* regularly suppresses the green hairy caterpillar in the Philippines, while an epidemic of *Zoophthora radicans* was observed on rice leaffolders after a typhoon where only flattened larval bodies adhering to rice leaves provided the evidence of their role. Brown planthopper which appears in dense numbers is particularly prone to a number of fungi such as *Entomophthora* spp., *Beauvaria bassiana*, *Erynia dephacis*, and *Metarrhizium anisopliae*. Armyworms are highly susceptible to nuclear polyhedrosis virus, especially when they aggregate.

General information on beneficial arthropods in rice fields can be sourced from the following references: Shepard et al. (1987), Barrion and Litsinger (1994, 1995). The natural fauna affecting key rice insect pests has been compiled for stemborers (Nickel, 1964; Khan et al., 1991), leaffolders (Khan et al., 1988; Barrion et al., 1991), leafhoppers and planthoppers (Ooi and Shepard, 1994), and rice skipper and greenhorned caterpillar (Litsinger et al., 1997).

There have been but few attempts to introduce natural enemies from one location to another, which is termed classical biocontrol (Ooi and Shepard, 1994). Continuous rice systems or asynchronous planting have been advocated to encourage natural enemies (Settle et al., 1996), however, this increases risk for virus diseases of rice (Koganezawa, 1998). Augmentation by spraying suspensions of pathogens onto rice was extensively tested but met with only limited success (Rombach et al., 1994). One great disadvantage of this method has been low toxicity and low fungal survival in storage as well as in the field after application. Inundative releases of egg parasitoids have been carried out against stemborers with little practical result (Ooi and Shepard, 1994). Consequently conservation of natural enemies is mostly advocated by minimizing insecticide application frequency and selecting materials less toxic to beneficials (Bandong and Litsinger, 1986; Heong, 1998).

One aspect of microbial insect pest control which has made substantial progress has been with *Bacillus thuringiensis* (Bt) which is highly effective against only lepidopterous insect pests. This bacterium occurs naturally but in very low densities as no natural epizootics have been recorded. The toxic crystal (endotoxin) extracted from the bacterium has been shown to have insecticidal properties and is available as a commercial insecticide (Tryon and Litsinger, 1988). A strain of Bt was genetically engineered by insertion of the endotoxin to be part of the rice genome known as Bt rice and has given excellent control of rice stemborers and leaffolders (Theunis et al., 1998, Ho et al., 2006). The endotoxin is carried in the seed just like a resistant gene from a resistant rice plant. Unfortunately policy leaders in a number of countries are skeptical of the safety and ecological consequences of this new form of rice breeding and have not allowed the seed to be tested or sold thus limiting this control option to only a few countries. In the US Bt maize and Bt cotton have been used by farmers for a number of years without any noted problems.

16.14.4 Chemical Control

Chemical control is placed last in the list of IPM tactics on purpose to stress that the central core of IPM is to minimize insecticide usage and spare natural enemies by reviewing other measures first. Beyond risking farmer health, insecticides also increase economic and ecological costs (Pingali and Roger , 1995; Schoenly et al., 1996; Heong and Schoenly, 1998). Chemical control of rice insect pests has been reviewed by Chelliah and Bharathi (1994).

Insecticide usage in the Philippines has declined since hitting its peak in the 1970s during an era of government sponsored credit programs (Bimas in Indonesia and Masagana 99 in the Philippines) designed to encourage farmers to adopt agrochemical inputs. Chemical control still remains as a viable control option to farmers but for only limited use as such a powerful tool can no longer be squandered indiscriminately in the name of increased yield. Safer and more selective materials (e.g. neem, Bt, imidacloprid, buprofezin) are replacing the broad spectrum organochlorine, organo-phosphate and synthetic pyrethroids that dominate the market. Unfortunately farmers prefer them as they are less expensive as their international patents have expired allowing many companies to manufacture them. Competition brings lower pricing however. As an IPM strategy there is a need to avoid excessive use that will inevitably lead to the familiar treadmill characterized by increasing pesticide use to maintain yield stability in the face of developing pesticide resistance, resurgence, and secondary pest outbreaks.

One method to minimize usage is to train farmers to engage in weekly monitoring of their fields for pest and natural enemy population assessment and to use simple guidelines for triggering an insecticide application. In India farmers are asked to place an old rubber bicycle tire in the field on a weekly basis in three locations. No insecticide application is warranted if the total number of stemborer deadhearts and gall midge onion shoots is < 15 or a mean of 5 per tire sample area. Often farmers apply insecticides when no pest is present in a stage that can be controlled.

Stemborer larvae in the stem or pupated leaffolders cannot be killed for example. The determination of accurate guidelines in small farm systems can be complex based on the discussion in this chapter on the push-pull interrelationship that exists between multiple causes of stress and environmental effects on crop compensation. Economic thresholds, or more realistically action thresholds, are best derived from empirical methods. Until crop modeling can incorporate with confidence the many interactions that impact the elucidation of damage functions, the empirically derived action thresholds of Litsinger et al. (2006a–2006c) can be used as a first estimate. Action thresholds should be tested and perfected locally and can be adjusted based on crop vigor, the density and species of natural enemies, farmers' ability to withstand risk, crop maturity class, and the number and type of stresses impinging on the crop at the time.

An important point is that the yield losses determined in the Philippines based on the insecticide check method (Litsinger et al., 1987a, 2005) were equally distributed over the three crop growth stages. If this is the general pattern found elsewhere this does not favor chemical control as the expected gains in any growth stage will be relatively small and in most cases uneconomical to prevent. The extensive yield loss study also found that it was uneconomical to use even one insecticide application in over half of the fields studied. In addition insecticide application technology practiced by farmers produces low kill coefficients. If farmers applied at higher dosages and with greater spray volumes perhaps the kill coefficients would increase but this will take an effective extension program.

Based on the evidence that if a farmer managed his crop well agronomically, it would not be necessary or profitable for him to apply insecticides unless a high insect pest infestation occurred such as an armyworm outbreak, high early vegetative pests, or a mass immigration of planthoppers occur. On the other hand, on a stressed crop caused from either poor management, lack of water, or low solar radiation it may be economically attractive to apply insecticide to benefit from a synergistic yield gain.

16.14.5 Agronomic Practices to Bolster Tolerance

Rice IPM is embedded within the realm of integrated crop management as the healthier the crop the greater the amount of damage it can sustain before economic loss occurs. Some examples of agronomic practices that can fulfill this goal are presented and first include selecting a longer maturing variety (within the range up to 125 days as much longer durations will favor greater stemborer buildup). Farmers should ensure good seed quality with removal of mixtures and undersized seeds as well as seeds infected with fungal diseases. In areas where animals are raised, farmyard manure added to the soil before land preparation ensures good soil texture and slow release and availability of nutrients to plants. Deep plowing should be done every few years to ensure good root development. Thorough land preparation to obtain level fields is important in irrigated rice. Unleveled fields cause not only inefficient use of irrigation water and broadcast nitrogen but poor weed control. Also the crop will not mature evenly which can lead to greater insect problems. Nurseries should be supplied with organic matter to minimize root damage when seedlings are pulled. Transplanting seedlings 3 weeks of age insures good tillering. Maintaining good water control (so as not to pond too deep to impair tillering and root growth but still maintain good weed control) is essential. Remove weeds from both the seedbed as well as the crop before canopy enclosure. Fine tuning the nutrient regime in terms of rates and timing is crucial. All phosphorous and potassium and about one third of nitrogen should be applied basally incorporated under the soil. The IRRI leaf color chart can guide the proper timing of nitrogen before maximum tillering and then a third nitrogen application 5–7 days before panicle initiation. In longer maturing varieties a fourth nitrogen application 5–7 days after flowering is important for even maturity. While it is true that insect pest populations do increase in well fertilized crops, it is also true that yields will be higher despite this.

16.15 Examples of IPM Practices

A few examples are presented to provide insight as to how compensation can be incorporated into IPM recommendations. The first comes from India where patches of severe defoliation appeared 4 w.a.t. from caseworm and rice hispa. The farmer's first reaction was to broadcast Phorate (methadmidophos) granules into standing water. The crop had no signs of foliar diseases, weeds were controlled, but the crop had not yet been fertilized. There were scattered egrets feeding on insects and aquatic life in the nearby rice fields. There was a need to control the defoliators in the most severely infested patches as the plants could be killed and gaps in the rice stand would appear. Methadmidophos is a highly toxic insecticide and would pose a danger not only to the farmer applying it, but also to the egrets that may think the granules were seeds. The farmer was asked if he could fashion an insect net and collect the caseworms and hispa from the patches of damage. He said he did not have the time. It was decided that he could spray a less toxic insecticide such as neem or imidacloprid in the worst damaged areas as it was only necessary to achieve $> 50\%$ control as a young crop still has time to compensate from this degree of defoliation. The farmer was also advised to broadcast 30 kg N/ha to foster compensation.

Another farmer complained of stemborer deadhearts at 6–7 w.a.t. and wanted to spray chlorpyrifos. It is at this stage that the rice plant is most resistant to stemborer entry (Bandong and Litsinger, 2005) thus there is less need to spray at this time as the first instar larvae cannot easily penetrate into the stem. The farmer should bolster the crop's ability to tolerate the few deadhearts that would occur by timing the next nitrogen application at 5–7 days before panicle initiation.

At 8 w.a.t. there was a mean of 10 brown planthoppers and 1 spider per hill. For each predator counted the farmer should deduct 5 planthoppers from the count. This density is very near to action threshold levels therefore the farmer should monitor his field twice a week to see if the predators can stop the buildup before reaching 1–2 per tiller after accounting for predator density. If the threshold is reached, insecticide, as a last resort, should be timed when the population is mostly composed of the 4–5th instar nymphal stage for greatest effect. If adults dominate then the eggs they laid, protected in the stems, would survive the insecticide application. The most appropriate insecticides are buprofezin or imidacloprid which will spare most natural enemies.

At 9 w.a.t. the percentage of leaffolder damaged leaves was rising but otherwise the crop is healthy and without other stresses present. The farmer can raise the action threshold to 15–20% under this condition as the crop can tolerate this level of damage. A lower threshold is used if the crop is under stress from other causes. The actual threshold depends on the risk the farmer is willing to bear as well as his goal of obtaining the either highest profit or highest production. A lower threshold would be in force if production were the goal or if the farmer is risk averse. A final application of nitrogen should also be considered to bolster compensatory capacity.

In the final example a wet season crop planted to an early maturing variety is under stress from a number of causes, e.g., several foliar diseases, weeds, and a gall midge infestation that is rising over 10% damaged tillers. In addition reduced solar radiation will dampen the crop's compensatory capacity along with the short season variety. The farmer should first remove weeds as much as possible as a first priority and then ensure that future nitrogen applications are timely. If gall midge keeps increases, the farmer should apply an insecticide which should give a yield boost not only from suppression of gall midge but also a synergistic yield gain from compensating for the foliar diseases. If gall midge is of a chronic occurrence the farmer should think of selecting a longer maturing variety and preferably one resistant or tolerant to gall midge in his future crops.

16.16 Conclusion

The spectrum of insect pests has changed over the past millennium that yield losses have been recorded in Asia. The earliest epidemics recorded in Japan and Korea on traditional varieties now occur on modern semi-dwarfs in not only temperate Asia but in tropical Asia as well (Litsinger, 2008). The causes in the two regions are different however. In temperate Asia rice planthoppers undergo massive long distance migration and arrive in single cropped rice overwhelming natural enemies, while in tropical Asia multiple rice cropping coupled with indiscriminate insecticide usage can spawn the epidemics which in the latter case also included green leafhoppers and virus diseases. There is some evidence that even in parts of tropical Asia that long distance migration of planthoppers occurs (Kisimoto and Rosenberg, 1994; Riley et al., 1995). Migrations into Central China from Vietnam occur annually and there is evidence that migrations occur from S. India and Sri Lanka up the eastern half of India following the path of the SW monsoon as Chhattisgarh state in India annually records hot spots of brown planthopper in the wet season where in only $<10\%$ of fields establish a dry season crop. Such populations can be explained only via immigration.

Throughout Asia before high tillering rices were developed, insect pests such as stemborers were chronically abundant on traditional rices. For example Wyatt (1957) stated that 50% of the tillers in Malaysia were normally infested. The factors favoring stemborer incidence on traditional varieties were their long maturation, tall stature, and being thick stemmed. Long maturation meant more stemborer generations developed on the crop. Tall stature meant that longer periods of elongation and hence longer periods of susceptibility occurred. Thick stems favored more species such as the larger bodied *Chilo* and *Sesamia* genera. Modern rices being earlier maturing, shorter stature, and thin stemmed have been less favorable to stemborers thus losses are less. The exception would be the white stemborer *S. innotata* which virtually disappeared from its range when photoperiod insensitive rices were bred allowing multi-rice cropping. Mortality was high during land preparation of the second rice crop for aestivating larvae. But early maturing modern rices, developed in the 1980s, allowed a resurgence of white stemborer throughout its range with devastating effects (Litsinger et al., 2006e). Early maturity meant that the dry season fallow was extended allowing survival of aestivating larvae after the second crop was harvested.

Traditional rices showed a high ability to compensate from defoliation mainly through transport of carbohydrates stored in the stems. Modern rices have demonstrated this ability plus have the capacity of extensive tillering to replace those lost or damaged due to insect pest damage. Both of these processes has meant that the semi-dwarfs have high capacities of damage tolerance, not only from insect pest damage but from other stresses. These qualities have been little appreciated to date but are apparent in all modern rices that have inherited the *indica* genotype, thus the appeals that have been made for rice breeders to breed for new genotypes that have the ability to tolerate more insect damage (Heong, 1999) actually had been answered when IR8 was bred in the early 1960s. All that was lacking was knowledge on how to exploit this trait. There is evidence of some genetic variability in rices with regards to compensatory abilities (Catling and Islam, 1999) but for the most part the high tillering has achieved high levels. Other physiological pathways may also be tapped in new genotypes to build up higher levels.

Yield loss studies have concluded that for farmers to harness modern rices' great capacities for damage compensation, IPM needs to be viewed in the context of integrated crop management as the more fit the crop is to the local conditions the greater will be its ability to tolerate pest damage and stresses in general. Results of yield loss studies revealed instances where very large yield gains occurred in insecticide treated plots which could not be explained by insect pest densities alone. This has led to the hypothesis of synergetic yield gain which is the corollary of synergistic yield loss to explain this phenomenon.

The wide range of yield within a farm community where ten-fold differences among fields are common show that many farmers have not mastered the agronomic practices needed to achieve the yield potential of modern varieties in order to capitalize on the great compensatory capacity. Studies have also shown that the same farmer in one season may reach the high yield potential only to be on the bottom of the yield distribution curve a season or so later. The challenge ahead will be to pull up yields in all seasons. From the results of the yield gap data one takes away the thought that farmers readily adopted modern rices but have had trouble adopting other management practices which continues to this day probably more from the lack of effective extension services than anything else. The more recent data on the wide variability of rice yields in a farm community further supports this conclusion. Modern rices grown in irrigated culture have an advantage over the era when only single crop traditional rice was grown is that the farmer can recoup his production within the next six months rather than having to wait a year for single crop rice culture.

If the synergistic yield gain hypothesis were correct the farmer would have more choices in how to achieve high yields. For example if there were three stresses affecting the crop in the same growth stage, the farmer would only have to resolve two of them and allow the crop to tolerate the third. Farmers could chose to correct the easiest to control stresses at great savings. In order to capitalize on the yield compensatory strengths of modern rices, the farmer needs to master agronomic management more effectively and to time his planting to receive the greatest incidence of solar radiation. Growing longer maturing rices is one key to achieving higher yields. Yield loss studies showed that insecticide application with a knapsack sprayer produces marginal returns at best as spray coverage is not adequate to realize the high kill ratios necessary to benefit from this technology. The farmer is better off using the money he would have spent on insecticides for use in other stress reduction methods and allow the crop to compensate.

Yield losses have been found to be highly variable by culture, location, season, and field. This is hardly surprising given the high field to field variability documented in this review as well as the revelation that even the same farmer in the same field experiences this same degree of variability as the farmer community as a whole crop to crop. Part of the reason for the variability is the propensity of farmers to change management practices season to season, variability in insect pest infestations season to season, variability in crop stresses season to season, and the variability of weather season to season. These factors are especially dynamic with regard to modern rices which have a high capacity of compensation but which outcome is highly influenced by the factors just described.

All methods developed to assess yield loss to date are flawed to varying degrees. Plot size is important regarding all methods as many trials have been conducted on areas that are too small to accurately measure yield and to take into account the hill to hill interactions between infested and uninfested plants. Extrapolating yields taken on a few hills to a hectare run risks of small errors being grossly magnified. Few studies to date have been repeated in more than one year or in a sufficiently large number of fields to be representative of a farm community or in enough areas to be representative of a region of a country. There is also difficulty in determining loss caused by one pest species while keeping other pests neutralized.

The insecticide check method which has been the most used has limitations, the most significant as illuminated in this review as it probably measures yield gain from compensatory suppression of a host of stresses rather than yield loss caused by insects alone. It also has problems with usage of phytotonic or phytotoxic chemicals or other materials that affect other pest groups such as diseases and nematodes, the difficulty of achieving > 90% pest control, and the difficulty of controlling insecticide drift. If the synergistic yield gain hypothesis were true then the effect of carbofuran would even be more insidious in that it would have allowed for even more compensation to occur. Damage simulation always begs the question of whether the method used accurately mimics that of the pest. Artificial infestation often uses cages which interfere with the natural growth of a crop mainly by shading. The yield potential comparison method is in question of whether the potential has been accurately determined. Modeling still is in its infancy with regard to discovering a pest's influence on plant physiological processes and accounting for the effects of the multitude of environmental interactions. It will require continual field validation during its elaboration.

As a result, more than one method should be employed as a cross check in crop loss assessment. Modeling needs to be validated to field situations. Some of the methods with the least problems were the artificial infestation of yellow stemborer eggs practiced by Bandong and Litsinger (2005). The caging was limited to only one week and the plot size was 25 hills, allowing for inter-hill competition to occur normally. Artificial defoliation or detillering with scissors showed the power of compensation while modeling has revealed its numerous physiological pathways. Potentially the most realistic would be developing designer variants of the same genotype having Bt genes and possibly other attributes that affected only certain pest guilds. Thus these genotypes could be grown on large plots under a variety of management situations to test these factors under realistic conditions.

The far majority of crop loss assessments have occurred on irrigated rice with only limited data from the other rainfed cultures. The conclusion of Cohen et al. (1998) rings true that very little of the voluminous data that exists on yield loss can challenge that produced by Cramer (1967) despite the fact that he used data from insecticide trials which are probably not representative as researchers conducting such trials generally time their plantings for the highest field densities.

The remarks of Kenmore (1987) that farmers stand to gain the most from the knowledge of crop loss assessments but now are the least likely to learn of any results ring true. As farmers need local prediction of crop losses, this information should be most efficiently and effectively collected by the farm community. The suggested method to achieve this end would be for farmers to develop their own database of yields from each field in the community each season. They then could compare each crop to the yield potential determined by the database by taking accurate yield cuts as well as gathering data on input usage and crop stresses that are at least semi-quantified. Farmers would convene after each season and discuss their yields as well as management practices of those attaining the highest yields that season so that the low yielders could learn of management practices they should adopt the next crop. Through such an iterative approach, yields of the whole farm community could be gauged against the historical yield potential and farmers would have a basis from which to work to make improvements season to season. Policy makers (through local extension agents) could tap such databases each season by a simple survey of the farm communities to get regional and national crop loss assessment data.

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