Chapter 2
Pillars of Integrated Disease Management

Economical and sustainable disease control can be obtained through the establishment of an integrated disease management system. The first integrated management system was developed by Dwight Isely to manage the population of cotton boll worm (*Anthonomus grandis*), which gave positive results for over 60 years in the United States (Newson 1980). Later, several other integrated management systems were developed and their basic concept was introduced to develop integrated management systems for diseases as well. Although there are several definitions of the integrated management system, according to Ledbetter et al. (1979) cited by Blair and Edwards (1980), "it is a system where all the possible pest control techniques are used to keep the pest population below the economic threshold. Each technique is eco-friendly and is compatible with the objectives of the user. Integrated management is more than merely the control of pests through chemicals. In several cases it includes the biological, cultural and sanitary control techniques for a complex of pests.

Thus the pillars of an integrated management system include several and all possible control measures and in case of wheat it should include cultivar resistance, seed health, cultural practices and fungicides (Mehta 1993; Cook 2000; Zambolim et al. 2001). As a rule, an integrated management system must always be eco-friendly. Some of these aspects are discussed in the following pages.

2.1 Genetic Resistance

Wheat cultivars developed after a long period of breeding work become vulnerable to new diseases or new races of a pathogen and thus lose all the investment made in creating new and high yielding cultivars (Van der Plank 1963). According to Van der Plank (1963), there are two kinds of resistance; one is referred to as vertical resistance (specific resistance) and the other as horizontal resistance (partial resistance). Vertical resistance is also known as complete resistance, specific resistance and monogenic resistance. The resistant cultivars can be classified into three groups: (a) specific resistance; (b) partial resistance and; (c) generalized resistance.

Y.R. Mehta, *Wheat Diseases and Their Management*,
DOI 10.1007/978-3-319-06465-9_2,

2.1.1 Cultivars with Specific Resistance

Cultivars with specific resistance are those which show resistance to a few races of a pathogen but not to all. Breeding for specific resistance is simple and is inherited according to Mendel's law of inheritance. Biffen (1905), studied this for the first time and reported that for yellow rust of wheat the plants segregated in a ratio of 1:3 (one resistant plant and three susceptible plants). Since then numerous studies have been made and several resistant cultivars against a number of diseases were created. The resistance is considered specific when the cultivars are resistant to a single or few races. By and large, this kind of resistance is governed by a single dominant gene. When a resistant cultivar is crossed with a susceptible cultivar, in the F2 generation segregation of plants can be observed. If the resistance is controlled by a major gene the plants segregate in a ratio of 3:1 (three resistant and one susceptible) and when the resistance is recessive the plants segregate in a ratio of 1:3 (1 resistant and 3 susceptible).

To control diseases plant breeders and pathologists have been using major gene since it is simple and easy to select because of the clear difference between resistant and susceptible plants. However, cultivars with this kind of resistance last only for a short duration because the resistance is lost as soon as a new race of the pathogen capable of attacking the cultivar evolves in nature (Van der Plank 1963). It is for this reason that the sowing of a single cultivar in a large area should be avoided (also see chapter on disease control by cultural practices).

Virulence and aggressiveness are the two terms to express the parasitic ability of a pathogen to cause disease. In fact, virulence is the capacity of a pathogen (race or pathotype) to overcome the resistance gene of the host plant. Aggressiveness is the ability of a virulent pathogen to colonize the host and develop symptoms at a rapid pace. A virulent pathogen may be aggressive or not depending upon the environmental conditions, nonspecific resistance, latent period, etc.

2.1.2 Gene-for-Gene Theory

The inheritance of resistance and susceptibility in plants and the virulence and avirulence in parasites were studied for the first time by Flor (1947). After completing studies on linseed rust, this author presented the theory of gene-for-gene. Flor's theory of gene-for-gene implies that each gene that governs avirulence or virulence in a pathogen has a corresponding gene in the host that governs resistance or susceptibility. If one avirulent gene in the pathogen does not match with a resistance gene in the host no infection occurs. The disease occurs when the gene that governs avirulence in the pathogen matches with a corresponding gene in the host. If the host has no gene for resistance the disease will result irrespective of whether the pathogen has a gene for virulence or not. Similarly, the disease will also occur when one gene that governs virulence in the pathogen matches a corresponding gene governing susceptibility in the host. This is an important aspect to be considered (Wilcoxson and Saari 1996; Vog et al. 2013). According to Elligboe (1976), the resistance and avirulence are normally dominant, whereas susceptibility and virulence are normally recessive.

The pairing of genes in other words is also called "compatibility" of genes. When the disease occurs it can be said that there is a compatible reaction between the gene of the pathogen and the gene of the host. It can also be said that the pathogen is avirulent and the host is resistant. In fact, compatibility and incompatibility are the specific reactions between the genes.

The gene-for-gene theory can be explained as follows. One gene of the host corresponds with a gene in the pathogen and makes a pair of genes. For each corresponding pair of genes, there exist at least two alleles in the host and two alleles in the pathogen.

There are four possible host-pathogen combinations for specific pair of genes. Interactions occur when two genes exist in the host R1 that governs the resistance and the r1 that governs susceptibility or when the complementary genes in the pathogen, called P1 which governs avirulence and the other p1 that governs virulence exist. The gene R1 shows an incompatible reaction with gene P1 but the gene p1 is compatible with both R1 and r1 genes. Specific recognition between the genes occurs in an incompatible reaction. Compatible reactions are the result of lack of recognition between genes (Elligboe 1976). The basic patterns of resistance about the host-pathogen interaction are explained in detail by several workers (Person 1959; Elligboe 1976; Mcintosh and Watson 1982; Loegering 1984; Roelfs 1988a, b; Roelfs et al. 1992; Wilcoxson and Saari 1996; Vog et al. 2013). Tosa (1989) has demonstrated that gene-for-gene relationship exists between forme specialis of *Erysiphae graminis* and genera of gramineous plants. Complete notion of the gene-for-gene theory is necessary to understand the specific host-pathogen interaction.

2.1.3 Fitoalexins × Specific Resistance

Resistance caused by rapid death of a host cell at the site of infection by a pathogen is normally referred as hypersensitive. Hypersensitivity may be considered as an essential component of specific resistance.

Hammerschmidt (1999) has given a comprehensive review about the research on phytoalexins.

While working on host-selective toxins produced by *Stagnospora nodorum* Friesen et al. (2009) reported that *S. nodorum* produces at least four proteinaceous host-selective toxins that interact with dominant host sensitivity/susceptibility gene products to induce Septoria nodorum blotch in seedlings.

The resistance of plants is governed by genes. In resistant cultivars the pathogen dies soon after penetration, due to extreme sensitivity of plant tissue, resulting in a hypersensitive reaction. This hypersensitive reaction is characterized as minute specks of infection resulting in tissue necrosis (Dixon et al. 2002; Silva et al. 2010; Purwar et al. 2012).

Several hypotheses have been postulated for the mechanism involved in the hypersensitive reaction of resistant tissue (Hammerschmidt 1999; Fan and Doemer 2012; Jalali 1999; Muhovski 2012; Zang et al. 2013). It is believed that in some host-pathogen interactions the genes that govern resistance in the plant activate the formation and the concentration of some phenolic compounds in the lesions that are toxic to pathogens as well as to the infected cells. The concentration of phenolic compounds may depend on the degree of resistance of the host plant. In other words, this means that the production of phytoalexins depends on the resistance genes. If the genes are strong, the production of phytoalexin and its accumulation near the point of infection is high and hence the pathogen dies immediately. In some cases, no hypersensitive reaction is observed and the host is considered as immune.

Phenolic compounds (aromatic compounds) are produced in the plants via the Shikimic acid pathway or else by other biosynthetic procedures in innumerable host-pathogen interactions. Such phytoalexins could be specific or non-specific. A specific phytoalexin is produced only as a result of invasion by a specific pathogen whereas a phytoalexin is produced by mechanical damage is referred to as non-specific.

However, in recent years, the development of specific phytoalexins in the resistance process has continued to be a matter of controversy. While according to Elnanghy and Shaw (1966), resistant cultivars after infection produce higher concentrations of phytoalexins than susceptible ones, Seevers and Daly (1970) believes that there is no correlation between the concentration of phytoalexins in the tissues of resistant wheat cultivars and the susceptible cultivars for leaf rust. Several other examples regarding this subject are cited in the literature. It is possible that the concentration of phenolic compounds necessary to inhibit the growth of the pathogen could be very low and may not reach the detection limit by normal analytic procedures. More investigations are necessary regarding the relationship between resistance and the biosynthesis of aromatic compounds.

There is still some controversy about the primary gene product involved in the host-pathogen interactions. Although a vast amount of literature is available on the high rates of phytoalexin production in resistant cultivars, there is still no evidence to conclude whether this is the primary product of the gene or genes that govern a specific host-parasite reaction (Hammerschmidt 1999; Dangl and Jones 2001; Divon et al. 2002; Purwar et al. 2012; Jalali 1999). It is not yet very clear how resistance genes function to confer avirulence recognition. Clear understanding about resistance gene functions requires focus towards biochemistry and cell biology (Dangl and Jones 2001).

Different theories have been put forward by researchers on phytoalexins (VanEtten et al. 1989; Kaué 1996; Nicholson and Hammerschmidt 1992). One is that the plants are resistant because they can rapidly produce phytoalexins in sufficient quantities to check the progress of the pathogen. In the susceptible plants, it is possible that the pathogen grows rapidly because the plants do not produce phytoalexins or else produce them in insufficient quantities.

The other hypothesis is that the plants produce phytoalexins when they are invaded by pathogens. Only those pathogens which are capable of degrading the phytoalexins can normally multiply and provoke disease. Pathogens which cannot degrade the phytoalexins will be paralyzed and cannot produce disease. Elligboe (1976) introduced arguments for both the hypotheses. One of his arguments is that if the basis for the pathogen's restriction and development is its sensitivity to phytoalexins and if a mutation in the pathogen occurs which is not sensitive to such phytoalexins, then in this case the mutant can grow in the plant and cause disease. The second hypothesis is that if a mutant of a pathogen (normally capable of causing disease) incapable of degrading the phytoalexin is created then it will not be able to develop in the host and provoke disease. If both the arguments are correct, it would mean that the production of phytoalexin is not a pre-requisite for any host-parasite combination and that phytoalexins would be the secondary product of a gene governing any host-pathogen interaction. The example of mutants of a pathogen in studies of phytoalexins is a relatively new concept and could lead to important discoveries.

2.1.4 Use of Multilines

Multilines are lines that are agronomically similar to each other but differ genetically as regards their resistance to different races of a pathogen. Multilines may be referred as a different form of specific resistance. Each line has specific resistance to a particular pathogen and when several such lines are mixed together they form a "multiline". Due to their large diversity, the multilines have a special advantage over the specific resistance cultivars since they reduce the initial inoculum (Xo) as well as the rate of infection (r). Each line contributes to an additional genetic factor without phenotypic uniformity of the mixture. Multilines are created based on appropriate knowledge about the characters of agronomically compatible lines and genetically incompatible ones and are mixed in equal proportions. The use of specific resistance can be more advantageous when more resistance genes are introduced in a cultivar.

The advantages of the use of multilines were recognized in 1898, but investigations into multilines were intensified only in 1960 (Bourlaug 1953). The wheat breeding program of the Rockefeller Foundation in Mexico, released two multiline wheat cultivars in 1960. The first commercially used multiline wheat cultivars in Colombia were Miramar 63 and Miramar 65. Research on multilines was also started in India and in 1979 a multiline KSML 3 was released in the State of Punjab. In the same year a multiline cultivar called Tumult was released in Holland and another named Crew was released in the United States in 1982. Multiline cultivar of oats composed of 13 pure lines in two maturity classes were cultivated with success in more than 40,000 ha in the State of Iowa, USA (Browning 1988). However the development and utilization of multiline cultivars was not significantly successful mainly because of the time-consuming and expensive development process. Besides, the genetic diversity of multiline was very much reduced because of its pure line nature.

2.1.5 Cultivar Mixture

Because of their excessive uniformity, multilines lost their importance and a new concept of cultivar mixture was introduced. Within the Integrated Disease Management concept diseases can be kept under low intensity in cultivar mixture without the use of fungicides. Advantages of cultivar mixture in wheat, soybean, maize, rice, oats, beans, onion and gram (chickpea) were reported by several researchers. In East Germany for example, about 60 % of barley used for malt was cultivated through the cultivar mixture. The use of cultivar mixture to control diseases was studied by Wolfe (1988) for 11 years using 152 types of mixtures and in 122 types of mixtures an increase in yield of about 8 % was obtained. Later, Cowger and Mundt (2002), studied four mixtures of moderately resistant and susceptible winter wheat cultivars naturally infected with *Mycosphaerella graminicola* to investigate impacts on disease progress in the field. They reported that mixture yields were on average 2.4 and 6.2 % higher than mean component pure-stand yields in 1999 and 2000, respectively, but the differences were not statistically significant. Most of these studies were performed considering agronomical and pathological aspects (Faraji 2011). There is a concern among scientists that in a cultivar mixture natural selection of the pathogen with combined virulence may occur.

Another alternative strategy to the use of multilines and cultivar mixture is the pyramidation of resistant genes in an agronomically desirable cultivar. The more the major resistance genes are incorporated in a cultivar the more it becomes resistant to different races of the pathogen. Incorporation of major resistance genes is a relatively simple process and the cultivar with different resistance genes will be long lasting because its resistance will not be easily met by the creation of new races of the pathogen. This is a modern tendency in developing new disease resistant cultivars in several breeding programs.

2.1.6 Advantages and Disadvantages of Specific Resistance

Generally speaking, specific resistance is expressed by several terms like specific resistance, vertical resistance, monogenic resistance, hypersensitivity and unstable resistance, but the first is most used. This is the most interesting type of resistance as long as a new race of the pathogen capable of attacking the cultivar is not created in the nature. Normally, this kind of cultivar is short lived because a single change in the genetic constitution of the pathogen may be necessary to overcome the resistance and such changes are very common in nature (Van der Plank 1963). In recent years, because of the short lived nature of this resistance different types of resistance mechanisms have been sought.

2.1.7 Cultivars with Partial Resistance

Non-specific resistance, is also referred to by different terms, like horizontal resistance, field resistance, non-specific resistance, polygenic resistance, uniform resistance, stable resistance and partial resistance. Here again, the terms partial resistance and non-specific resistance are widely used. Partial resistance is effective against all the races of the pathogen and is governed by different genes. Contrary to specific resistance, partial resistance is of longer duration. The genes that govern this type of resistance are denominated as "minor genes" or non-specific genes and are not easily identifiable. Being polygenic in nature breeding for partial resistance becomes difficult. The difference between resistant and susceptible plants is not very clear and hence selection of plants is hampered or becomes doubtful.

Since partial resistance is governed by polygenes, it is less probable that a new race will appear in nature and be capable of matching all the genes of the host and breaking its resistance. In other words, partial resistance is difficult to be overcome by the evolution of new races of the pathogen. It is believed that, generally all cultivars have at least some quantity of partial resistance and the level of this resistance varies from cultivar to cultivar. It is not known how many genes are needed for the partial resistance to be highly effective and to satisfactorily control the diseases.

To accumulate partial resistance in a cultivar against a given pathogen, it becomes necessary to know different sources of the partial resistance. If there is no way to identify the genes that govern partial resistance, how can one be sure that different sources of partial resistance which show some level of partial resistance have the same or the different genes? If the genes are the same the breeder will be wasting his time and if the genes are different it will be possible to increase the level of resistance through breeding procedures. However, partial resistance can easily be lost during the traditional process of breeding. That being the case, it will be necessary to use different breeding procedures such as recurrent selection which is being used by several breeders (Singh et al. 2007).

For an effective selection for this kind of resistance the quantity of inoculum present in the field becomes very important. This is because partial resistance only reduces the rate of infection. If the selection for resistance is made in populations planted beside a highly susceptible cultivar, then the partial resistance may be ignored or else may be under estimated. Normally, the selection pressure in the experimental fields is very high and for this reason some breeding material with lower level of partial resistance may be lost. However, for the selection of high level of partial resistance even a high natural selection pressure is felt desirable (Mehta and Igarashi 1978). These are some of the aspects which make breeding for this kind of resistance rather difficult.

Partial resistance is preferred when the rate of infection of a disease is very high as is the case with biotrophic leaf rust and stem rust pathogens. Efficiency and economy in controlling the diseases will depend on the level of partial resistance of a given cultivar. The higher the level of partial resistance the higher will be the efficiency and economy in controlling the disease through the use of fungicides.

Partial resistance is considered durable. On the other hand, resistance governed by specific genes can also be long lasting in some cultivars and hence long durability does not necessarily mean partial resistance. Partial resistance governed by non-specific polygenes could last for several years more than the resistance governed by a combination of specific genes. Durable resistance against stem rust of wheat for example, is conferred by a combination of specific genes like *Sr2*, *Sr23*, *Sr36*, whereas for leaf rust it is conferred by the combination of specific genes *Lr13* and *Lr34* (Roelfs 1988a, b; McDonald 2010).

Roelfs (1988a, b) and Singh et al. (2007), reported that some wheat cultivars having the gene *Sr2* in combination with other genes are being cultivated in North America to control stem rust without having been attacked by stem rust in the past 30 years. Similarly, examples of durable resistance for leaf rust are based on the utilization of a group of specific genes like *Lr12*, *Lr13* and *Lr34*. There exist other examples of durable resistance using a combination of specific genes. At times, this kind of resistance is referred to as "multigenic resistance" (Knott 1988; Parlevliet 1988).

Sometimes partial resistance is confused with "tolerance". The concept of the word "tolerance" is completely different from the concept of resistance. A cultivar tolerant to a particular disease is in fact susceptible and no resistance mechanism operates against the disease but it tolerates the infection and could perform well in the field.

2.1.8 Controversies About the Genes That Govern the Partial Resistance

The concept of partial resistance has created lot of interest among the pathologists and the plant breeders. As a result more and more reports on this issue have raised new ideas and concepts. Nelson (1971) believed that the genes which govern specific resistance or those which govern partial resistance are the same genes. According to this author, when more the specific genes are present in a cultivar more will be its chance to express partial resistance to which it has no genes for such kind of resistance.

While working on powdery mildew Ellingboe (1975) observed the phenomenon of "slow mildewing" in wheat cultivar "Genesse" either in the field or under controlled conditions. After inoculating the F2 plants derived from the cross between Genesse and a cultivar where the powdery mildew used to develop rapidly in the field, it was observed that if the plants were maintained in the glasshouse then segregation was continuous without showing highly resistant plants. Based on these results he concluded that the "slow mildewing" was governed by several genes. However, when the plants were maintained under controlled conditions he observed a segregation ratio of 3 slow mildewing plants and 1 fast mildewing plant and believed that this was due to a dominant gene for 'slow mildewing'. Later, he concluded that the genes that govern specific or partial resistance are the same genes.

Theoretically, there could be genes that do not follow the gene-for-gene theory. However in the experimental work conducted by different scientists to investigate the natural occurrence of variability, a gene-for-gene relationship always existed irrespective of the presence of specific major genes or the partial resistance genes (Elligboe 1976; Parlevliet and Zadoks 1977; Parlevliet 1981; Parlevliet and van Ommeren 1975; Gonzalez et al. 2012). Roelfs (1988a, b) and Tosa (1989) also reported that in the majority of cases there exists a gene-for-gene relationship. This evidence does not support the concept of Van der Plank's (1963) view of partial resistance where he believed that gene-for-gene relationship exists only in case of specific resistance.

Different genes that govern specific resistance show intermediate effects and produce results similar to partial resistance (polygenic or non-specific). Parlevliet (1985) reported that the partial resistance genes also follow the gene-for-gene relationship. Considering these two aspects, Knott (1988), raised doubts about whether there exist difference in resistance mechanism or physiological difference between the two types of resistance. However, this author believes that the basic difference between these types of resistances is that major genes of specific resistance acts independently from one another, whereas the polygene of partial resistance act additively.

Strictly speaking, with the exceptions of leaf rust and yellow rust of wheat, substantial success in wheat breeding for partial resistance has not been achieved so far. Some success has been achieved in accumulating partial resistance against leaf rust and powdery mildew in barley by the recurrent selection method of breeding.

It may still take some time before the existence of a gene-for-gene relationship in partial resistance becomes conclusive and throws more light on the revolutionary idea that the same genes govern both types of resistance.

2.1.9 Cultivars with Generalized Resistance

When dealing with partial resistance one should specify the pathogen in question. While partial resistance is effective against all the races of a single pathogen, the cultivars with generalized resistance offer partial resistance against all the pathogens and their respective races. This may be considered as a modified form of partial resistance. One practical method for this kind of resistance was suggested by Robinson (1976) and it includes polycrossings between different cultivars susceptible to a specific race of each pathogen against which partial resistance is desired. This author suggested that polycrossing and high selection pressure should be exerted continuously for 6–8 generations until a uniform cultivar with a satisfactory level of partial resistance is achieved against different pathogens and their races. In this method complete selection pressure can be exerted only in the absence of specific resistance. When specific resistance is operating the partial resistance cannot be easily identified in the segregating populations. So far, success in this methodology has not been obtained.

2.1.10 Production of Dihaploid Through Wheat × Maize Hybrids

Breeding efforts to transfer resistance in desirable high yielding cultivars has been a high priority in recent years especially for *Gibberella zeae*, *B. sorokiniana, Pyricularia grisea, Pyrenophora tritici-epentis and X. t. pv. undulosa,* using the available sources of resistance. Since resistance to these pathogens is not complete, success in breeding is not very encouraging. The production of wheat haploids via chromosome elimination is one of the latest and most useful techniques in gene transfer experiments (Laurie and Bennet 1988; Riera-Lizarazu and Mujeeb-Kazi 1990; Riera-Lizarazu et al. 1992; Zang et al. 1996). Production of haploid wheat plants and subsequent production of dihaploids (double haploids) can fix characters in a single generation. The procedure using wheat × maize hybrids allows complete homozygosity within one or two generations and facilitates the somaclonal variant selection process.

Somaclonal variation exists and has been proven to be genetically inherited (Vasil and Vasil 1986). Although several transformation techniques have been developed, generally speaking such techniques are highly sophisticated and depend on availability of an efficient and reproducible tissue culture system (Jahne et al. 1994). Somaclonal variation, on the other hand, is a relatively simple technique, usable where other methods are not feasible or where resistance genes of interest are not available.

Gametoclonal variation is known to occur in doubled haploids (Rode et al. 1987; Gallais 1988; Bjornstand et al. 1993; Bakshi et al. 2012; Kelm et al. 2012; Christiane et al. 2012). Kelm et al. (2012) studied inheritance of seedling resistance to seven worldwide isolates of *Mycosphaerella graminicola* in a doubled-haploid population. Multiple quantitative trait loci mapping revealed major and minor genetic effects on resistance. These authors suggested a complex inheritance of resistance to Septoria tritici blotch in the seedling stage in terms of isolate-specificity and resistance mechanisms.

According to Zang et al. (1996), haploid embryo production frequency and plant regeneration are affected significantly by maize genotypes but not by wheat genotypes.

Mehta and Angra (2000) reported that it was possible to produce hybrid embryos and haploids in six wheat cultivars, thereby indicating that wheat genotype did not affect haploid plant production. According to these authors hybrid embryo production varied between 0 and 25% and the chromosomes had a constant number as observed in their original hexaploid wheat genotypes ($2n=6x=42$), whereas the haploid plants had $n=21$. Fig. 2.1 shows wheat caryopsis with embryo formation through wheat × maize hybridization (Mehta and Angra 2000).

Further research in this area might lead to the creation and release of new cultivars with a desirable level of resistance especially against the necrotrophic plant pathogens.

Seeding resistance to Septoria tritici blotch in the winter wheat doubled-haploid population (Solitar × Mzurka) was studied by Kelm et al. (2012). According to these

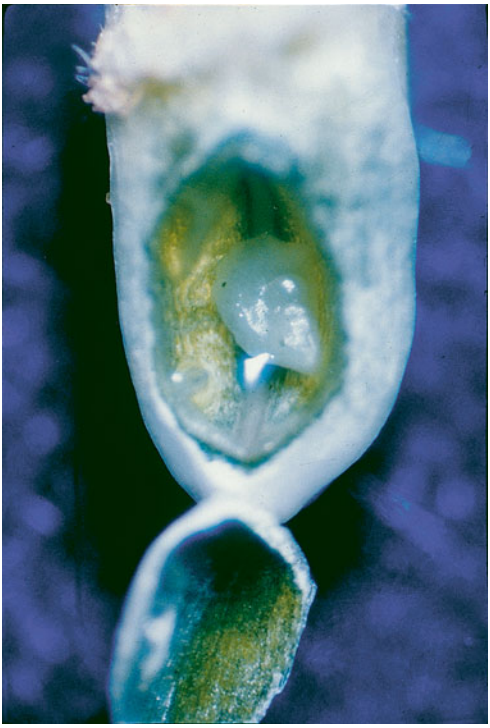

Fig. 2.1 Wheat caryposis with embryo formation through wheat × maize hybridization. Source: Mehta and Angra (2002)

authors, multiple quantitative trait locus (QTL) mapping revealed major and minor effects on resistance as well as several epistatic relationships in the seedling stage. The results suggest a complex inheritance of resistance to STB in the seedling stage in terms of isolate-specificity and resistance mechanism.

2.1.11 General Considerations

Breeding for resistance to some necrotrophic pathogens is still not adequate. As a rule, in breeding for disease resistance, it is necessary to have ample genetic variability within the host populations, as well as within the pathogen populations. To exploit existing genetic variability in the host plant, it is important to determine the genetic variability of the pathogen populations. For this purpose, different virulent strains of the pathogen must be identified. In this case, establishment of a differential set of cultivars may be very helpful. Screening for resistance is an important step in breeding for resistance. Screening techniques must be reliable, so that the resistant material thus selected can be incorporated into the crossing blocks with confidence.

Screening for resistance is generally done in the glasshouse or in a walk-in cold chamber, but always under controlled conditions. All plant material must be tested under standard and uniform conditions. Any change in the quality of inoculum, inoculation technique, incubation period and environmental conditions may alter the reaction pattern.

For screening purposes, a good inoculum must include a mixture of several virulent isolates and an appropriate and constant amount of conidia in the suspension. It is also preferable that plant material be tested in the glasshouse for resistance at two growth stages, at seedling stage and also at adult plant stage. It has been shown that seedling reaction does not necessarily correspond to adult plant reaction. Although adult plant resistance is always preferred, tests done also on seedlings stage help to determine lines that show resistant reaction at both growth stages. Such lines are of great interest in breeding programs for resistance.

Although glasshouse tests are reliable, it is often necessary to conduct field trials to confirm cultivar reaction under natural conditions. It is important that the tests be performed at three to four "hot-spot locations" each year. Resistant and susceptible checks should be included and the trial be surrounded by a susceptible spreader also inoculated with a mixture of isolates varying in virulence. Disease ratings should be taken at different stages of crop development. For the disease progress curves the rate of infection can be calculated: the lower the rate of infection, the higher the degree of resistance. Agronomically desirable lines with low infection rates are used as sources of resistance in the breeding programs.

There is a need to identify resistant sources in alien species like *Aegilops squarrosa, Agropyron curvifolium, Elymus curvifolius, Hordeum chilense, Triticum tauschii* and *Thinopyrum curvifolium*. These species may offer genes of major interest. Transfer of resistance from such species to *T. aestivum* is a rather complicated and difficult task. Difficulties in making interspecific crosses are mainly due to differences in levels of ploidy. However, problems such as lack of chromosome pairing and crossing over, failure of crosses after fertilization, difficulties in rearing hybrid plants and the lack of vigor and fertility of hybrid plants can be overcome by the use of various techniques and chemicals such as colchicine and gibberellin.

Finally, it is evident that for the Integrated Disease Management system, cultivar resistance plays an important role. As far as rusts are concerned, spectacular achievements have been obtained in the creation of new and resistant wheat cultivars. In Brazil, for example, the majority of wheat cultivars until the 1980's were susceptible to two rusts, because most of the cultivars were introduced from other States or from other countries. Today, most of the wheat cultivars are of Brazilian origin, although some have CIMMYT germplasm when used as parent. These cultivars have wide adaptability and disease resistance. It is believed that these cultivars possess genes for specific resistance as well as for partial resistance. (*Lr13, Sr2*, etc.). Rajaram et al. (1988) reported that during the last several years semi-dwarf cultivars occupied over 50 million hectares in the world without having reported any severe leaf or stem rust epidemics. The modern tendency is to develop new wheat cultivars with a combination of specific and non-specific resistance genes against major diseases.

2.2 Fungicides and Their Application in the Field

Within the Integrated Management concept use of fungicides also play an important role, however, they are applied only when their use becomes necessary. Although the cultivars have specific and non-specific genes against leaf rust, they are not protected against all the races and hence one or two applications of some specific fungicides become necessary. Considering different problems involved in fungicidal applications like development of new mutants of a pathogen resistant to fungicide or to a group of fungicides, their toxic and residual effect, fungicides are being used rationally.

Besides, some reduction in the use of fungicides is recommended in some countries. In Sweden for example, the use of agricultural chemicals was reduced by over 50 %, whereas Denmark established a limit of 50 % in the use of agro-chemicals till the year 1997. Similarly, Great Britain experienced a reduction of 41 % in the use of active ingredients. Considering the complexity of the problem, Germany decided to reduce the use of agricultural chemicals and adopt Integrated Disease and Pest Management practices (Warrel 1990).

In Latin America including Brazil, there is no fixed limit for the use of agrochemicals. However, substantial emphasis is being placed on the rational use of these chemicals as well as development of Integrated Disease and Pest Management systems by ANDEF. Through the development of different Disease Management Systems rational and effective use of fungicides can be obtained, as evidenced by several publications (Mehta 1978; Reis 1985, 1987). The generalized fungicidal use for wheat in Brazil, between 1974 and 1980, was 2–3 applications during the crop cycle, which after 1984 was reduced to 0–2 applications (Mehta et al. 1992; Mehta 1993). Thus it is estimated that due to the rational use of fungicides, Brazil has been economizing around 50 million dollars annually.

Reduction in the use of fungicides in the Rio Grande do Sul, Brazil, for example, is in part because of the modeling systems to predict the severity of wheat diseases, especially the wheat scab (Fernandez et al. 1993; Fernandes and Picinnini 1999; Vargas et al. 2000; Fernandes and Pavan 2002; Fernandes et al. 2004, 2005; Del Ponte et al. 2009; Pavan et al. 2011). In Brazil, efforts have been made during the last 30 years in developing mathematical models for predicting severity of several diseases with the aim of achieving rational and effective use of fungicides. None-the-less, during the past few years Brazil has been using increasing amounts of fungicides to combat newly emerging diseases like soybean rust, Ramularia leaf blight of cotton, among others.

2.2.1 Selection of Fungicides

Different types of fungicides exist for aerial application in wheat. These fungicides can be protectants or erradicants. The former control the infection but cannot eradicate it once it has established itself in the plant. For this reason the protectant fungicides are applied before the onset of the infection. On the other hand, eradicant fungicides are those which eliminate the fungus after it has caused infection and thus cure the plant. Most systemic fungicides are classified in this group. For loose smut of wheat for example, carboxin + thiram is considered an eradicant fungicide. New fungicides whether specific or non-specific are constantly emerging in the market. For basic information about fungicides in general, the reader may refer to some specific publications.

While a wealth of information is available about the use of different fungicides under different epidemiological conditions, a lot still needs to be done regionally. Each region poses a different and specific problem demanding an independent approach. While wheat rust can be controlled using the existing fungicides, wheat scab and Pyricularia blast for example, are not satisfactorily controlled by using the existing fungicides and the technology of their application, whereas wheat leaf rust can be controlled through the existing fungicides.

Experiments on fungicides are somewhat difficult to conduct. A global knowledge about the development of an epidemic is essential to study the efficiency of fungicides. Before a fungicide is recommended several aspects are taken into consideration like: (a) Adequate dose of the fungicide, (b) Methods of application, (c) Appropriate spraying schedule, (d) Final effect on the yield and the quality of product; (e) Economy in use of certain types of fungicides; (f) Residual effect on the plant; and finally, toxic effects on plants, human beings and animals.

Normally fungicides have been evaluated based on the gain in yield (Mehta 1978). Thus, if the efficiency of fungicides is only based on the yield data then all the fungicides which increase the yield should be recommended, irrespective of whether they controlled the disease satisfactorily or not. Fungicidal evaluation can also be based on the economy involved in the operation. However, the economical aspects involved in the use of fungicides are somewhat complicated since they also depend on the resistance level of the cultivar (fungicides may be economical for a specific cultivar but not for another), fungicidal dose and finally the cost of the fungicide which varies from year to year.

Considering these aspects Mehta et al. (1978) established a criterion for the evaluation and selection of fungicides against foliar diseases of wheat. According to this criterion all fungicides which maintained the level of disease below 50 % of the leaf area infected at growth stage 83 (Zadoks et al. 1974), were selected and recommended. Growth stage 83 was used as a reference because after this stage of development the leaves, especially the flag leaf and the flag leaf-1 do not contribute to the formation of grain and hence fungicide use becomes unnecessary. According to these authors, all the fungicides classified using this criterion, without exception, were superior to the check plots in yield as well. However, further research is needed to establish appropriate criteria for the new moderately resistant cultivars.

2.2.2 Fungicide Spraying Schedule

An appropriate fungicide spraying schedule plays an important role in Integrated Management Systems. The spraying schedule includes the time of first application, interval between the applications, the number of applications and the time of last application, considering always the cultivar and the disease in question.

Under the Latin-American conditions the first application is of the utmost importance. Fungicides should be applied starting from the first appearance of the disease symptoms. The first symptoms of the disease especially spot blotch and leaf rust are observed 40–45 days after sowing in early maturing cultivars and 50–55 days after for the late maturing cultivars. Thus the first application can be made after 45–55 days after sowing depending upon the type of cultivar. However, if the first disease symptoms appear 70 days after sowing, for example, the first application should be made then and not before. With some exceptions, fungicidal application before the onset of the disease is not advisable.

It is well known that the earlier the disease epidemic starts the higher will be the loss in yield. Fixing a foliar disease level of 5–10 % of the leaf area infected for the first application, for example, is difficult and risky. If the farmer has to wait until the level of infection reaches this level and if it is followed by a prolonged rainy period, the disease will proliferate rapidly and the farmer will have to wait for several days before he can enter the field for application with tractor. Besides, it must be remembered that field applications with tractor are time consuming and the rate of infection of the majority of diseases is very high. If the disease is not controlled at the beginning the control may then be inadequate or even uneconomical. Thus the tolerance limit for most of the foliar diseases could be traces of infection for the first fungicidal application. The objective is not to control totally the disease but to retard the start of the epidemic by 30–40 days, or else reduce the rate of infection so that the disease level does not reach over 50 % of the leaf area infected at soft dough stage 83 (Zadoks et al. 1974; Mehta et al. 1978).

The rate of infection of different pathogens could be very high and would depend on the spore production potential of each pathogen. Leaf rust and Heminthosporium for example, are considered diseases of high infection rate. Table 2.1 shows comparison between the spore production potential of the pathogens of these diseases. *Puccinia triticina* for example, needs 8 days of incubation period, whereas *Bipolaris sorokiniana* needs only 2 days. Irrespective of the period of infection in both the cases the sporulation starts 11 days after the incubation. The delay in 6 days in the incubation period of *P. triticina* is compensated by double the number of spores produced per day per lesion. However, *P. triticina* loses 1–2 days in relation to *B. sorokiniana* as regards the maximum duration of spore production. Once again, this loss is compensated by a superior period of double the amount of sporulation

Table 2.1 Spore production potential of *Puccinia triticina* (PT) and *Bipolaris sorokiniana* (BS), in susceptible wheat cultivars under controlled conditions

Pathogen	PT	BS
Period of incubation	8 days	48 h
Beginning of sporulation days after inoculation	11	11
Maximum No. of spores produced per day/lesion	767	487
Maximum duration of spore production	1 day	2–3 days
Maximum period of sporulation	72 days	30 days
Relation between weight of spores and the weight of the spore producing leaf or % leaf area infected by a single lesion	01:01	22.70 %

per lesion, lasting for 72 days and 30 days in the case of *P. triticina* and *B. sorokiniana,* respectively (Mehta and Zadoks 1971; Mehta 1981).

Finally, as a result of high spore production potential the dry weight of total spore produced during 72 days by *P. triticina* equals the dry weight of the leaf that produced the spores. On the other hand, a single lesion caused by *B. sorokiniana* could reach up to 22.7 % of the leaf area. Thus, considering the compensation in spore production potential of the two pathogens using different parameters, it can be concluded that both pathogens are very aggressive and so special care must be taken towards the management strategies in controlling these two diseases.

Success in fungicidal applications also depends on the interval between the applications. Systemic fungicides for foliar diseases offer 20–22 day of protection whereas the non-systemic fungicides (protectant fungicides) offer a protection of only 12–15 days. When the climatic conditions are favorable for diseases the fungicidal applications can be repeated considering the interval between the applications and the type of fungicide. However, if the climatic conditions are not favorable for the disease as happens with prolonged periods of drought, then the rate of disease multiplication is drastically reduced and hence the interval between the applications may be increased. In any case, constant field monitoring for the disease spread is deemed necessary.

The number of application for foliar diseases cannot be pre-established and is variable depending on the cultivar, fungicide and weather conditions. It also depends on the time of appearance of the first symptoms of the disease before which fungicides may not be applied. In some years the first symptoms of the disease may appear after 60–70 days after sowing necessitating only one application, of a systemic fungicide. Similarly, if the first disease symptoms appear only after the growth stage 83 for example, then in this case fungicidal application may not be necessary. Irrespective of the number of applications the last application may be performed preferably up to the time of flowering but not after the milk-stage. A susceptible cultivar may need more applications than a less susceptible or moderately resistant cultivar.

Generally speaking, non-systemic fungicides are applied more number of times than the systemic fungicides, during the crop cycle especially when the weather conditions are favorable for the disease. The number of applications also depends on the system of cultivation. In no-tillage cultivation, for example, the first disease symptoms of tan spot are observed as early as 20–25 days after sowing. If crop rotation is not followed, the number of applications will no doubt be more than for the conventional system of cultivation.

By and large, wheat is attacked by a number of diseases. As stated earlier, cultivars that are moderately or highly resistant to all the diseases do not exist. Cultivars differ in their degree of resistance and susceptibility to a particular disease or a group of diseases and hence different fungicidal schemes need to be considered for each group of cultivars in a particular area. For moderately susceptible or moderately resistant cultivars, only some reduction in the rate of infection is necessary. On the other hand, for susceptible or highly susceptible cultivars, it will be necessary to delay the start of a disease epidemic by 30–40 days. Delay in the initiation of epidemic can be obtained by systemic fungicides, whereas reduction in the rate of infection may be obtained by non-systemic fungicides.

2.2.3 Management of Systemic Fungicides

Resistance of pathogens to some fungicides was discovered at the beginning of the 1940s. One of the examples of this kind of resistance is experienced by Japanese farmers in controlling rice blast caused by *Pyricularia grisea*. In the 1960's antibiotics were introduced to control rice blast replacing organomercurial compounds. In the year 1971, a few years after the introduction of the antibiotic kasugamycin some resistant biotypes of *P. oryzae* were identified especially in some districts where kasugamycin was extensively and intensively used. In the following year 97 % of the *P. oryzae* isolates were resistant to kasugamycin in those districts. The application of kasugamycin was stopped and as a result the resistance level was reduced to 20 % within 3 years (CERES 1982).

Boukef et al. (2012) studied frequency of mutations associated with fungicide resistance and population structure of *Mycosphaerella graminicola* in Tunisia. They reported that few mutations associated with fungicide resistance were detected. They further reported that no evidence for strobilurin resistance was found among 357 Tunisian isolates and only two among 80 sequenced isolates carried mutations associated with azole resistance.

There are several examples of resistance of some pathogens to fungicides of the group benzimidazol. Other examples of resistance like powdery mildew fungus of Cucurbitacea to dimetirimol, of *Alternaria kikuchina t*o polioxina and *Erwinia amylovora* to streptomycin are wellknown. The history of resistance to fungicides was well covered by Delp (1980), who used a theoretical (mathematical) model to understand the development of resistance to benomyl considering leaf spot disease of the perennial crop caused by *Cercospora* sp. According to this model, the problem of resistance was drastically reduced when benomyl was used in combination with maneb from the beginning of its utilization (Heitefuss 2012).

Considering these examples, it is evident that the use of systemic fungicides should always be based on some criteria. However, irrespective of the criteria used, constant monitoring of the biotypes of the pathogen is indispensable so that the resistant biotypes be identified as soon as they emerge. Investigations in this area are encouraged by Fungicide Resistance Assessment Committee (FRAC) and intensified because the range of chemical groups is very much narrow and may favor the emergence of resistant biotypes. In addition to this, there also exists the problem of cross resistance where a biotype resistant to one fungicide is also resistant to another fungicide of the same group.

The dose of the fungicide should not be altered during the crop cycle. Considering economical aspects sometimes a farmer uses half of the recommended dose of the fungicide to control the powdery mildew at its initial stage and later when other foliar diseases start appearing, he uses the same fungicide but with a normal or even higher dose, because the lower dose will not control other foliar diseases. This is a very dangerous practice since it may provoke the pathogen to adopt the fungicide and create resistant biotypes. The problem of resistance can be minimized by using a mixture of systemic fungicides with non-systemic fungicides.

2.2.4 Fungicide Application Techniques

The efficiency of a fungicide in controlling a disease will depend on the application method. Normally, a good coverage of the plant is important and can be obtained by high or low volume sprays. High volume sprays using 200 l of water per hectare are applied by tractor. In this case the equipment should be well regulated in order to avoid the run-off of the fungicide. It should however be remembered that the better the coverage of the plant with fungicide the better will be the efficiency in controlling the disease. Tractor spraying causes mechanical damage to the crop, but it is compensated by the gain in yield obtained by the disease control (Boller et al. 2007, 2008; Cunha et al. 2011; Tormen et al. 2012).

While the low volume (30–40 L ha^{-1}) aerial applications overcome the problem of mechanical damage to the crop, they pose different problems. Good aerial application depends on the velocity of the wind, experience of the pilot and the height of flying. The smaller the spray particles the higher will be their dispersion and evaporation and consequently the higher their deposition on the plant. Normally speaking, an average of particle size in aerial applications of 200 μm is considered optimum, since particle size smaller than this does not give a good coverage of the plant.

Another type of equipment for aerial applications is called “micronair” and is being used with success. This kind of equipments has a special advantage over the conventional hydraulic equipments, in which the size of the spray particles can be easily adjusted. However they are more expensive than the conventional ones. For aerial applications cross winds of about 10 km ha^{-1} are considered ideal. Presence of free water including dew formation on the plants is not considered prejudicial. On the contrary, it helps in the distribution of the fungicide because in the aerial applications the size of the spray particles is rather small. On the other hand, with tractor application (high volume) the size of the spray particles is big and in the presence of free water may cause run-off of the spraying product. In such a case fungicidal applications during the early hours of the day may be avoided. In both kinds of application the quantity (dose) of the fungicide should remain the same. The dose of the fungicide should be calculated per unit of area and not by volume of the water to be used either for tractor or for aerial application.

2.3 Disease Forecast Modeling

Besides the above mentioned aspects, in recent years emphasis has been given to the disease forecasting computer models. Through such models it is possible to provide estimates of disease likelihood and forecast outbreaks which in turn avoid unnecessary fungicidal applications. They give guidelines for timely applications and consequently make the control measures more cost effective. Computer modeling when validated, should necessarily become a part of the integrated disease management systems.

Traditional plant disease climatological models have used accumulated hours of wetness duration combined with temperature requirements to predict the infection process and identify times of high disease risk. These types of models use recorded weather data to track enough favorable disease hours to warrant management action. In Brazil, the revolutionary web-based technologies have been studied for the past few years; these are known as SISALERT (Vargas et al. 2000; Fernandes et al. 2007, 2011; Ponte et al. 2005; Pavan et al. 2011). A simulation model developed for Fusarium head blight (FHB) has a component for the disease cycle and component for growth and development of wheat spikes. According to this model, a successful infection on a particular day depends on host tissue susceptibility factor, inoculum density, temperature, daily precipitation and mean relative humidity in a 24-h window. FHB risk maps were elaborated which are computer-generated images depicting infection risk using special interpolation techniques for point estimations of the risk by site-specific weather stations and forecasted weather within a wheat growing area. The goal of this predictive system is to help growers assess the risk of the FHB in their region (CNPtrigo—Embrapa, personal communication with J. M. Fernandes).

A disease forecasting computer model is being developed also for Pyricularia blast of wheat. However, because of the absence of a significant amount of quantitative data, exploratory simulation was developed. Model output was used for producing maps for a large geographical region.

To date, SISALERT is operating to predict risk of infection of the two aforesaid wheat diseases (FHB and Pyricularia blast). However, one of the major obstacles in computer disease forecasting models is the lack of their validity data. Although a lot of progress has been made, such models need to be improved further and validated regionally so that they can be successfully used by a variety of wheat growers practicing different cropping systems, which would finally make the integrated wheat disease management programs eco-friendly and cost effective.

2.4 Seed Transmitted Pathogens

The importance of proper seed health testing in general has been somewhat neglected. In Brazil for example, in the case of wheat there was little or no need to study seed health since most of the seed-borne fungi were controlled by compulsory seed treatment through legislation. During the early seventies this law was relaxed and also the use of mercurial fungicides was restricted or even prohibited due to their high toxicity. New fungicides have been introduced as substitutes for the highly effective mercurial fungicides and therefore it has become inevitable to perform the proper seed health testing and evaluate the fungicides to avoid their indiscriminate use.

Seed health testing has been practiced for a long time and was initially started by L. C. Doyer as the first official seed pathologist in the Netherlands. Since then much progress has been made in the world but it has not yet reached the point of meeting the expectations of the seed producing industries.

Normally, pathogens transmitted through wheat seed are *Stagnospora nodorum*, *Bipolaris sorokiniana*, *Drechslera tritici-repentis*, *Fusarium graminearum*, *Pyricularia grisea*, *Ustilago tritici* and some bacteria including *X. t. pv. undulosa*. Results of seed health testing are necessary to advocate proper sanitary practices which, in turn, may considerably reduce the yield losses caused by several diseases and to check the introduction and spread of new diseases from one region to another. Recommendations about sanitary practices should be made after careful considerations of several factors like, testing procedures, level of seed infection of a particular pathogen or a group of pathogens, epidemiology of the disease, cost and efficiency of fungicides and in certain cases the earliness of treatment after harvest.

2.4.1 Seed Health Testing

Seed health testing has the principal aim of establishing percentages of infection of different pathogens. Needless to say, saprophytes should not be taken into consideration. Several methods for seed health testing are available and selection of a particular method will depend upon the pathogens under study. For example, in the case of *S. nodorum* and *F. graminearum* a good correlation is observed between results from the laboratory and field (De Tempe 1958; Hewett 1975) and hence the commonly used tests such as pre-treated seed on malt extract agar, pretreated seed on potato-dextrose agar (PDA) + 0.2 % oxgall or non-pretreated seed on PDA + 0.2 % oxgall are quite satisfactory. For details on specific methods related to specific pathogens the reader may refer to Mathur and Cunfer (1993) and the ISTA publication—*Seed-borne fungi:* A contribution to routine seed health analysis (Machado et al. (2002).

For *B. sorokiniana* and *D. tritici-repentis* the commonly used tests are not satisfactory since these two fungi are very variable. Several strains of these two species exist of which some may be pathogenic whereas others may not. Infection percentage determined by routine methods would be an overestimation of the true infection that may occur in field conditions. According to the author's experience, very little or no correlation between field and laboratory testing with routine methods was observed. Such findings were observed also by Jorgensen (1974) and Mead (1942), even when the barley seeds were rather heavily infected by *B. sorokiniana. Drechslera* spp. may only cause severe root infections (root browning) without affecting emergence. These effects cannot be examined in field tests and consequently poor correlation is observed.

Undoubtedly, in certain cases the poor effect of the seed-borne inoculum on the emergence may be due to some phytotoxic effect of the fungicides. Special health test techniques should be used in the laboratory to determine the infection percentage of seedlings and not the seeds. Such percentages would be much closer to field conditions and would eliminate all saprophytic strains of the pathogen. If good correlation between such percentages and the infection percentages in the field are observed, then the recommendations on seed treatment can be made depending on the level of infection.

A method for detection of loose smut infection in the seeds of barley for example, was introduced in early fifties (Pederson 1956). Later, several modifications were made in the technique and also a few new techniques were introduced. These techniques were also used for wheat without having sufficient experimental evidence regarding their efficiency and reliability for wheat. Pederson (1956) reported that diseased embryos with loose smut were less easily extracted than healthy ones and advocated the extraction of all embryos. Later, Hewett (1972), in contrast to Pederson's results, demonstrated that partial or complete extraction of embryos is not important and does not alter the results even at lower infection rates when sampling errors are greater. In most techniques currently used for barley, extraction of all the embryos is not considered important. However, sufficient evidence is still lacking regarding the extraction of wheat embryos. Standardization of the technique is extremely important and without it a good correlation between laboratory and field tests could not be expected.

Determination of loose smut infection percentage in wheat is a problem. Loose smut infections in wheat and barley are determined by extracting the embryos and examining them under a binocular microscope for the presence of the mycelium of the fungus. The correlation between the infection percentage in the laboratory test and the field test is expected to be almost 1:1.

While establishing loose smut infection percentage and making recommendations about the seed treatment against loose smut, germination percentage of the seed sample should be considered. In case of very low germination percentage (below 70) it is possible that many of the infected seeds are incapable of germination and may affect results in field tests. Consequently, this would give a low correlation ratio when compared with laboratory results. The use of seed dressing fungicides will be uneconomical, especially when infection percentage in a seed sample with low germination percentage reaches the limit of tolerance and the seed treatment is recommended without correcting ratio of infection percentage to germination percentage. Hence, infection percentage must always be correlated with the germination percentage.

Correlation between laboratory and field tests depends upon cultivar resistance. Hewett (1975) reported that no smutted ears were produced in a field test using three samples of barley (cv. Emir) when the infections determined in laboratory test were 0.4 %, 0.8 % and 1.0 % respectively.

Several fungicides are available on the market for seed treatment. Most of these are effective against a particular pathogen or a group of pathogens. Broad-spectrum fungicides that are effective against all the important pathogens of a particular crop are rare. Moreover, degree of effectiveness may vary from fungicide to fungicide. Economics in the use of seed dressing fungicides invariably depends on the level of seed infection and resistance of the cultivar (Rubiales and Moral 2010).

It is wellknown that seed infections with fungal and bacterial pathogens tend to decline during storage. This leads to another question. Why cannot seed health testing be done just before sowing? But, if the seed health testing is left till the sowing time then the seed health testing laboratories may not be able to analyze large quantities of seed sample before the end of the officially recommended sowing period.

Also they may not have enough time to perform different tests for different pathogens. This leads to another question. Should the test be performed twice, once soon after harvest and again just before sowing? The cost of repeated tests would thus be very high.

Wheat bunt has been eradicated in Brazil. However, it is still an important disease in many countries. Seed infection percentage of *Tilletia* spp. causing bunt is determined by a relatively simple method. In this method, concentration of spores in a suspension is determined with the help of a hemocytometer and finally the percentage of seed infection/contamination is determined. Spores of *Tilletia* spp. are heavier than water and consequently their rate of sedimentation is very high. Because of the sedimentation problem in suspension with water, correct determination of spore concentration cannot be achieved. Spore suspension should be made in a solution (water + glycerin) in such a way that its specific gravity is equal to the specific gravity of the spores. This would avoid spore sedimentation. The spore suspension made in this way may be further subjected to a vibrator for one minute after adding a few drops of Tween-20. This would be beneficial, especially to get a uniform spore suspension. These are some of the points one needs to consider while using the techniques for *Tilletia* infections.

2.4.2 Level of Seed Infection

What should be the level of seed infection of a particular pathogen or a group of pathogens to advocate the use of fungicides? What is the minimum level of infection which permits recommendation of seed treatment and guarantees economical return in the field? Answers to such questions would prevent the indiscriminate use of fungicides. In certain cases, recommendations on seed treatments are based more on personal opinions and judgments rather than actual experimental evidence. If the minimum tolerance limits of infections are not established, then the whole purpose of seed health testing vanishes. Since bunt diseases are eradicated, tolerance level for seed infection with *Tilletia* spp. in Brazil is zero. Undoubtedly, recommendations for seed treatments may be made to check the introduction and spread of pathogens from one region to another or one country to another without any immediate considerations.

2.4.3 Epidemiological Aspects of the Disease

Epidemiological aspects of the disease are also important while considering the effectiveness of seed treatment. If the pathogen is not only seed-borne but also soil-borne and if the soil is heavily infested with such a pathogen, then seed treatment would be of little or no practical importance. For example, soils in the southern region of Brazil are heavily infested with some pathogens like *S. nodorum* and

P. tritici-repentis. Viable perithecia of these pathogens are observed throughout the year on wheat stubble (Mehta 1975, 1993; Mehta et al. 1992). By and large, these fungi are highly predominant in soils with no-tillage cultivation. In such cases, fungicidal seed treatment would only improve emergence and for some time the general health of the seedling. Other control measures like crop rotation and aerial fungicidal applications and use of resistant cultivars thus become necessary (Singh et al. 2007; Gurung et al. 2011).

2.4.4 Time of Seed Treatment

As mentioned earlier, questions such as when should the seed be treated, are most frequently asked by the seed growers and answers to these questions are manifold. Early seed treatment soon after harvest could be an important factor in economical seed treatment, depending upon the storage conditions and the moisture content of the seed. Seeds with about 12 % moisture content, when stored at about 5–10 °C, will not pose any problem. In such a case, earliness of treatment would not alter the results and seeds could be treated just before sowing. On the other hand, seeds with high moisture content stored at a high temperature will allow the fungal pathogens to grow which in turn will affect seed germination and emergence. Once the seed quality is affected by fungi, seed treatment would not do any good. Hence, in poor storage conditions seed treatment should be practiced soon after the harvest to prevent seed damage during the storage period.

All the above mentioned factors should be taken into consideration towards the production and use of healthy seed. Generalization regarding seed treatment cannot be made merely on the basis of high infection percentages. There are several ways of controlling seed-borne diseases of which seed treatment with chemicals is one that has been much talked about in recent years. It may be remembered that for seed transmitted bacterial pathogens, to date, no chemicals are available. Seed health problems can be minimized to a great extent by proper fungicidal sprays in the seed multiplication farms and also by strict inspection of such farms throughout the growing season.

The spot blotch pathogen (*B. sorokiniana*) is transmitted through seed, air and soil. In Brazil, for example, from 1970 to 1980, spot blotch was very important due to the cultivation of highly susceptible Mexican dwarf cultivars like Jupateco, Inia, Tanori, etc. in large areas. After 1980's new resistant or moderately resistant wheat cultivars were released. Tan spot caused by *Drechslera tritici-repentis* has now become much more important than the spot blotch caused by *B. sorokiniana*. It is important to note that in 1975–1980 only 80.000 ha were covered by no-tillage cultivation whereas at present more than 85 % of the wheat area of the State of Paraná, for example, is covered by no tillage cultivation system either fully or partially (without crop rotation). This has provoked the intensity and spread of tan-spot disease.

The existing reports demonstrate a higher transmission rate of *B. sorokiniana* through seed (Mehta 1993; Forcelini 1995). However it must be remembered that

B. sorokiniana is a facultative parasite, attacks various grass hosts and survives on the crop residue of different plant species throughout the year. The pathogen survives in the soil and with a higher concentration of its propagules in the no-tillage cultivation system (Mehta et al. 1992; Mehta 1993).

The pathogen survives in the soil in the form of conidia, mycelium and clamydospores. According to Diehl et al. (1983), root rot of wheat caused by a complex of pathogens could be responsible for a yield loss of about 18 %. In recent years, the severity of root rot has been drastically reduced because of cultural practices and cultivar resistance (Mehta 1993). During harvest time 2–3 days rain favor the fructification of the fungus and contaminate the seed (Mehta 1978). In the majority of cases the seed is externally contaminated and not truly infected. The severely infected seeds are shriveled and are eliminated during the seed processing. Besides, during the storage the level of seed contamination/infection falls drastically depending upon the time and condition of storage (Mehta 1993). This is a common phenomenon for several fungal and bacterial seed infections. For this reason, the recommendation would be to treat seed only if the infection/contamination is below 30 % and seeds having higher infection level are discarded. This criterion helps to a great extent in reducing the initial infection of seedlings and guarantees a good and uniform "stand". However, it must be remembered that the use of uncertified seed (pirated seed) with no seed health control represents 30 % of the total commercialized wheat seed sold in Brazil.

Glume blotch (netch blotch) of wheat caused by *Stagonospora nodorum* (Syn. *Septoria nodorum*) is an important disease especially in the southern region of Brazil. During 1980s glume blotch infections were noticed in northern Brazil on some Mexican cultivars like Tanori, Jupateco and Anahuac, due to excessive applications of nitrogen. The yield potential of Mexican cultivars could only be exploited to its maximum when heavy doses of fertilizers, especially the nitrogen fertilizers, were applied. This in turn predisposes the plant to *S. nodorum* infection (Mehta 1978). Similar to tan spot, *S. nodorum* survives in the left-over wheat stubble from one season to another in its sexual form *Leptosphaeria nodorum* and serves as an important source of primary infection. It is for this reason that the severity of netch blotch is higher in no-tillage cultivation system. However, the severity of the disease depends on the weather conditions such as continuous rain fall for 3–4 days or more and the temperatures varying between 15 and 22 ° C.

The level of tolerance for seed infection is interesting and even necessary in certain cases. Tolerance levels for seed infections must be established considering several aspects. For this purpose, the seed health tests must be based on research data, must be repeatable, easy to perform in different laboratories and should be based on epidemiological aspects of the disease in question. Ideally, the seed should be free from any pathogen, especially when the seed is the only source of infection.

It is evident that as a first step, comparative seed health tests should be performed in different laboratories to verify that there exist very few or no discrepancies between the results of different laboratories. This will permit the recommendations on tolerance limits for seed infections with much accuracy and credibility. In fact, comparative seed health tests have been practiced in several countries since 1975

(Yorinori et al. 1979; Machado et al. 2002). Such tests are necessary especially for newly developed seed health techniques. In the case of wheat, soybean and beans (*Phaseolus* spp.), there are several pathogens to be tested in seed health testing and some of the fungal and bacterial pathogens demand specific media and methodology.

In the USA, for example, almost 100 % of the bean seeds (in the State of Idaho >80 % and in Michigan 18 %) are official and there is very little or no pirated seed. The seed certification laws in these two States establish zero level of infection for seed multiplication farms as well as for laboratory tests for *Pseudomonas syringae* pv. *phaseolicola* and *Xanthomonas axonopodis* pv. *phaseoli* (Lahman and Schaad 1985). It must also be remembered that *X. a.* pv. *phaseoli* and *X. a. pv. phaseoli* var. *fuscans* are two distinct pathogens that cause bacterial blight in beans and also there are different non-pathogenic strains of these two pathogens.

2.4.5 General Considerations

Brazil is considered to be a "showcase" for the international agro-business. Establishment of tolerance limits would be useful especially when the use of illegal pirated seed is reduced to zero because pirated seeds are largely responsible in a major part for the dissemination of different pathogens. Brazil, for example, annually loses over 50 million tons of agricultural production due to the pirated seed of different crops, other than causing numerous phytosanitory problems.

2.5 Cultural Practices

Cultural practices constitute an important aspect in the integrated disease management programs. Through these practices severity of some of the diseases can be minimized or even eliminated without the use of the agrochemicals. Some of the aspects of cultural practices are discussed below.

2.5.1 Fertilizers

The growth and the productivity of a plant will depend on the availability of the macro and micro nutrients in adequate and balanced quantities. If these nutrients are not available in sufficient quantities in the soil, it will be necessary to complement them to the economic threshold level.

The principal macronutrients like N (nitrogen), P (phosphorus) and K (potassium) are needed in large quantities by plants and are responsible for increments in yield. In some cases the application of P alone for example, could be necessary to obtain maximum economic yield. However, the unilateral application of fertilizers could be only transitory and later may induce deficiency of other nutrients in the soil and may limit the yield.

The application of N may be fractioned by applying a part of it during seeding and the rest as top dressing between tillering and early boot stage. Other than the macronutrients, for achieving higher productivity, a supply of secondary elements like Ca (calcium), Mg (magnesium) and S (sulfur), as well as micronutrients is necessary. The lack of one element or its presence in excessive quantities in the soil will reduce the efficiency of other elements and consequently reduce the yield.

The supply of one element in excess could induce physiological problems which in turn could reduce the yield and even could favor the attack of some pathogens. Excessive calcium in the plant reduces its resistance to loose smut and susceptibility to leaf rusts (Hubber 1976).

The availability of P may be limited in many tropical soils necessitating its application to increase the yields. In Brazil, in many cases this element has been applied in excessive quantities in the soil. Potassium is an essential element to increase plant vigor and in some cases it is also responsible for inducing plant resistance to pathogens. Vergenes et al. (2007), reported that potassium deficiency significantly increased spot blotch severity in two genotypes BL 2217 (moderately resistant) and Ciano 79 (susceptible) and stressed the importance of the soil fertility as part of an integrated crop management of Helminthosporium leaf blights.

In general, because of the lack of response in yield to the application of K many farmers have lost interest in applying this element to the soil in sufficient quantities. This is an essential element to increase plant vigor and in some cases it is also responsible for inducing resistance of the plant against pathogens.

Balanced fertilization implies consideration of a series of factors (EMBRAPA 2011). Although health and vigor of the plant have a major influence on its predisposition to diseases, no generalization can be made for all the host-pathogen interactions with respect to a particular nutrient. Some diseases are not influenced by nutrients while others show drastic effects. Although resistance is genetically controlled, it is expressed through the physiological process inter-connected with the nutritional state of the plant and the pathogen (Hubber 1976).

2.5.2 Soil Conservation and Tillage

Since the most remote antiquity, accumulated experiences have evidenced a series of advantages in soil mobilization for good crop development. Soil mobilization destroys the seeds of the weeds, larva and insects. However, for the tropical and sub-tropical regions soil mobilization is very much condemned and a no-tillage cultivation system has been introduced in the recent years. Several advantages of this system of cultivation are well documented. There is a general agreement among the growers, the scientific community and extension workers that soil mobilization as well as excessive traffic on the soil should be reduced as far as possible.

Tropical and subtropical regions of the world are known for their notorious instability in agricultural production and for their fragile eco-system. The gradual degradation of the soil structure is attributed to the excessive and heavy mechanization reducing the water infiltration rate, increasing soil compaction and soil erosion and consequently loss of soil organic matter.

The cultivation systems practiced in the Southern-Cone Region of Latin America can be classified into four categories:

1. The traditional system which includes residue burning after wheat harvest followed by one heavy disk plowing and two to five light disk harrow plowing to level the soil before seeding. This leads to soil compaction layer of 10–15 cm deep.
2. The conventional system which includes one heavy disk plow (Rome plow), followed by two light disk harrow.
3. The reduced tillage system (vertical tillage) which includes one chisel plow followed by one field cultivator.
4. The no-tillage cultivation system (direct drilling) where the soil is not mobilized and wheat is sown directly by special equipment.

No-tillage is a part of the conservation system of cultivation and as mentioned earlier it is practiced either partially or completely in over 80 % of the area of the State of Paraná, Brazil. A somewhat similar area exists also in the State of Rio Grande do Sul. The no-tillage system includes operations which maintain a sufficient quantity of crop residue on the soil surface, not revolving the soil, improves the soil quality, involves minimum tillage and consequently reduces soil traffic with agricultural machinery, avoids soil erosion and reduces infestations of weeds. The advantages of this system are well-known and its use is being widely practiced all over the world (Roberts and Johnston 2007). The conservation system of cultivation includes, other than no-tillage, crop rotation, crop-livestock integration (crop-pasture rotations in mixed farming), consortium of crops, permanent soil coverage with mulch or green crops and integrated management of pest and diseases.

Crop-livestock integration has twofold aims to achieve, in other words, production of fodder and mulch to keep the soil covered. While the brachiaria has an allelopathic effect for some soil pathogens, in 2011 some root and stem infections of soybean (*Glycine max*) caused by *Macrophomina phaseoli* were observed in some brachiaria fields in the State of São Paulo. One of the principal objective of the conservation system is to keep the soil permanently covered with mulch or with green crops (Denardin et al. 2007).

Since the advantages of conservation tillage including the no-tillage and crop rotations are widely accepted it is also necessary to admit and accept the challenges they face for their long term adoption. Under certain situations, some modifications in the no-tillage cultivation system may seem necessary. Influence of some of these practices on the severity of diseases is discussed in the following pages.

To start with, the no-tillage system should be implemented after careful consideration of several factors. Areas with heavy infestation of weeds, areas with heavy infestation of *Sclerotinia sclerotiorum*, areas with soil compaction, areas with soil erosion and sloping land (steep inclination of land), etc., should be avoided for implementing no-tillage system. Some of the farmers are destroying terrace mainly to facilitate the field operations, thereby creating once again the problem of soil erosion and canceling most of the benefits of no-tillage. Thus, the soil terracing practice must be maintained. The reader may refer a specific publication available in this respect (Denardin et al. 2007; Caviglione et al. 2010).

Several fungal, bacterial and viral diseases of different crops under no-tillage cultivation can cause severe yield losses. Some pathogens attack all the plant parts while others attack only the above ground parts causing leaf necrosis and defoliation. The majority of diseases are transmitted through seed but some are transmitted through soil and air. The fungal diseases which survive in the soil or on non-crop residue from one season to another in the absence of living plants, are called necrotrophic (facultative parasites). Thus they serve as the initial source of inoculum and infect the plant soon after its emergence. On the other hand, the pathogens which need living plants for their survival are called obligate parasites or biotrophic pathogens, like rusts, smuts and bunts of wheat, rust of soybean and beans (*Phaseolus vulgaris*). The biotrophic pathogens are disseminated by seed or by air from one region to another and can cause infection in plants in both systems of cultivation traditional or no-tillage, depending on the weather conditions. The volunteer plants give shelter to some biotrophic pathogens and play an important role in the epidemiology of the disease.

The necrotrophic pathogen *Stemphylium* attacks different crops like potato (*Solanum tuberosum*), tomato (*Solanum esculentum*), onion (*Allium cepa*) and garlic (*Allium sativum*). The Stenphylium spot bloch caused a severe cotton (*Gossypium hirsutum*) leaf blight epidemic, in the State of Paraná, Brazil. The pathogen is not seed transmitted but transmitted through the crop residue. The severity of this disease was three times more in no-tillage than the conventional system of cultivation. The pathogen survives on the crop residue from one season to another and produces large quantities of spores under no-tillage cultivation.

Angular leaf spot of beans caused by *Phaeoisariopsis griseola*, is economically very important. In Brazil, beans are cultivated during the whole year being termed the rainy season crop, dry season crop and autumn/winter crop, but mainly it is a dry season crop. The pathogen survives on the bean crop residue from one season to another, mainly under the no-tillage cultivation system and continues producing the spores. The rate of seed transmission is between 1.5 and 2.0 %. Since the pathogen survives on the crop residue, the air-borne inoculum is not very important for the onset of the disease. In the United States of America, for example, the survival of *P. griseola* on the crop residue was up to 12 months (Celetti et al. 2005). Under Brazilian conditions the survival of the pathogen was observed for only 4 months under no-tillage cultivation

Tan spot of wheat *Pyrenophora tritici-repentis* is more severe in no-tillage than in the conventional system of cultivation. As mentioned earlier, in recent years the area under no-tillage has increased to over 80 % of the total area of the State of Paraná, under wheat cultivation and in the State of Rio Grande do Sul, it is around 1.5 million hectares. The quick expansion of this system of cultivation has brought some disease problems. The severity of some diseases is directly related to the introduction of the no-tillage cultivation system.

Mehta (1978, 1993) reported that the severity of tan spot in no-tillage during three years of experimentation was substantially higher than the conventional system of cultivation and that the disease caused a yield loss of 40 %. In no-tillage the perithecia of the sexual stage of the fungus survives on the crop residue for 2 years or more and continues liberating the ascospores which serve as the initial source of inoculum. The ascospores are not carried to long distances. In no-tillage the symptoms of the disease are noticed within 20–25 days after sowing. The disease lesions produced by the ascospores produce the first cycle of asexual spores (conidia) which in turn infect the wheat in the conventional as well as in the no-tillage cultivation system.

Unlike the ascospores, the conidia travel long distances. In the conventional system the symptoms of tan spot are observed 15–20 days after the appearance of the first symptoms in the no-tillage cultivation. Consequently, the secondary conidial production cycle disseminates the disease still further in other fields either of conventional or no-tillage. Normally, the high severity of the disease in no-tillage is related to continuous precipitations during the initial period of the crop cycle (Mehta and Gaudêncio 1991). It must be remembered however, that wheat is still one of the best options for winter and appropriate crop rotations would reduce the intensity of tan spot in no-tillage cultivation (see chapter on crop rotation and their role in disease management).

The spike diseases of wheat and triticale (*X.Triticosecale*) caused by *Pyricularia grisea* and *Gibberella zeae*, can cause losses of up to 40 % (Mehta and Baier (1998). Very little information is available as regards the influence of system of cultivation on the severity of these two diseases (Zambolim et al. 2001).

Black oat has been used in crop rotations over two decades because of its resistance to some soil-borne diseases and because of its large amount of green matter (mulch). During this period only the cv. IAPAR 61 of black oats was used without any cultivar diversification. As a result, the resistance of this cultivar to *P. grisea* was broken in 2005. Later, cultivars of white oat (*A. sativa*) were found resistant to *P. oryzae* (also see chapter on *P. grisea*). Recently, the resistance of one of the white oat cultivars IAC 7, to *P. grisea* was also overcome.

The severity of Cercospora leaf spot of maize caused by *Cercospora zeae-maydis* is normally more severe in no-tillage. However, there is no exact information about the loss in yield caused by this pathogen in no-tillage cultivation.

The severity of soybean stem canker caused by *Diaporthe phaseolorum* f. sp. *meridionalis*, has always caused more problems in no-tillage than in the conventional system of cultivation. The pathogen survives on crop residue for over 2 years. Because of the availability of resistant cultivars, this disease now poses no problem.

The bacterial diseases caused by different pathovars of *Pseudomonas*, *Xanthomonas* and *Curtobacterium*, attacking several economically important crops, are basically seed transmitted and hence their severity does not depend on the system of cultivation.

In tropical and semi-tropical regions, it is known that most of these bacteria do not survive in the soil because of the high temperatures which prevail during 4–5 months in the summer (Mehta 1993). Nonetheless, some of the bacteria like

Curtobacterium flaccumfaciens pv. flaccumfaciens (Cff) of beans may survive on the leftover stubble from one season to another (Leite Junior et al. 2001).

These are only a few examples of some diseases in which the tillage practices may have some influence on disease incidence and severity.

2.5.3 Crop Rotations and Their Role in Disease Management

Crop rotation implies altering plant species in a given period of time within the same cropping area. The objective should be to maintain the diseases below threshold level in no-tillage because total control will be difficult to obtain and it will not be necessary or cost effective. Intelligent crop rotation is an inherent part of conservation tillage and it basically includes six aspects: (1) Maintaining biodiversity, it must be remembered that diversity includes diversity of plant species as well as diversity of cultivars of the plant species in question; (2) Reducing infestation of weeds; (3) Breaking the disease cycle; (4) Keeping the soil always covered with mulch or green crop; (5) Supplementing some of the nutrients essential for crop development; and finally; (6) Increasing the profit of the farmers over a period of time.

The use of different plant species in crop rotation is very important since most diseases are specific to a given species and do not attack other species of plant. Thus, an appropriate use of non-host crops for subsequent planting helps in breaking the disease cycle especially of the necrotrophic plant pathogens. Sufficient care should be taken while selecting a particular crop and its cultivar to be used in the rotation. In wheat growing areas, triticale and rye (*Secale cereale*) are not ideal crops for rotation since both are susceptible to pathogens that attack wheat and may contribute to maintain the cycle of the diseases. Wheat is a cash crop and economically more important than the other two crops. Similarly, if foxtail (*Setaria italica*) is preferred for crop rotation, it should not precede wheat, barley, triticale and rye, since it is also highly susceptible to Pyricularia blast (*P. grisea*).

As mentioned earlier, rusts and smuts are biotrophic pathogens and do not survive in crop residue so they are not controlled by crop rotation. Triticale and rye are susceptible to tan spot pathogen. White oats (*A. sativa*), maize, pigeon pea (*Cajanus cajan*), crotalaria (*Crotalaria juncea*), millets *(Pennisetum americanum;* Syn. *P. typhoides*), radish (*Raphanus sativus*) and the leguminous crops can be used for rotation. These crops can be used for grain production and for green manuring as well (Calegari et al. 1993; Denardin et al. 2007).

The cotton pathogen *C. gossypii* var. *cephalosporioides* can survive on crop residue for over 2 years. While seed inoculum is normally eliminated through fungicidal seed treatment, the soil inoculum can be eliminated or drastically reduced through crop rotation with non-host crops like millet, pigeon pea (*Cajanus cajan*), maize and soybeans. Millet serves as an alternative to soybean and pigeon pea as a complement to maize (Zancanaro and Tessaro 2006; Scaléa 2007).

Potential fungal pathogens transmitted through soil and causing economic losses include species of *Sclerotinia, Rhizoctonia, Phytopthora, Fusarium, Macrophomina, Ophiobolus* and *Diaporthe*.

The millet and sorghum (*Sorghum vulgare*) are attacked by *Claviceps purpurea*, commonly referred as ergot, posing a new threat since these crops are used in crop rotation especially for animal food and/or for keeping the soil covered. Animal feed-stuffs contaminated with sporidia of this fungus are poisonous to animals. In this case appropriate alternatives should be worked out (Bogo and Boff 1997; Cultivar 1999).

Beans and peas (*Pisum sativum*) are susceptible to *Fusarium oxysporum* f. sp. *phaseoli*, *F. semitectum* and *F. solani* f. sp. *phaseoli* (Mehta and Gaudêncio 1991; Zambolim et al. 2001). Besides, *F. oxysporum* f. sp. *vasinfectum*, *F. moniliforme* and *F. semitectum*, are also pathogenic to cotton, wheat, maize and soybean and hence resistant cultivars of these crops should be used for rotation only in soils that are not highly infested with these pathogens. In the case of cotton, the severity of *Fusarium* (*F. oxysporum* f. sp. *vasinfectum*), tends to increase when associated with nematodes (*Meloidogyne incognita*, *Rotylenchus reniformis* and *Pratylenchus brachyurus*) making a disease complex. The integration of livestock-cropping especially in the Cerrado region of Brazil and the use of *B. decumbens* reduce populations of *M. incognita*, *M. javanica* and *P. brachyurus* in no-tillage cultivation (Campos et al. 1997).

Other than the *Fusarium* spp. the soil-borne pathogens include *Sclerotinia sclerotiorum*, *Rhizoctonia solani*, *Sclerotium rolfsii* and *Macrophomina phaseoli*. These are problematic pathogens since they have a wide host range and demand 4–6 years of rotation with non-host crops. For this reason, constant soil monitoring is desirable, besides reducing the frequency of using susceptible hosts in time and space. On the other hand for the necrotrophic foliar pathogens like *B. sorokiniana*, *Drechslera tritici-repentis*, *P. griseola*, *C. gossypii* var. *cephalosporioides* and *C. zeae-maydis*, crop rotation of 1–2 years would be sufficient. Because of its high susceptibility to *S. sclerotiorum* sunflower is not usually chosen for large scale planting in the State of Paraná, Brazil (Cardoso and Mehta 1997). Some *Vicia* spp. (*Vicia villosa, V. sativa*), *C. cajan* and cowpea (*Vigna unguiculata*) may be considered as good options (Calegari et al. 1993).

Chickpea (*Cicer arietinum*) can be another option for crop rotation especially for the semi-arid tropics. Being a leguminous winter crop and with a crop cycle of only 120 days, chick-pea is also tolerant to long dry periods. The deep root system of chickpea helps in breaking the soil compacted layer, produces abundant nodulation and hence fixes atmospheric nitrogen. It tolerates low temperatures and its yield potential can vary between 2.0 and 4.0 t ha^{-1}. Other than these advantages, introduction of chickpea in a crop rotation system would help break the disease cycle of some wheat pathogens and would contribute towards increasing bio-diversity in cropping systems.

However, as regards crop rotations, there is still a lack of information with respect to: (a) Influence of different crops used either to cover the soil and/or for grain production, on the severity of diseases of the principal crop; (b) Knowledge about the host range of the major pathogens of different plant species; (c) The level of disease resistance of different cultivars of each one of the plant species to be used in crop rotation.

Very few farmers use the crop rotation. There are several reasons including lack of adequate orientation, lack of enough seed, lack of appropriate machinary for seeding and difficulty in commercialization of the harvested grain at the right time because of lack of demand. As a consequence, the use of some crops in rotation may not be cost effective. It is also necessary that the majority of farmers should practice crop rotation because the farmers who do not do so may let their land become infested with necrotrophic pathogens and serve as a source of primary inoculum to the other neighboring farms.

Monoculture of cotton grown over the crop residue of millet for example, is a common practice in the Cerrado region of Brazil. For cotton it may be difficult to follow all the basic rules of no-tillage in the Cerrado region of Brazil, mainly because of the nature of the crop itself. Besides having a long crop cycle, the cotton crop residue has to be deeply buried mainly to break the life cycle of boll worm (Zancanaro and Tessaro 2006).

Finally, the crop rotation which does not bring economic returns for a period of 3–4 years, will not be sustainable. When a mixture of seeds of different crops is recommended for planting for green manuring and to create a mulch on the soil, it is necessary to take into consideration the cost of seed, the cost of operations involved, the quantity of green matter really required and the frequency of such operations in a given time and space. The majority of farmers do not possess machinery either for planting or for managing the cover crops. It must be remembered once again that the basic objective of crop rotation is always to maintain the soil covered for most of the year. Depending upon microbial activity, a part of the nitrogen is consumed by the micro-organisms. Nitrogen is easily leached into the soil and also volatilized.

One of the arguments is that the higher the amount of dry matter on the soil surface the higher will be the richness of soil in terms of nitrogen and phosphorus. However, one should fix a limit for this. A minimum quantity of the dry material on the soil should be worked out. In fact, the maximum amount of organic matter on the soil surface is the one which the soil can mineralize. It is time to establish the optimum quantity of dry organic matter needed to cover the soil so that the operation becomes economical and sustainable and the crop rotation does not become a "fairy tale".

Wheat is still one of the best options for winter in the Latin-American region. There are several options for crop rotation and selection of a particular crop depends on whether it is for grain production, for green manuring, or for mulch (Gazziero 1994). It also depends on the government incentive and the local commercial needs. Choosing white oats as well as maize and sunflower seems appropriate for most of the area. However, wheat should not be followed by maize or sunflower because of the deficiency of nutrients and the resulting diseases like Fusarium root rot. Use of some leguminous crops is interesting since they generally are not attacked by most of the wheat and soybean pathogens and at the same time improve the soil fertility.

In Argentina, in some disease prone areas the soil is ploughed once a year after the soybean harvest and before sowing wheat to incorporate the crop residue and minimize the early infections of tan spot (Fernando et al. 1987).

Integrated foliar disease management to prevent yield loss in Argentina wheat production was investigated by Simón et al. (2011). They evaluated the combine effect of tillage, N fertilization, fungicides and resistant cultivars in reducing foliar disease severity. According to these authors the disease was less severe in zero tillage which received a fungicide compared to conventional tillage plots that were not treated with fungicide. They concluded that in spite of the increase of necrotrophic diseases, developing no-till system in wheat monoculture is possible without significant yield losses if effective disease management practices are applied.

The effect of crop rotation on the severity of wheat root diseases has been extensively studied in Brazil (Diehl 1979; Diehl et al. 1982, 1983; Reis 1985; Reis and Baier 1983; Fernandez et al. 1993). Diehl et al. (1982) reported a loss of 20 % because of the monoculture (wheat-soybean-wheat). Reis and Ambrosi (1987) reported that the increase in wheat yield due to crop rotation was noticed only after 5 years. In the following years, Reis and Santos (1989), reported that 1, 2 and 3 years of rotation without wheat in the winter, did not increase wheat yields statistically. Mehta and Gaudêncio (1991), also did not observe any gain in wheat yields after 4 years of crop rotation without wheat in the winter. Thus, it seems that crop rotation with more than 1 year without wheat in the winter may not be very profitable. However, due to the expansion of no-tillage cultivation and consequent increase in tan spot severity, an appropriate crop rotation should be worked out considering the epidemiological aspects of this particular disease. Soils severely infested with the fungus *Gaeumannomyces graminis*, need special attention. In this case, crop rotation with non-host leguminous species becomes extremely important. White oats are more resistant to this pathogen and may be a good option for winter.

2.5.4 Crop Residue

Residue burning to reduce the soil-borne inoculum of some pathogens has been extensively discussed during the past few years. Considering the problems of loss of organic matter and soil erosion, residue burning is generally condemned. It may reduce the soil inoculum but does not eliminate it completely. Rees and Platz (1979) reported that burning wheat residue drastically reduced the soil inoculum of tan spot pathogen but did not eliminate it completely and with the result that the little inoculum left-over on the soil surface could still be enough for tan spot epidemic. Destruction of crop residue or its deep incorporation in the soil is practiced in some special cases like the boll worm of cotton caused by *Anthonomus grandis*.

The organic material in the form of left-over crop residue undergoes the process of decomposition (degradation of protein) and liberates nitrogen for the plant and remains in the soil as a fertilizer (Roberts and Johnston 2007). The burning of crop residue signifies loss of fertilizer and thus increases the cost involved in supplying an additional amount of nitrogen in the soil. The process of degradation of protein and the cycle of organic material is somewhat complex as can be summarized in Fig. 2.2.

The discovery of bacteriostatic substances could bring additional benefits. Bacteriostatic nitrapirina, inhibits the growth of bacteria *Nitrosomonas* of the soil and blocks the conversion of ammonia into a leaching form of nitrogen. Consequently

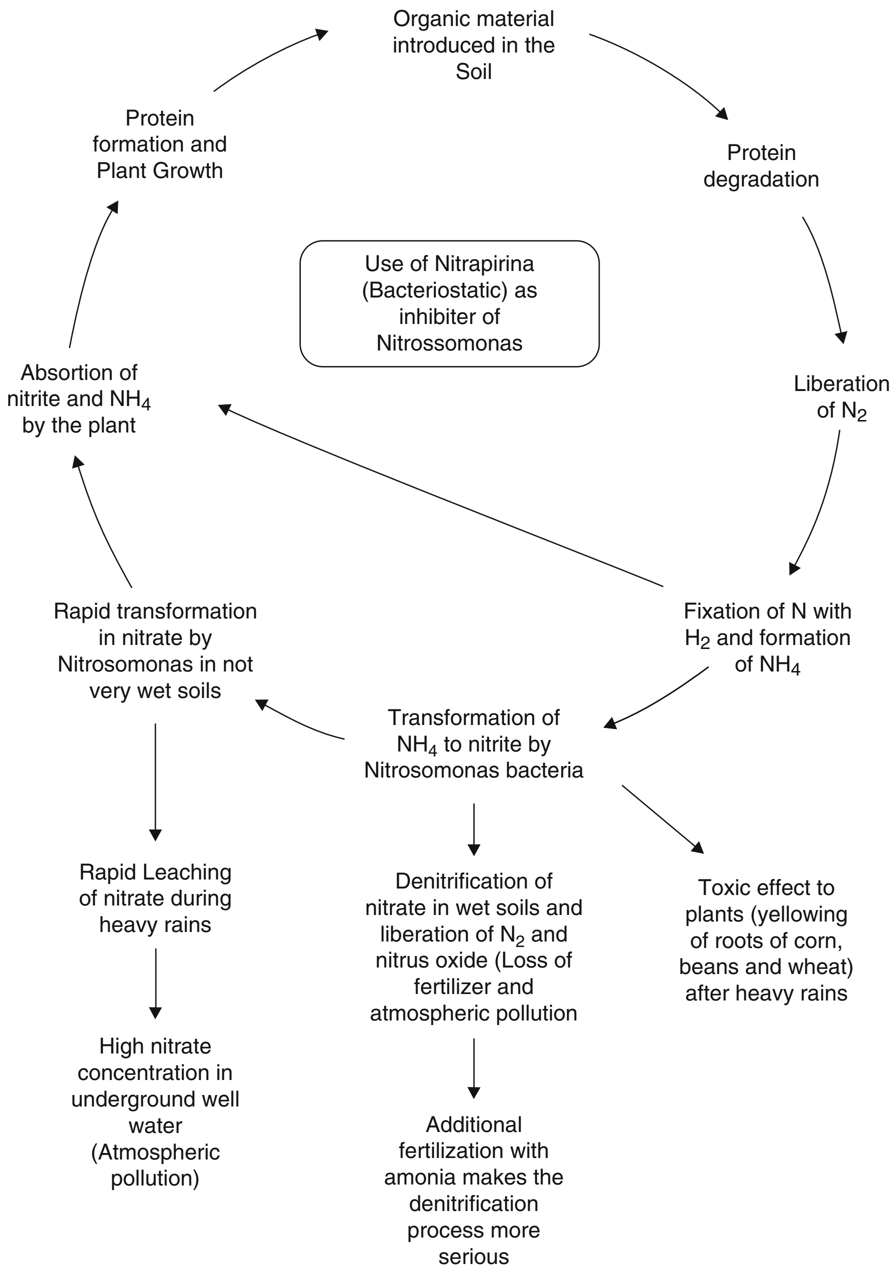

Fig. 2.2 Process of degradation of protein of organic matter

the loss of nitrogen is reduced and the crop productivity is increased (Barrons 1980). Nitrapirina can be incorporated in the soil together with the fertilizer, but this is not yet a common practice on a commercial scale.

2.5.5 Diversification of Sowing Dates and Cultivars

The severity of some diseases could be reduced by simply changing the seeding dates and/or by diversification of cultivars. Stem rust of wheat for example, is controlled in the South of Brazil by changing the sowing dates. Before the 1980's wheat had been sown until the end of June. No severe epidemic of this disease has been noticed since 1982 when change in sowing dates to the period between April 1 and May 10 was effected.

Stem rust prefers hot temperatures (25–28 °C) which normally occur after the first week of August. During this time, the wheat planted between April and May has reached its maturity and the rust does not reach epidemic proportions such as to cause damage to the plant.

Wheat blast caused by *Pyricularia grisea*, is partially controlled by change in sowing dates. In the wheat region above parallel 24 south for example, the sowing dates were altered and recommendations were made to seed wheat not before 10th of April. This strategy is working well since the late 1980's (Kohli et al. 1996).

Diversification of cultivars is another strategy to reduce the severity of diseases. As far as possible, more than one cultivar should be planted in a particular area and planting the whole area with a single cultivar should be discouraged even when a particular cultivar is most preferred by the farmer.

The problem of wheat blast caused by *P. grisea*, during 1985–1987 was probably provoked by planting a single rice cultivar in the North of Paraná, Brazil. Rice cultivar Cica 9 was immune to rice blast pathogen and hence within a few years over 90 % of the rice area of the State was covered by Cica 9. Later, within few years its resistance was broken by a new race (pathotype of *P. grisea*). It is presumed that this is the race which attacked wheat eliminating unnecessary virulence genes of rice and creating a new virulence gene to wheat. Perhaps for this reason the *P. grisea* isolates of wheat do not attack rice. Valent and Chumley (1991), also believed that the pathogen that attacks wheat is distinct form than the one that attacks rice.

In fact, during 1985–1987, late rice was planted in the month of December-January, whereas early wheat was planted during the same years during the second week of February. During the rice harvest the release of clouds of *P. grisea* spores coincided with the emergence of wheat spikes which was planted not too far from the rice fields and the spores were deposited on the rachis of the wheat spikes causing infection.

Thus, from this point onwards, the *P. oryzae* of rice became adapted to wheat which had never been its host, at least in Brazil. This assumption seems to be more convincing. Since there is no experimental proof for this assumption it is considered only as circumstantial evidence. There have been several unanswered questions about the origin of the inoculum which initially attacked wheat and they may remain so, for a long time to come. In any case, the wheat blast story, once again emphasizes the need for diversification of cultivars and the sowing dates.

2.5.6 Alternative Methods for Disease Control

Management of Sclerotinia (*S. scerotiorum*), *Rhizoctonia solani* and *Fusarium* spp. of soybeans and other leguminous plants could be achieved through biological control using *Tricoderma asperellum* and *T. harzianum* as well as mulch of *Brachiaria ruziziensis* (syn. *Urochloa ruziziensis*) (Pomella 2007). Gorgen et al. 2007) reported a reduction in initial inoculum of the pathogen in the soybean crop through the application of spores of *T. harzianum* (2×109), at a rate of 1.5 L ha^{-1}, along with the fungicidal seed treatment. They observed 100 % parasitism and death of 70–100 % scleroids. In contrast, they observed only 16–75 % parasitism in uncovered soils. Further experimentation seems necessary before the use of *Trichoderma* spp. can be practiced on a commercial scale.

It is believed that maize cultivated in consortium with *U. ruziziensis* can drastically reduce the soil inoculum of *S. sclerotiorum* in comparison with maize cultivated alone. Costa and Rava (2003) reported that in the integrated crop-livestock system, the crop residue of *U. brizantha* and *U. ruziziensis* cv. Marandu, has a positive effect in controlling *F. solani, R. solani* and *S. sclerotiorum*. On the other hand, as stated earlier, infections of *Urochloa* spp. caused by soil-borne charcoal-rot disease (Macrophomina) caused by the fungus *M. phaseoli* have been recently observed in the State of São Paulo. Since *M. phaseoli* has a wide host range including maize and sorghum, soils not highly infested with *M. phaseoli* should be carefully identified for crop rotations.

The integrated crop-livestock system has several advantages including the reduction in disease severity as well as reduction in pests and weed outbreaks (Studdart et al. 1997; Franzluebbers 2007; Gorgen et al. 2010; Vilela et al. 2012). Considering several advantages of the integrated crop-livestock system (agrisilvipasture), especially in the Cerrado region of Brazil, the USA and a part of Africa, it is believed that this system will gain a much greater momentum over the course of time.

The use of calcium silicate (Si) in agriculture has long been investigated. Depending upon the plant species the quantity of Si in the plant biomass varies between 1 and 10 %. Other than this, one of the effects of the presence of Si is in the reduction of disease severity. A literature review in this matter is presented by Rodrigues and Datnoff (2007). According to Seebold et al. (2004), calcium silicate applied at the rate of 0.1 t ha^{-1} was efficient in controlling rice blast of wheat.

Control of other pathogen species like *Sphaerotheca, Pythium, Uncinula, Blumeria* and *Fusarium* was also demonstrated by (Rodrigues and Datnoff 2007). Control of powdery mildew of beans (*Erysiphe poligoni*) was observed by us under glasshouse conditions with soil application of calcium and magnesium silicate at the rate of 0.2 t ha^{-1}. The treated plants showed higher vigor than the untreated ones (Unpublished data). Further research is needed to shed more light on this matter.

Undoubtedly, the conservation system of cultivation would be most welcome to overcome several problems including the disease problems allied with other integrated disease management practices as discussed in earlier chapters.

To achieve success in sustainable and eco-friendly conservation system of cultivation an integration of specialist of different disciplines and the collaboration of farmers and the extension workers become inevitable (Mehta 1996a).

2.5.7 Precision Agriculture and General Considerations

In recent years, precision agriculture has been much talked about. Initially, precision agriculture was aimed at image-based satellite remote sensing for soil monitoring for rational use of fertilizers and to detect water logging and sloping areas, so as to make appropriate use of natural resources. Now precision agriculture is dealt with in a much broader sense. According to Moran et al. (1997), multispectral images can be used for: (1) identifying and monitoring soil moisture content; (2) crop phenology stage; (3) crop biomass and yield production; (4) crop evapotranspiration-rate; (5) crop nutrient deficiencies; (6) crop disease; (7) weed infestation and; (8) insect infestation.

By and large, precision agriculture is achieving accuracy in different aspects of agriculture production, in order to obtain food security through more efficient use of natural resources.

Any change in agricultural practices towards increasing safe food production without degrading soil and water resources and the atmosphere, would necessarily be a part of precision agriculture. In this respect, a few examples can be cited.

In Loess Plateau (China), for example, the use of plastic film mulch on over 51,000 km^2 is being used to increase soil temperature (Turner et al. 2011). According to these authors, the use of plastic film mulch to warm the soil in spring has enabled the economic production of maize in the colder regions of the Loess Plateau where it was not possible without mulch. For precision farming, on the other hand, Romanenko et al. (2007), suggested planting of different cultivars in a commercial wheat farm, each one having a different gene for disease resistance and thus forming a mosaic pattern of genes in the field and consequently increasing yield.

Precision agriculture demands future trends in developing cultivars through modern biotechnological tools in resource poor areas, including areas with frequent droughts and heat waves (Turner et al. 2011).

Precisely, all aspects dealt with in the preceding chapters should form the basis for precision agriculture and even a little more (Fig. 2.3). In addition to eight points raised by Moran et al. (1997), issues pinpointed in the preceding chapters should be intrinsic of precision agriculture and can be summarized as: use of

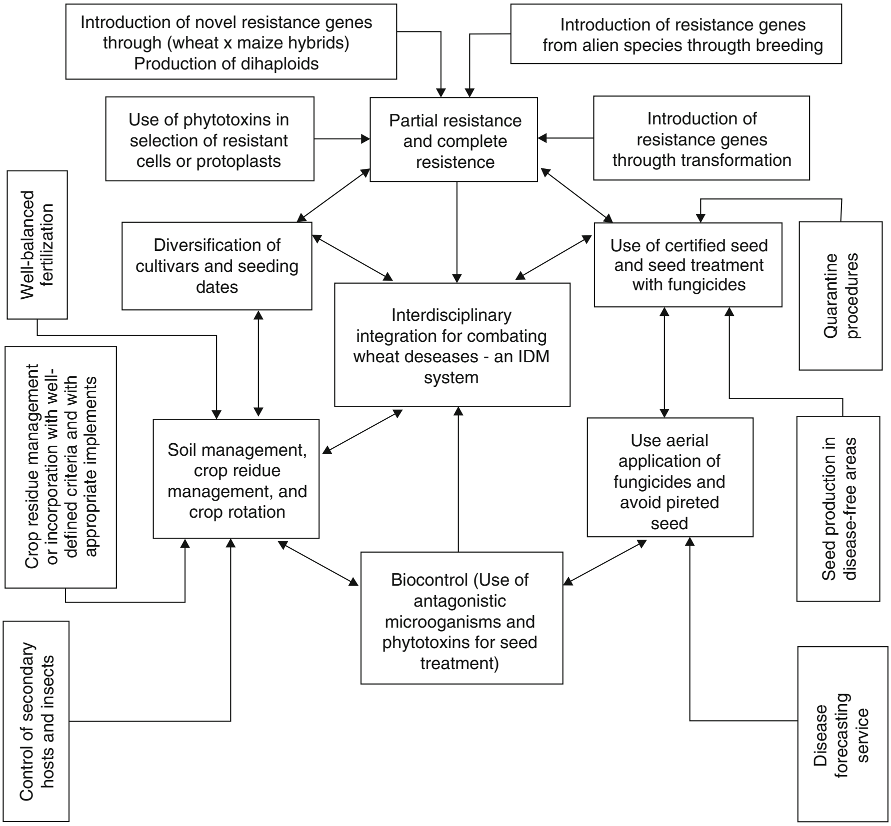

Fig. 2.3 Wheat disease control tools and their integration

appropriate mineral fertilization depending upon the soil analysis; use of healthy and certified seed and avoidance of pirated seed; use of conservation tillage practices like appropriate control of weed and soil structure before implementing no-tillage cultivation; rain water-use efficiency; intelligent crop rotation including biodiversity of plant species and their cultivars for green manuring or for grain production; crop residue management; integrated pest and disease management practices; use of disease forecasting models; as well as analysis of pesticide residue in grains (Cook 2000).

Precision agriculture should also deal with demand of wheat buyers to insist phytosanitory certificates to insure no risk for consumers especially for fungi associated toxins [alkaloids produced by *Claviceps purpurea* (ergot); Ochratoxin A, produced by *Penicillium* and *Aspergillus* during storage (tolerance limit 5 μg/kg for grains); Vomitoxin produced by *F. graminearum* (tolerance limit 500 μg/kg in grains)]. (Peña 2007).

Wheat quality attributes, other than phytosanitary and flour qualities like gluten and protein, involve a series of transactions in the process of value chains, adding value at each stage till the processing and marketing of the farm produce to the final consumer. While the precision agriculture may reduce the cost involved in some inputs, in the end it may in some cases, increase the cost of the final product.

The recent food crisis has been provoked by population growth, climate change, water scarcity and the use of crops for biofuels (Amuzescu 2009; Chakraborty et al. 2011; Pritchard 2011; Shaw and Osborne 2011; Turner et al. 2011; Barak and Schroeder 2012; Serge et al. 2012). Due to the climate change phenomenon crop yields are predicted to decrease in the near future especially in the semi-arid regions. Precision agriculture is expected to address these issues and suggest appropriate changes for a more effective, sustainable and eco-friendly agriculture production system as a whole.

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http://www.springer.com/978-3-319-06464-2

Wheat Diseases and Their Management
Mehta, Y.R.
2014, XII, 256 p. 107 illus., 76 illus. in color., Hardcover
ISBN: 978-3-319-06464-2