Monitoring of wheat rusts in the Indian sub-continent

L M JOSHI, K D SRIVASTAVA and D V SINGH
Division of Mycology and Plant Pathology, Indian Agricultural Research Institute, New Delhi 110012, India

Abstract. Epidemiological studies of rusts of wheat were first taken up in India by Mehta who showed that due to intense summer heat the inoculum of rusts in any form is completely destroyed in the plains during the summer months. But the rust survives in the hills of North and South India. Recent work has identified different foci of infection and has shown that the primary source of stem rust lies mainly in the South Indian hills and that the North Indian hills contribute very little, if at all. Stripe rust, on the other hand, comes mainly from the northern hills while leaf rust is contributed both by southern and northern hills. This view is supported by detailed studies of temperature profile, incubation period, disease gradient etc. Moreover, it has been shown that the cyclones in the Bay of Bengal play a very vital role in dissemination of stem and leaf rusts from Nilgiri and Pulney hills. The ground survey data and information collected through rain sampler, satellite television cloud photography etc. are being utilized for developing bioclimatic models and linear prediction equations. For the disease management, erecting genetical barriers through gene-deployment has been suggested.

Keywords. Wheat rusts; epidemiology; directional movement; dissemination; prediction; management.

1. Introduction

Wheat (Triticum spp.) constitutes a very important source of food to a vast population of many developing countries. In recent years some of these countries have registered a high growth rate (Rajaram et al 1984). In India no other major crop has achieved a growth rate in production comparable to wheat. The production of the country from nearly 7 million tonnes in 1948–49 has gone up to 45.5 million tonnes in 1983–84. Not only the production but the yield per unit hectare has also increased by almost three folds and today amongst wheat growing countries of the world India ranks 4th after USSR, USA and People Republic of China. However, there is still scope to enhance the productivity as vast areas of the country, suitable for wheat cultivation have not yet been fully exposed to modern wheat improvement technology. Pal (1978) has drawn attention to the fact that the production can be stabilized and increased to a great extent by mitigating the losses caused by diseases and pests. Swaminathan (1978) also felt that major problems faced by the scientists in stabilizing production of the dwarf varieties, is the reduction in genetic vulnerability to the major diseases of wheat in the sub-continent.

A major cause of instability of wheat production has been the rusts (stem rust = Puccinia graminis Pers. f. sp. tritici Erikss. & Henn. leaf rust = P. recondita Rob. ex. Desm. f. sp. tritici Erikss. & Henn. and stripe rust = P. striiformis West.). Wheat rusts have a long history of epidemics and have attracted the attention of plant scientists for a long time. A chronological account of the epidemics in India has been provided by Nagarajan and Joshi (1975) and Joshi et al (1980). Several workers have estimated the yield loss caused by rusts from time to time (Barclay 1890; Mehta 1940; Asthana 1948; Prasada 1960; Joshi et al 1975).
2. Early phase of rust research in India

The early research work of British Mycologists on rusts was restricted to taxonomical aspects and the role of alternate and collateral hosts in the annual recurrence of rusts. As early as in 1887 Barclay in India described Uredinales in the neighbourhood of Simla (western Himalayas) and recorded an aecidial stage on Berberis aristata, which he felt, could be of wheat rust. Barclay was not certain about the relationship of this aecial stage with wheat rust and therefore remarked, "this is identical with P. graminis as described by De Bary, though I have not confirmed its genetic relationship with Puccinia on cereals which occur very abundantly in all the fields around Simla. I am also not quite certain that all the three forms of Berberis which occur in Simla (B. vulgaris, B. lycium and B. aristata) bear the same species of aecidium. The subject is one which requires further investigations and I will, therefore, leave it at present an open question". Butler (1905) too had some doubts on the role of Berberis in the perpetuation of stem rust under Indian conditions. Butler's investigations were followed by detailed and systemic investigations on cereal rusts by Mehta from 1922-1950. He conclusively proved that the aecial stages occurring on Berberis spp. in the hills, are of no consequence in the perpetuation of stem rust in India (Mehta 1929, 1940, 1952). His views were further collaborated by subsequent workers. Prasada (1947) connected an aecial stage occurring on Berberis spp. with the rust on Agropyron semicostatum. Joshi and Payak (1963) established that the aecial stage on Berberis jaeschkenana in Lahaul valley of western Himalayas is connected with Poa nemoralis. Payak (1965) recorded that rust of Brachypodium has its aecial stage on Berberis.

Similarly it has been proved that Thalictrum species occurring in hills are non-functional as far as perpetuation of leaf rust is concerned (Mehta 1940). The aecial stage occurring on Thalictrum javanicum in Simla hills has been connected with brown rust (Puccinia persiciana) of Agropyron semicostatum (Prasada 1946).

Mehta (1940, 1952) has shown that due to the high temperature prevailing in the plains of India during summer months and the following rainy season, wheat rusts in general, cannot survive while they could over summer in cooler climate of the hills on self sown plants, ratoon tillers and also on the regular summer crop of Nilgiri and Pulney hills. His studies proved that the chief source of infection of stem and leaf rusts are overwintering/oversummering of uredospores in the sub-Himalayan ranges particularly in central Nepal in the North and Nilgiri and Pulney hills in the South. Mehta (1952) also visualised the Sivalik ranges, the Hindukush mountain and the North-western Frontier Province (now in Pakistan) to be active foci in spreading the uredospores of leaf rust to the Indo-Gangetic plains. He felt that central Nepal is an active centre for spread of stem rust.

Mehta (1940, 1952) also studied the possible role of grasses in the annual recurrence of rusts and recorded the occurrence of Puccinia graminis tritici on Brachypodium sylvaticum, Bromus patulus etc. in the hills but could not establish any definite relationship. Later Prasada (1951), Vasudeva et al (1953), Lele and Rao (1961), Joshi and Manchanda (1963), Bahadur et al (1973) and Pathak et al (1979) tested a number of grasses against wheat rusts under glasshouse conditions and found a number of them to be susceptible. Some grasses like Bromus coloratus, B. carinatus, B. mollis, B. patulus, Hordeum distichum, H. murinum, H. stenostachys, Lolium perenne, Brachypodium sylvaticum, Hilaria jamesii, Aegilops squarrosa, A. ventricosa, A. trineccila and Bromus japonicus were recorded to be susceptible to wheat rusts under natural conditions in the
Monitoring of wheat rusts

plains and a few of them even in hills. However, the exact role of grasses in the perpetuation of wheat rust in the sub-continent needs more detailed investigations. It is worthwhile to mention here that in the Nilgiri and Pulney hills *Vulpia myuros* and *Briza minor* were thought to be the host of stem rust pathogen. Later on Joshi and Lele (1964) proved by cross inoculation experiments and race identification that the rust occurring on these grasses is *P. graminis avenae* and not *P. graminis tritici*.

Hardly any work on wheat rust epidemiology appears to have been done after 1940. Epidemiological studies were taken up only after 1968 when India ushered in the era of dwarf wheats.

3. Epidemiological studies in dwarf wheat era

The high yielding dwarf varieties, mainly carrying Norin-10 gene, were first introduced from Mexico in 1965 and their impact in Indian agriculture was felt only after 1967. The introduced wheat varieties, Sonora 64 and Lerma Rojo, though better yielders, did not possess the required level of rust resistance under Indian conditions. It was, therefore, felt in some quarters, that the newly introduced varieties might be totally destroyed by rusts and hence there is a need of close vigilence on the possible rust epidemics. With this aim in view, a National Wheat Disease Survey and Surveillance Programme was initiated in 1967 (Joshi 1975). This disease monitoring system has not only provided some very useful information on the performance of newly evolved varieties but also rejuvenated the interest in the epidemiological studies in India. Some results of recent epidemiological findings are discussed in the article.

3.1 Stem rust epidemiology

Mehta (1929, 1940, 1952) showed that stem rust can oversummers in the uredial stage on wheat either on the cultivated crop in Nilgiri and Pulney hills or self sown (volunteer) plants in the sub-Himalayan ranges, mainly in central Nepal. He considered northern hills, particularly central Nepal as “the most dangerous foci of infection”. Recent investigations, however, are at variance with Mehta’s conclusion about stem rust. It is now established that in case of stem rust, “the South Indian hills are the chief foci of infection and that the hills in North India contribute little, if at all, to stem rust epidemic in the main wheat belt” (Joshi et al 1971, 1974).

It is worthwhile to record that mobile survey-teams, in the last 16 years, have never recorded the incidence of stem rust in the foot hills or plains of Punjab, Himachal Pradesh, Haryana and western Uttar Pradesh before the middle of March (Swaminathan et al 1969; Joshi and Gera 1971; Joshi et al 1984b) while in certain pockets in the foot hills of North India such as Rupar, Gurdaspur (Punjab), Dhaul Kuan (Himachal Pradesh) and Pantnagar (Uttar Pradesh), leaf and stripe rusts appear between middle of December and early January. Even Butler (1918) recorded that stem rust in North India does not appear on wheat until late in season. According to him it is often not seen until March, a time when wheat is in ears. If Himalayas were the active foci of infection for stem rust it should have normally appeared at the foot hills in western India at the most a fortnight later than leaf and stripe rusts. On the other hand stem rust appears as early as December/January in many places in peninsular India. This view that the bulk of inoculum of stem rust is introduced from South India was further substantiated by quantification of inoculum in North and South Indian hills by
Nagarajan and Joshi (1977). Using glass-rod impaction technique Roelfs et al (1968), found that the cumulative values of stem rust uredospores over naturally infected fields in southern hills have 20 to 25 times more uredospores in the air than the artificially infected field of North in the month of November (table 1).

The movement of stem rust from South to North has been well documented by ground survey data. Gokhle and Patel (1952) also reported similar movement of stem rust in erstwhile Bombay State. The present findings of Joshi (1976, 1978, 1982) and Nagarajan and Singh (1976) lead to the same conclusion for the whole country.

3.2 Leaf rust epidemiology

Leaf rust is the most important rust, widely distributed and most frequently occurring disease in the Indian sub-continent (Joshi et al 1970, 1984a). Somehow its importance has been overlooked in the past not only in India but elsewhere also (Chester 1946).

Mehta (1940, 1952) has shown that leaf rust spreads both from South and North Indian hills. Wheat disease surveys conducted since 1967 have also demonstrated that the first build up of leaf rust like stem rust takes place in the plains of Karnataka in South India, generally in the last week of December. At the same time the infection is also established in the foot hills of Bihar and eastern part of Uttar Pradesh. The rust population from southern foci moves Northwards towards Maharashtra and Madhya Pradesh and another population moves from the northern foot hills towards the South and finally both the populations, moving in opposite directions merge into each other (Joshi et al 1974).

Analysis of data, on rust appearance for over a decade and half, reveals that a number of foci get established all along the Himalayan foot hills, Bihar, East and central Uttar Pradesh between Christmas and middle of January. Such foci have been found up to 270 km from the nearest foot hills into parts of North east India (Joshi et al 1977). In the eastern region by mid January these isolated foci of the leaf rust infection multiply many times more while the isolated pockets of infection along the foot hills of Jammu

<table>
<thead>
<tr>
<th>Location</th>
<th>No. of uredospores</th>
</tr>
</thead>
<tbody>
<tr>
<td>South India</td>
<td></td>
</tr>
<tr>
<td>Semabahnur</td>
<td>21</td>
</tr>
<tr>
<td>Coonoor</td>
<td>119</td>
</tr>
<tr>
<td>Wellington</td>
<td>94</td>
</tr>
<tr>
<td>Nanjad</td>
<td>194</td>
</tr>
<tr>
<td>North India</td>
<td></td>
</tr>
<tr>
<td>Palampur*</td>
<td>2</td>
</tr>
<tr>
<td>Solan*</td>
<td>0</td>
</tr>
<tr>
<td>Bhowali</td>
<td>6</td>
</tr>
<tr>
<td>Almora</td>
<td>12</td>
</tr>
</tbody>
</table>

* No infection recorded on wheat.
and Kashmir, Punjab, Haryana, Himachal Pradesh and western Uttar Pradesh remain more or less localised possibly because of non-congenial climatic reasons. In early February leaf rust is well established in the eastern regions of Indo-Gangetic plains and then the inoculum moves from central and eastern Uttar Pradesh towards North-west direction and rust appears uniformly all through western Uttar Pradesh and parts of Haryana. By the end of February with rise in average temperature, the less active infection centres along the foot hills of North-western India also become active and spread slowly and finally get mixed with the actively spreading population of uredospores from the East (figure 1). Thereafter, the two migrating populations are undistinguishable (Joshi et al 1977). Like stem rust the long distance dissemination of leaf rust from the southern foci to central India is reported to be associated with cyclonic rains (Nagarajan and Singh 1973, 1974).

3.3 Stripe rust epidemiology

Stripe rust has been found to survive during summer at several locations in the Himalayan ranges in the absence of alternate host (Mehta 1940). He reported that stripe rust could not be found throughout the year at higher altitudes like Narkanda in Simla hills (2850 m a.s.l.) due to very low temperatures. Joshi et al (1976a) have shown that there are probably very few foci which are capable of harbouring stripe rust all the year round but in general it survives within a range of 2200–2500 m a.s.l. or above, shifting up and down from one place to another as the environment changes. Joshi et al (1977) have further shown that normally this rust appears by the end of December and early January along the foot hills of Punjab, Haryana and western Uttar Pradesh and establishes primary foci of infection in this region as it can withstand cooler temperate conditions much better than other rusts. From this region, the stripe rust spreads
southward and becomes well established in the northern parts of the country by the end of February.
During January and February the spread of stripe rust is much faster than leaf rust. However, by the end of February or beginning of March the temperature starts rising and further spread of rust stops and it develops into a telial stage. Therefore, the stripe rust remains essentially a major disease problem of North and North-western region (figure 1). Sometimes it also appears in Bihar, eastern Uttar Pradesh and even in central India (Joshi 1978). Very often these infections remain isolated and seldom become serious threat to wheat. The limited spread in South-central and eastern parts of the country is due to the prevalence of high temperature quite uncongenial for stripe rust development. The disease can survive in Nilgiri and Pulney hills but it cannot spread even to the foot hills of Nilgiris due to unfavourable weather. So far there is no evidence to suggest that stripe rust inoculum from Nilgiri hills is being introduced in the northern wheat belt (Joshi et al 1984a).

The present knowledge of stripe rust epidemiology is somewhat limited. Some question regarding the foci of infection need further elaboration. Is some inoculum in the North western Indian plains like Rajasthan (Joshi et al 1978) introduced from Pakistan also? What is the role of western mountains (Hindukush and Sulaiman ranges) in Pakistan itself? Yet another intriguing question, which remains unanswered is the appearance of a new virulent form of stripe rust in Nilgiri hills akin to Turkish virulence. Was it a case of 'introduction' or 'man guided evolution' as visualized by Zadoks (1959) and Johnson et al (1967) for similar cases elsewhere.

4. Climatic factors in relation to wheat rust epidemiology

4.1 Temperature profile

Temperature apparently is a major deciding factor in the development and spread of wheat rusts in the Indian sub-continent. Thorpe and Ogilvie (1961) also considered temperature as well as humidity to be the important climatic factors affecting the establishment and further growth of stem rust pathogen. In addition to this a free film of water on the leaf surface of the host influences the germination of uredospores and production of fungal hyphae (Rowell et al 1958; Sharp et al 1958). Temperature requirement for germination of spores of stem rust, appressorium formation and penetration are given in table 2.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Minimum</th>
<th>Optimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germination*</td>
<td>2</td>
<td>15-24</td>
<td>30</td>
</tr>
<tr>
<td>Penetration and sub-stomatal vesicle formation</td>
<td>15</td>
<td>29</td>
<td>35</td>
</tr>
<tr>
<td>Germ tube growth</td>
<td>—</td>
<td>20</td>
<td>—</td>
</tr>
</tbody>
</table>

* Free water necessary.
The temperature required for uredospore germination and penetration by germ tube leading to the formation of substomatal vesicle as indicated in table 2, are lacking in western Himalayas from November onwards. Joshi (1976) on the basis of 50 years meteorological data concluded that climatic conditions in the Himalayan region and even parts of North-western plains in winter months are not suitable for multiplication of stem rust inoculum. Therefore, he considered that stem rust inoculum surviving in Himalayas cannot be a source to Indo-Gangetic plains before middle of March and by then the crop is at an advanced stage.

Stem rust in northern hills probably remain dormant with almost no sporulation during winter months. This view gets support from an experiment conducted at Almora (5200 ft. a.s.l.) in 1972–73. Natural infection of stem rust, at Almora, was observed in October in a susceptible wheat cultivar. Immediately the same cultivar was sown surrounding it on all sides but the rust did not spread further in subsequent months and remained inert till late March. First pustule on the surrounding crop was seen on 26th March. This shows that the conditions for sporulation and subsequent spread of stem rust from the Himalayan region to the plain is not possible prior to March and then within 2–3 weeks the crop matures in the plains. Such late arrival of inoculum, if any, is hardly of any consequence. In all possibilities, the northern source of inoculum has very little role to play in the spread of rust to the plain to cause an epidemic.

As regards the effect of temperature on the spread of leaf rust, it has been noticed that North-eastern India is warmer in comparison to the North western parts in winter months (Nagarajan et al. 1978b), and there is a gradual rise in temperature from North-east to North-west (table 3). Due to comparatively higher temperature and favourable climate in the eastern region in January and February there is a quick and fast multiplication of inoculum while the infection in the western region remains more or less inactive till middle of February on account of low temperatures. By the third or fourth week of February the foci established in the western region also become active mainly due to rising temperature, and rust begins to spread in the whole of the north-western plains.

Stripe rust can stand cooler temperatures much better than other rusts (its optimum being 9–11°C), therefore, it seems to form a closed circuit in North-west India. On the other hand, its absence practically from the entire South-central India except Nilgiri and Pulney hills, can be attributed to the prevalence of uniformly high temperatures

Table 3. Temperature profile in winter months in North-eastern and North-western region of India based on 30 years (1931–60).

<table>
<thead>
<tr>
<th>Region</th>
<th>Average temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>January</td>
</tr>
<tr>
<td>North-eastern zone (Bihar, east and central Uttar Pradesh)</td>
<td>9.8</td>
</tr>
<tr>
<td>Mid zone (Western Uttar Pradesh)</td>
<td>8.1</td>
</tr>
<tr>
<td>Western zone (Punjab and Haryana)</td>
<td>5.6</td>
</tr>
</tbody>
</table>
during crop season (table 4). The average minimum temperature in South India except hills seldom go below 15°C.

4.2 Incubation period and rust development

Incubation period is the time lapse between entry of the fungus into the host and the expression of first symptom. Low temperature greatly influences the establishment, development and further spread of the rusts. As reported by Stakman and Harrar (1957) the incubation period of stem rust can vary from 5 days to 3 months depending upon the prevailing temperature (table 5).

In India the incubation period in relation to rust development has been investigated by Mehta (1923), Sahni and Prasada (1963) and Pandey (1976). Sahni and Prasada (1963) reported the long interval up to 65 days between the establishment and first outbreak of stem rust infection and also reported that the incubation period of *P. graminis tritici* in the neighbourhood of Delhi was as long as 40 days. It is a bit puzzling (Johnson et al. 1967). Pandey (1976) recorded that incubation period of stem rust varied from 22 days in January to 8–10 days during March at Delhi. Joshi *et al.* (unpublished data) also reported that incubation period of stem rust in Delhi, in winter months was 15–18 days while in Simla (outer Himalayas) it ranged from 40–50 days, and this period was from 9–14 days in Indore in central India during crop season. Such a prolonged incubation period in the hills of North India, where low temperature persists from November to February, the multiplication rate of stem rust is either very low or almost nil. With the onset of congenial conditions in the northern hills after the

<table>
<thead>
<tr>
<th>Location</th>
<th>November</th>
<th>December</th>
<th>January</th>
<th>February</th>
<th>March</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kathmandu</td>
<td>7.6</td>
<td>22.6</td>
<td>3.1</td>
<td>18.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Mukteshwar</td>
<td>6.0</td>
<td>14.8</td>
<td>3.5</td>
<td>11.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Nainital</td>
<td>5.3</td>
<td>15.6</td>
<td>2.2</td>
<td>11.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Mussoorie</td>
<td>9.2</td>
<td>15.2</td>
<td>4.2</td>
<td>12.0</td>
<td>2.9</td>
</tr>
<tr>
<td>Simla</td>
<td>10.3</td>
<td>6.7</td>
<td>4.0</td>
<td>4.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Dalhousie</td>
<td>7.7</td>
<td>17.1</td>
<td>3.7</td>
<td>12.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Dharmsala</td>
<td>10.7</td>
<td>20.1</td>
<td>7.2</td>
<td>15.9</td>
<td>6.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>November</th>
<th>December</th>
<th>January</th>
<th>February</th>
<th>March</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kodaikanal</td>
<td>9.6</td>
<td>15.9</td>
<td>8.4</td>
<td>16.5</td>
<td>8.1</td>
</tr>
<tr>
<td>Ootacamund</td>
<td>8.9</td>
<td>17.6</td>
<td>8.8</td>
<td>19.7</td>
<td>6.1</td>
</tr>
<tr>
<td>Coonoor</td>
<td>11.8</td>
<td>19.4</td>
<td>10.7</td>
<td>20.5</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Table 4. Temperature range (in °C) for the hill stations of North and South India during winter months (Mean of 30 years).

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>0.5</th>
<th>5.5</th>
<th>10.5</th>
<th>12.2</th>
<th>19.1</th>
<th>21.1</th>
<th>23.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days</td>
<td>85</td>
<td>22</td>
<td>15</td>
<td>12</td>
<td>9</td>
<td>7</td>
<td>5+</td>
</tr>
</tbody>
</table>

Table 5. Incubation period for establishment and development of stem rust.
middle of March some inoculum of stem rust, theoretically may be introduced from these hills but in North-western plains the remaining period is so short that rust cannot complete more than 1 or 2 uredial cycles till harvest time. In contrast to northern hills, the climatic conditions in Nilgiri hills in South are more uniform and the incubation period of stem rust is only 8–10 days in the cropping season. And many a times rust gets established in the foot hills and plains by middle of December. Moreover, climatic conditions in the entire South even in winter months are most congenial for stem rust development. Naturally huge amount of inoculum is present which actively multiplies from December to March in the whole of South while the northern hills are still under prolonged cold spells.

In case of leaf rust the incubation period varies from 10–25 days at Delhi in winter months (Sahni and Prasada 1968). Srivastava (1981) also observed that both at Delhi and Wellington (Nilgiris) weather conditions are congenial for rust development and therefore, the incubation period is more or less identical. The number of uredial generations calculated on the basis of incubation period revealed that it took 35–40 days for the completion of five uredial generations at Delhi and Wellington during crop season to build up leaf rust intensity to an epidemic level.

Disease gradient studies conducted at Karnal (altitude 2915 N and 74 D in North India) by Joshi and Palmer (1973) have shown that the weather in the month of January and February is generally too cool for stem rust development but the conditions, at that time, are favourable for leaf and stripe rusts development. It has been demonstrated that stripe and leaf rusts spread 100 and 92 m respectively from the source of inoculum in 55 and 75 days in 1970 and 1971 whereas stem rust spreads only 22 m in 1970 and 13 m in 1971 during the same period (figure 2). Joshi (1982), therefore, holds the view that even if stem rust is somehow established in northern parts in winter months it would either remain dormant or the rate of multiplication would be negligible till middle of March and by that time the crop is well in an advanced stage of growth.

4.3 Role of cyclonic disturbances in the spread of rusts

Sleeman (1839) was the first to correlate unusually wet weather due to heavy rains, with a severe epidemic of stem rust around Sagar in Madhya Pradesh during November, 1829. Moreland (1906) observed that the amount of rainfall in October is not a determining factor for rust development in Uttar Pradesh, but in Madhya Pradesh which is predominantly a stem rust sensitive area, the disease is influenced by rains. Mallik (1958) attempted to correlate stem rust epidemic with the unusual November rainfall in central India. It has now been proved that cyclonic disturbances in the Bay of Bengal have a direct bearing on the dissemination of uredospores of stem rust (and also leaf rust) from Nilgiri and Pulney hills to central India (Nagarajan 1973; Nagarajan et al 1975).

Nagarajan and Singh (1973, 1974) examined the rain samples collected in a rain sampler designed by Roelfs et al (1970) along with wind trajectories and satellite television cloud photography (srcp) and proved that uredospores of rusts from Nilgiris are lifted by conviction currents to 700 mb level and are transported to hundreds of kilometers towards North. In nature vertical mixing and small eddies occur which help to maintain the height of the spore cloud during transport (figure 3). Nagarajan and Singh (1975, 1976) suggested that the following synoptic weather conditions termed “Indian Stem Rust Rules” are associated with the transport of rust inoculum from Nilgiri hills to central India.
Figure 2. Wheat rust severity and distance from source 75 days after inoculation at Karnal, India, 1970.

Figure 3. Dissemination of the three rusts from foci of infection.
(i) A storm of depression should be formed either in the Bay of Bengal or in the Arabian Sea between 75 and 85°E, 10–15°N and should end over central India.
(ii) A persistent high pressure cell over the southern part of central India (not far from the Nilgiris) must be present.
(iii) Appearance of a deep trough extending up to southern India and caused by onward movement of the easterly disturbance.

Many trajectories have been plotted and a number of cases of rust appearance have been investigated (Nagarajan et al 1976, 1977). These have conclusively shown that the cyclones were directly responsible for stem rust appearance in central-peninsular India. A typical case study of stem rust appearance in central and peninsular India during 1976 crop season is discussed here. It showed that synoptic weather conditions (i.e. the formation of a storm of depression in the Bay of Bengal, and the presence of high pressure cell in central India prevailed for more than 48 hr over central India (figure 4a). The backward trajectories drawn for Powerkheda, Indore and Malegaon (figure 4b) ended very close to the source area in the Nilgiri in about 56 hr. Resultantly the disease appeared in many parts of Madhya Pradesh and Maharashtra (figure 4c) as per expectation (Joshi et al 1976b; Nagarajan and Joshi 1980).

The correlation of the weather situation on the ground by visible and IR spectrum has shown that a more quantitative assessment of the weather is possible by IR images (Nagarajan et al 1982a, b). The IR images were superior to normal ones as they show more clearly the areas where the cyclone is dissipated. Results indicate that weather satellite scans in IR spectrum of light have some scope as a technique for predicting crop health.

Figure 4a. Synoptic map for 700 mb level for one of the days (23rd 0000 GMT) when southerly winds prevailed due to tropical cyclone in November, 1976.
Figure 4b. Backward drawn 700 mb level trajectories for the rain deposited uredospores sampled at 1. Powarkheda 2–3. Indore and 4. Malegaon for November 1976.

November 30, 1976

Figure 4c. Early November prediction of rust appearance. Dark dots—places where stem/leaf rusts appeared as predicted.
Monitoring of wheat rusts

Like stem rust, the long distance dissemination of leaf rust from southern foci to central India is also associated with cyclonic rains (figure 3). Investigations have shown that a spread occurs to a distance of 600 km or more in central India from Nilgiri and Pulney hills without infecting the fields in between (Nagarajan and Singh 1973, 1974; Joshi 1976). Furthermore, it has been shown that the uredospores of leaf rust from North-eastern region are carried westwards by western disturbances. It has also been shown that the amount of precipitation and number of rainy days are more in epidemic than non-epidemic years (Nagarajan and Joshi 1978a). Keeping in view these conditions, they concluded that if more western disturbances accompanied by frequent rains occur in North India, there is apparently good chance for the spread and build up of leaf rust in North-west India to lead to an epidemic (Nagarajan et al 1978b).

A severe epidemic of stripe and leaf rusts occurred in some parts of Pakistan during 1978 (Hassan 1978; Kidwai 1979). In the absence of the daily weather report of Pakistan, Nagarajan et al (1980, 1982a) analysed weather data of Ganganagar, Ferozepur, Amritsar, Ludhiana, Jammu and Srinagar along the Indo-Pakistan border and found that crop season 1978 was very cool, wet and had an extended winter favourable for generation of more uredial cycles. Towards early April there was sudden rise in maximum temperature by 5-6°C. Such weather patterns were associated with western disturbances, which were congenial for rusts epidemic. It is presumed that similar climatic conditions prevailed in Pakistan region and due to the availability of susceptible cultivar (Maxipak, Chenab 70, Punjab 76 etc.), a severe epidemic occurred. On the other hand in the Indian side, the susceptible variety Kalyansona (a sister strain of Mexipak) had been largely replaced after 1973 by a number of varieties like Sonalika, WL 711, WG 357 etc. and this mosaic pattern of varieties averted the possible catastrophe.

5. Management strategies

5.1 Rust prediction models

Disease prediction is of fundamental importance for successful and efficient use of suitable chemicals for the management of rusts. The ground survey data and the information collected through rain samplers, sprces etc. are being used as basis for developing bio-climatic models as well as linear prediction equations. Multiple regression analysis of various environmental factors has been used by several workers to work out mathematical equations for wheat rusts (Dirks and Romig 1970; Eversmeyer and Burleigh 1970; Eversmeyer et al 1973; Burleigh et al 1972; Kranz 1974).

As pointed out earlier, the cyclonic disturbances in the Bay of Bengal to a great extent are responsible in the dissemination of stem rust in India. A bio-climatic model has been developed to predict stem rust appearance in central India based on stem rust rules (Nagarajan and Singh 1976; Nagarajan 1977). On the basis of the cyclonic rains coupled with southerly winds during November, availability of susceptible cultivars and the detection of uredospores in rain samples some successful predictions were made on the probability of rust appearance during the years of cyclones. It was observed that between 1974-75 to 1983-84 seasons, cyclones over foci of infection occurred during 1976-77, 1977-78 and 1978-79 seasons. It is interesting to note that the disease appeared with wide prevalence during the years, of cyclonic disturbances, than in non-cyclonic years between 1980-81 to 1983-84 crop seasons which proved
the validity of prediction system based on rain analysis technique (Joshi et al. 1984a).

Like stem rust some common feature on the development of leaf rust in North India, occurring every season have also provided the basis of bio-climatic prediction model in North-western India (Nagarajan et al. 1979b). This model indicates that the following criteria must be satisfied if leaf rust is to occur:

(i) At least 5-6 infection sites should be observed at a maximum distance of 25 ± 5 km around 15-20 January in Uttar Pradesh and North Bihar.
(ii) The number of rainy days between January to middle of April over North-western India should be at least twice the normal number.
(iii) The weekly mean maximum temperature during March to middle of April should be within 1°C of the normal temperature.

It has been assumed that if the susceptible cultivar in the entire Indo-Gangetic plain are cultivated (although in reality they are not) and 1st and 2nd criteria are satisfied then a severe epidemic will tend to occur. If they are partly satisfied, isolated outbreaks may probably occur. The testing of this model is under way.

The bio-climatic model can give an idea of probable dates of rust appearance but further development of the disease will depend on environmental factors prevailing after the establishment of infection. In this direction Nagarajan and Joshi (1978b) attempted to develop a mathematical model for a seven day forecast of stem rust severity based on environmental variables. The linear equation outlines as under:

\[ y = -29.3733 + 1.820 x_1 + 1.7735 x_2 + 0.2516 x_3 \]

where \( x_1, x_2 \) and \( x_3 \) were previous disease severity, minimum temperature and maximum relative humidity.

The above linear model has been tested and found valid for prediction at Delhi and Niphad under natural conditions of stem rust infection (Karki et al. 1979).

A similar study was undertaken by Srivastava (1981) to evolve a functional equation for seven day prediction of leaf rust. The prediction equation being

\[ y = -83.53084 + 1.55172 x_1 + 0.54158 x_2 + 1.75326 x_3 \]

where \( x_1, x_2 \) and \( x_3 \) were mean of weekly maximum temperature, relative humidity and previous level of disease severity.

These mathematical models may be useful in estimating the severity of the disease a week before under local conditions, thereby giving enough time to decide, the economic use of chemicals for the disease management.

5.2 Genetic barriers

The epidemiology of rusts has an important bearing on their management in India. The efficiency of gene combination shows that the management of rusts may be possible by deploying the resistance genes (Nagarajan 1984). Gene deployment visualised a centrally planned, properly executed strategic use of vertical resistance genes over a large area to minimise the threat of rust epidemics or pandemics (Joshi and Nagarajan 1978; Nagarajan and Joshi 1984). This strategy can be quite useful in the case of pathogen where its epidemiology has been studied in depth and an organised machinery exists for seed distribution.

Nagarajan and Joshi (1980) considered the whole Indian sub-continent to be a single
Monitorin 9 of wheat rusts

epidemiological zone for stem rust which can be split into three sub-zones. They have also defined the "Puccinia Path" i.e. the usual dissemination pattern of the spread of inoculum from foci of infection (figure 5). According to them sub-zone 1, by virtue of its proximity to the source-area, gets inoculum by means other than rain such as katabatic wind current. This sub-zone, however, is not of much economic significance as the wheat acreage in this area is negligible. In sub-zone 2, the inoculum arrives either by wind current or with rain around November while in sub-zone 3 the inoculum is transported by cyclonic disturbances and deposited by rain during late October to November. This zone is epidemiologically important because the upper air transportation and rain deposition of uredospores can create an epidemic. This zone can also serve as the main secondary focus for zone 4. If there is quick and early built up of inoculum in this zone sometime in November or early December it can provide adequate inoculum to the eastern regions of sub-zone 4. Sub-zone 4 remains almost free from stem rust in the absence of an appropriate tropical cyclone.

This basic information on dissemination of rust can be utilized in erecting suitable genetic barriers in "Puccinia Path" by effective gene deployment to mitigate the rust menace. It should be possible, to delay the spread of the rust disease in the major wheat area by obstructing the "Puccinia Path" by growing genetically different resistant material in different zones. This sort of gene deployment could be practised at regional and national level (Swaminathan 1978). Similar recommendations have been proposed

Figure 5. The 'Puccinia Path' as it occurs in India between the southern hills (darkly shaded) to central India and its sub-epidemiological zones 1-4.
for obstructing “Puccinia Path” of crown rust of oat in USA by deploying different vertical genes by Browning et al (1969).

The epidemiology of leaf rust in India reveal that the Indo-Gangetic plains and sub-Himalayan ranges act as a single epidemiological unit for this rust. This region can further be divided into four zones (figure 6) mentioned below (Swaminathan 1978; Nagarajan et al 1979).

<table>
<thead>
<tr>
<th>Zone</th>
<th>Zone Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>Eastern zone</td>
</tr>
<tr>
<td>Zone 2</td>
<td>Mid zone</td>
</tr>
<tr>
<td>Zone 3</td>
<td>Western zone</td>
</tr>
<tr>
<td>Zone 4</td>
<td>Himalayan zone</td>
</tr>
</tbody>
</table>

- Bihar and eastern Uttar Pradesh
- Western Uttar Pradesh
- Punjab, parts of Haryana and Himachal Pradesh.
- Hilly region of Himalayas and mid-low altitudes of central Nepal.

In Zone 1, not only leaf rust gets established quite early but the multiplication rate of inoculum of the rust is also quicker and faster than the western zone with the result that by middle of February enough inoculum is build up in this zone, which is then transported to the western zone by easterly winds. It is, therefore, obvious that by checking this inoculum load coming from the eastern zone in February, the chances of epidemic can significantly be minimized. It can be achieved by growing highly resistant varieties with different genetic make up than those for the western zone. Such diversification of varieties will prevent introduction of matching genes from one zone to another. Survey and meteorological data between 1973–1978 have shown that by such varietal diversification in the Indo-Gangetic plains, a possible calamity of rust epidemic
in 1976–77 was prevented. It could be possible because the predominant cultivar Kalyansona possessing *Lr* 13, *Lr* 14b and *Lr* 18 genes in Indo-Gangetic plains had already been replaced by wheat cultivars such as Sonalika (*Lr* 2a, *Lr* 11, *Lr* 13), Arjun (*Lr* 10), WG 357, WG 377 and C 306 during this period (Nagarajan et al 1978a). A varietal change every 4–5 years in eastern and western zones with varieties possessing diverse gene for resistance has been recommended for leaf rust control in North India (Joshi and Nagarajan 1978; Nagarajan et al 1979). Nagarajan et al (1984) considered that there is scope for gene deployment on national level to check the spread of leaf rust. Srivastava *et al* (1984a,b) have explored the possibility of deployment of multilines in the eastern zone to mitigate the leaf rust epidemics.

From 1967 to 1975 the stripe rust remained very much restricted in the Indo-Gangetic plains due to extensive cultivation of Kalyansona, than a resistant cultivar (Joshi 1976). Kalyansona was withdrawn from cultivation in North-western India due to stripe and leaf rusts epidemic of 1971–72 and 1972–73 and was replaced by other resistant cultivars such as WL 711, Sonalika etc. Sharma *et al* (1973) has reported that Sonalika has now become susceptible to new stripe rust virulence (Race I) but for some unknown reasons the race has not spread much in the last decade. Anyway it poses a threat to Sonalika. Moreover, Sonalika is quite susceptible to a few races of leaf rust also. It is, therefore, essential to replace Sonalika by new genotypes in North-western region.

**References**

Barclay A 1887 A descriptive list of uredinales occurring in the neighbourhood of Simla (western Himalayas); *J. Asiat. Soc. Beng.* 56 (Part II) 350–375
Barclay A 1890 On some rusts and mildews in India; *J. Bot.* 20 257–261.
Burleigh J R, Roelfs A P and Eversmeyer M G 1972 Estimating damage to wheat caused by *Puccinia recondita tritici*; *Phytopathology* 62 944–946
Butler E J 1905 Some Indian forest fungi, *Indian Forester* 31 670
Butler E J 1918 Fungi and diseases in plants; Thacker Spink and Co., Calcutta pp 547
Chester K S 1946 The cereal rusts, the nature and prevention of the cereal rusts as exemplified in the leaf rust of wheat; *Chronica Botanica* Co. Welham, Mass. pp. 269
Dirks V A and Romig R W 1970 Linear model applied to variation in number of cereal rust urediospores; *Phytopathology* 60 246–251
Eversmeyer M G and Burleigh J R 1970 A method for predicting epidemic development of wheat leaf rust; *Phytopathology* 60 805–811
Eversmeyer M G, Burleigh J R and Roelfs A P 1973 Equation for predicting wheat stem rust development; *Phytopathology* 63 348–351
Joshi L M 1975 Surveys on wheat rusts in India: The rust situation since 1972; *Cereal Rusts Bull.* 3 7–9
Joshi L M 1976 Recent contributions towards epidemiology of wheat rusts in India; *Indian Phytopath.* 29 1–16
L M Joshi, K D Srivastava and D V Singh

Joshi L M 1978 Dissemination of wheat rusts in the Indian sub-continent; Botanical Progress 1 1-5
Joshi L M 1982 Wheat rust management—present knowledge and future prospects; Kakatoe 10 1-12
Joshi L M and Gera S D 1971 Wheat Disease News Letter IARI New Delhi 5 1-8
Joshi L M and Lele V C 1964 Role of Vulpia myuros and Briza minor in the perpetuation of black rust of oats, in the Nilgiri Hills; Indian Phytopath. 17 245-248
Joshi L M and Manchanda W C 1963 Bromus japonicus Thumb. susceptible to wheat rusts under natural conditions; Indian Phytopath. 16 312-313
Joshi L M and Palmer L T 1973 Epidemiology of stem, leaf and stipe rusts of wheat in northern India; Plant Dis. Repr. 57 8-12
Joshi L M and Payak M M 1963 A Berberis aecidium in Lahaul valley Western Himalayas; Mycologia 55 247-250
Joshi L M, Renfro B L, Saari E E, Wilcoxson R D and Raychaudhuri R D and Raychaudhuri S P 1970 Rust and smut diseases of wheat in India; Plant Dis. Repr. 54 391-394
Joshi L M, Srivastava K D and Ramanujam K 1975 An analysis of brown rust epidemics of 1971-72 and 1972-73; Indian Phytopath. 28 138
Joshi L M, Goel L B and Sinha V C 1976a Role of Himalayas in the annual recurrence of yellow rust in northern India; Cereal Rust Bull. 4 27-30
Joshi L M, Nagarajan S and Srivastava K D 1977 Epidemiology of brown and yellow rusts of wheat in North India: Place and time of appearance and spread; Phytopath. Z. 90 116-122
Joshi L M, Srivastava K D, Singh D V and Ramanujam K 1980 Wheat rust epidemics in India since 1970; Cereal Rust Bull. 8 17-21
Joshi L M, Singh D V and Srivastava K D 1984a Fluctuations in the incidence of rusts and other wheat diseases during past decade and strategies for their containment; 23rd All India Wheat Research Workers Workshop (ICAR) held at Kanpur Aug. 1984
Joshi L M, Srivastava K D and Singh D V 1984b Wheat Diseases News Letter 17 1-120
Karki C B, Pande S, Thombre S B, Joshi L M and Nagarajan S 1979 Evaluation of a linear model to predict stem rust severity; Cereal Rusts Bull. 7 3-7
Kidwai A 1979 Pakistan reorganises agricultural research after harvest disaster; Nature 227 169
Lele V C and Rao M H 1961 Further studies on the susceptibility of some grasses to cereal rusts; Indian Phytopath. 14 154-159
Mailik A K 1958 An examination of the crop yields at crop weather stations with special reference to rainfall; Indian J Nat. Geophys. 9 1-8
Mehta K C 1923 Observations and experiments on cereal rusts in neighbourhood of Cambridge with special reference to their annual recurrence; Trans. Brit. mycol. Soc. 8 124-176
Mehta K C 1929 Annual recurrence of rusts on wheat in India; Proc. 16th Indian Sci. Congr. pp 199-223
Mehta K C 1940 Further studies on cereal rusts in India. Part I. Sci. Monogr. Imperial Counc. agric. Res. India 14 pp 224
Moreland W H 1906 The relation of weather to rust on cereals; Mem. Dep. agric. Indian Bot. 1 53-57
Nagarajan S and Joshi L M 1975 A historical account of wheat rust epidemics in India and their significance; Cereal Rusts Bull. 3 29-33

Nagarajan S and Joshi L M 1978a Epidemiology of brown and yellow rusts of wheat over North India. II. associated meteorological conditions; *Plant Dis. Reptr.* 62 186–188

Nagarajan S and Joshi L M 1978b A linear model for seven day forecast of stem rust severity; *Indian Phytopath.* 31 504–506

Nagarajan S and Joshi L M 1980 Further investigations on predicting wheat rusts appearance in central and peninsular India; *Phytopath. Z.* 98 84–94


Nagarajan S and Singh H 1973 Satellite television cloud photography as a possible tool to forecast plant disease spread; *Curr. Sci.* 42 273–274

Nagarajan S and Singh H 1974 Satellite television cloud photography—a new method to study wheat rust dissemination; *Indian J. Genet.* 34A 486–490

Nagarajan S and Singh H 1975 The Indian stem rust rules—an epidemiological concept on the spread of wheat stem rust; *Plant Dis. Reptr.* 59 133–136

Nagarajan S and Singh H 1976 Preliminary studies on forecasting wheat stem rust appearance; *Agric. Meteorol.* 7 281–289

Nagarajan S, Singh H and Joshi L M 1975 Climatic factors in relation to stem rust epidemiology; *Plant Dis. Reptr.* 59 670–672

Nagarajan S, Singh H, Joshi L M and Saari E E 1976 Predictition of *Puccinia graminis* tritici uredospores in India; *Physopathology* 66 198–203

Nagarajan S, Singh H, Joshi L M and Saari E E 1977 Prediction of *Puccinia graminis* f. sp. tritici on wheat in India by trapping the uredospores in rain samples; *Physoparassitica* 5 104–108

Nagarajan S, Joshi L M, Srivastava K D and Singh D V 1978a Epidemiology of brown and yellow rusts of wheat in North India. III. Impact of varietal change; *Plant Dis. Reptr.* 62 694–698

Nagarajan S, Joshi L M, Srivastava K D and Singh D V 1978b Synoptic meteorological conditions in relation to leaf rust spread in northern India; *Proc. First Intern. Conf. Aerobiology, held at Munich, West Germany, August 1978* pp 446–451

Nagarajan S, Joshi L M, Srivastava K D and Singh D V 1979 Epidemiology of brown and yellow rusts of wheat in North India. IV. Disease management recommendations; *Cereal Rusts Bull.* 7 15–20


Nagarajan S, Selboldt G, Kranz J, Saari E E and Joshi L M 1982b Utility of weather satellites in monitoring cereal rust epidemics; *Pflikrankh* 89 276–281

Nagarajan S, Bahadur P and Nayyar S K 1984 Contemplating the management of brown rust resistance genes to mitigate the spread of *Puccinia recondita* f. sp. tritici; *Indian Phytopath.* 37 490–497

Pal B P 1978 Wheat research—the early phase, *Indian Fmg* 27 3–5

Pande S 1976 Studies on the epidemiology of stem rust on wheat with special reference to sporulation of the pathogen (*Puccinia graminis* tritici); Ph D Thesis, IARI, New Delhi 172 p

Pathak K D, Joshi L M and Chinnamani S 1979 Natural occurrence of *Puccinia graminis* tritici on *Brachypodium sylvaticum* during off season in Nilgiri hills; *Indian Phytopath.* 32 308–309

Payak M M 1965 *Berberis* as the aecial host of *Puccinia brachypodii* in Simla hills (India); *Phytopath. Z.* 52 49–54

Prasada R 1946 The uredostage of aecidium found on *Thalictrum* in Simla Hills; *Curr. Sci.* 15 254–255

Prasada R 1947 Discovery of the aecidio-stage connected with the aecidium so commonly found on species of *Berberis* in the Simla hills; *Indian J. agric. Sci.* 17 137–151

Prasada R 1951 Rusts on wild grasses; *Curr. Sci.* 20 243

Prasada R 1960 Fight the wheat rust; *Indian Phytopath.* 13 1–5


Roelfs A P, Dirks V P and Romig R W 1968 A comparison of rod and slide samplers used in cereal rust epidemiology; *Phytopathology* 58 1150–1154
Roels A P, Rowell J B and Romig R W 1970 Sampler for monitoring cereal rust uredospores in rain; Phytopathology 60 187-188
Rowell J B, Olien C R and Wilcoxson R D 1958 Effect of certain environmental conditions on infection of wheat by Puccinia graminis; Phytopathology 48 371-377
Sahni M L and Prasad D 1963 A study on the environmental conditions influencing the development of the three rusts of wheat in the neighborhood of Delhi. Incidence of wheat rusts in relation to initial spore showers and weather condition; Indian Phytopath. 16 285–294
Sharma S K, Singh S and Goel L B 1973 Note on a new record of Sonalika infecting race of yellow rust in India and sources of its resistance; Indian J. agric. Sci. 43 964–965
Sleeman W H 1839 Extracts Major Sleeman's diary; Trans. Agric. Hortc. Soc. India 6 79–87
Srivastava K D, Joshi L M and Nagarajan S 1984a An assessment of leaf rust in multiline population of wheat; Indian Phytopath. 37 306–311
Stamkan E C and Harrar J G 1957 Principles of Plant Pathology; (New York: Ronald Press Co) pp 581
Swaminathan M S 1978 Wheat revolution the next phase; Indian Fmg 27 7–17
Vasudeva R S, Joshi L M and Lele V C 1953 Susceptibility of some grasses to cereal rusts; Indian Phytopath. 6 39–46
Zadoks J C 1959 On the formation of physiologic races in plant parasite; Euphytica 8 104–116