Hindawi
Advances in Agriculture
Volume 2019, Article ID 2673706, 7 pages
https://doi.org/10.1155/2019/2673706

Review Article

Description of Wheat Rusts and Their Virulence Variations Determined through Annual Pathotype Surveys and Controlled Multi-Pathotype Tests

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Received 1 July 2019; Accepted 17 October 2019; Published 6 December 2019

Academic Editor: Innocenzo Muzzalupo

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Wheat production started in Australia around 1788 using early maturing varieties adapted to Australian conditions that were able to escape diseases as well as moisture stress conditions. Wheat production is concentrated on mainland Australia in a narrow crescent land considered as the wheat belt occupying an area of about 13.9 million hectares. Rusts are the most important production constraints to wheat production in the world and Australia causing significant yield losses and decreased the qualities of grains. Wheat is affected by three different types of rust diseases: leaf rust, stripe rust or yellow rust, and stem rust. Each species of the rust pathogen has many races or pathotypes that parasitize only on certain varieties of host species, which can only be traced and identified by differential cultivars. Pathotype surveillance is the basis for information on the virulence or pathogenic variations existing in a particular country or wheat growing region of the world. Studies in pathotype variation are conducted in controlled environments using multi-pathotype tests. The currently cultivated commercial wheat varieties of Australia possess leaf rust resistant genes: *Lr1, Lr3a, Lr13, Lr13+, Lr14a, Lr17a, Lr17b, Lr20, Lr23, Lr24, Lr26, Lr27, Lr31, Lr34, Lr37*, and *Lr46*; stem rust resistance genes: *Sr2, Sr5, Sr8a, Sr8b, Sr9b, Sr9g, Sr11, Sr12, Sr13, Sr15, Sr17, Sr22, Sr24, Sr26, Sr30, Sr36, Sr38*, and *Sr57*; and stripe rust resistance genes: *Yr4, Yr9, Yr17, Yr18, Yr27*, and *Yr33*. This paper discusses the historical and current significance of rusts to wheat production in the world with particular reference to Australia viz-a-viz detail description of each of the three rusts and their respective virulence variations through the resistance genes deployed in the commercial cultivars.

1. Introduction

Wheat is one of the major cereal crops in the world in terms of area of cultivation and quantity of grain produced [1]. In 2014/15 cropping season, 729.1 million metric tons of wheat were produced in the world, and the major producing countries were China, India, USA, Russia, France, Canada, Germany, Pakistan, and Australia in that order [2]. Wheat is a major staple food for 35% of the world's population [3]. Due to the rising population of the world, global wheat production must increase by 2% annually until 2020 to offset the food shortage [4].

Majority (over 90%) of the wheat production in the world comes from bread wheat (*T. aestivum*) that is used mainly as flour for the making of a large variety of leavened and flat breads, and for the manufacture of various baking products. The remaining (<10%) is mainly durum wheat (*T. durum*), which is utilized to manufacture pasta and macaroni [5].

The ideal place for wheat growth and development lies between latitudes 30°N and 60°N, and 27°S and 40°S, however, it is being successfully growing beyond these limits up to 67°N and 45°S; and close to the equator in tropical highlands of East Africa, Central America, and Latin America [6] as rain fed crop (in ME2) and even in hot and dry lowlands using irrigation [7].

1.1. Wheat Production and Utilization in Australia. Wheat production started in Australia in 1788 during the colonial era using late maturing European cultivars that failed to adapt due to the summer heat and drought conditions prevailing in the country. However, William Farer (1845–1906) developed early maturing wheat varieties adapted to Australian conditions that were able to escape diseases as well as moisture stress conditions [8].

Wheat production is concentrated on mainland Australia in a narrow crescent land considered as *the wheat belt*

occupying an area of about 13.9 million hectares [9]. The wheat belt stretches in a curve from central Queensland through New South Wales, Victoria, and southern South Australia. In Western Australia, the wheat belt stays around the south–west of the state and some way north, along the western edge of the continent [9, 10].

In 2014 cropping season, Australia was the ninth largest producer and the fourth top exporter of wheat in the world with annual production of 25.3 million metric tons [2]. In Australia, bread wheat is mainly considered as "soft wheat" and extensively used for breads, cakes, biscuits, and fermented to make beer, vodka, and biofuels. The most commonly cultivated cultivars are Janz, Westonia, Kukri, and Frame [11]. Durum wheat varieties of Australia are considered as "hard wheat" and are mostly used for pasta and noodle production. The current Australian best durum varieties such as Kamilaroi, Wollaroi, Yallaroi, and EGA Bellaroi are known for their resistance against stem, leaf, and stripe rusts [12].

1.2. Wheat Rusts. Wheat, however, is prone to both biotic and abiotic stress that cause significant yield losses. Among the biotic stresses, diseases are the most important production constraints to wheat. It is attacked by 40 fungal, 32 viral, and 81 bacterial diseases [13]. Among the fungal diseases of wheat, rusts are economically the most important diseases. Rusts of wheat might be the oldest plant parasites (pathogens) as evidenced by the excavations of urediniospores of stem rust in Israel that dated back 1300BC and were reported as serious diseases of cereals in Italy and Greece more than 2000 years ago [14–16]. The occurrence of widespread epidemics of wheat rusts at the beginning of the 20th century initiated the need for in-depth studies in genetics of disease resistance in plants, life cycle of plant pathogens, and genetics of host-parasite interactions [15, 17].

Rust diseases of plants are generally caused by fungi pathogens of phylum Basidiomycota, class Urediniomycetes, order Uredinales, family Pucciniaceae, genus *Puccinia* [18]. The rust fungi attack mostly leaves and stems of specific genera or even some of the varieties of a species. Those fungal pathogen species, which are morphologically identical but attack different host genera, are known as special forms (formae speciales). Several special forms or species of *Puccinia* cause rust disease to all the species of grasses [19]. Further, each formae speciales has many races (also called: physiological races, pathotypes, or infection types) that parasitize only on certain varieties of host species, which can only be traced and identified by differential cultivars [15, 16, 19].

Rust diseases are still the major threats of wheat plant causing significant yield losses and decreased qualities of grains [17, 19, 20–22]. In particular, the emergence of the new race of stem rust of wheat (*Ug99*) has brought a major anxiety in world wheat production.

2. Descriptions of Wheat Rusts

Wheat is affected by three different types of rust diseases; leaf rust (caused by *P. triticina* Eriks), stripe rust or yellow rust (caused by *P. striiformis* Westend. f. sp. *tritici Eriks*), and stem rust (caused by *P. graminis* Pers:Pers. f. sp. *tritici Eriks*) [16, 20, 23]. A brief account of each disease follows.

2.1. Leaf Rust of Wheat. Leaf rust or brown rust is the most common and widespread rust of wheat across the world [16, 17]. It attacks mostly the leaf blades, and under more favorable conditions can also attack leaf sheaths and glumes [16, 24].

The causal agent (*P. triticina*) is an obligate parasite, which has the capacity to create infectious urediniospores only on live leaf tissues. It has primary (telial or uredinal) and secondary (pycnial or aecial) hosts to complete its full life cycle. The known primary hosts are bread wheat, durum wheat, cultivated, and wild emmer wheat, *Ae. speltoides, Ae. cylindrica,* and triticale; and the secondary or alternate hosts are *Thalictrum speciosissimum* and *Isopyrum fumaroides* [18]. The urediniospores, once produced can be widely spread by wind and contaminate host plants found several miles away that will ultimately result in rust epidemics across countries and even continents [16, 18].

2.1.1. Geographical Distribution of Leaf Rust. Wheat leaf rust is more frequent in almost all global regions than stem rust or stripe rusts of wheat [18]. Leaf rust is a major concern in North Africa, Asia (central, south and southeast), Europe, North and south Americas, Australia, and New Zealand [16, 17]. Depending on the direction of wind spread of urediniospores in each cropping year, wheat growing areas of the world were clustered in to 9 epidemiological regions: Mexico, Canada, and the USA, South Asia, West Asia, Eastern Europe, and Egypt; Southern Africa; Northern Africa and Western Europe; the Far East; Southeast Asia; South America; and Australia–New Zealand [24, 25].

2.1.2. Economic Importance. The importance of leaf rust was highlighted when it attacked the wheat variety "Thatcher" in 1938 and destroyed millions of hectares of wheat farms across North America. Since then leaf rust was considered as a harshly damaging disease on partial wheat growing areas of USA, former USSR, and China [26]. Modern wheat cultivars still continue to be affected by this disease worldwide. CIMMYT [27] has anticipated a 1 : 27 ratio of cost-to-benefit analysis for leaf rust resistant cultivar development [17]. The disease causes grain yield loss mainly by reducing the number and weight of wheat kernels [24].

In the US, wheat yield losses due to leaf rust were estimated at $350 million between 2000 and 2004 crop seasons; in Mexico, $32 million from 2000 to 2003, and again from 2008 to 2009, $40 million. In South America (Argentina, Brazil, Chile, Paraguay, and Uruguay) between 1996 and 2003, the yield loss amounted to $172 million; leaf rust causes average annual yield loss of about 3 million ton in China, whereas in Pakistan in 1978 crop season alone severe leaf rust epidemics caused 10% yield loss, estimated at $86 million. In Australia, the annual potential yield losses due to leaf rust are estimated at AUD$197 million if susceptible cultivars are grown, the use of resistant cultivars minimized the loss to about AUD$12 million [24, 25, 28].

2.1.3. Life Cycle of Wheat Leaf Rust. The leaf rust causing pathogen, *Puccinia triticina* is a macrocyclic and heteroecious

fungal species that has five distinct spore phases [17, 29] entailing genetically distant different host species. Under suitable environmental conditions (about 10–25°C and availability of free water on the leaf surface), the wheat plant produces dark brown, two-celled teliospores [17, 18, 30]. The teliospores sprout to yield haploid basidiospores on the wheat leaf tissue. Then the basidiospores are moved by wind and infect the alternate host to develop haploid pycnia in the pycnial structures [17, 18].

Consequently, the pycniospores are carried by insects to other pycnial infections whereby sexual propagation between two genetically dissimilar cells (opposite mating types) takes place, which results in the formation of plasmogamy [29]. Finally, the aecial cups release aeciospores that will be broadcasted by wind to infect wheat. The sexual phase of *P. triticina* facilitates exchange of genetic material among physiological races and possibly populations, however, it makes minimal contribution to the direct inoculum source of *P. triticina* to wheat species [17, 30] as the alternate hosts do not exist in most wheat growing regions of the world.

2.2. Stem Rust of Wheat. Across the world, black rust or stem rust has been one of the most devastating diseases of cereal crops known to cause famines, and economic as well as political crises particularly in south Asia that led to the inception of the Green Revolution [25]. Stem rust incidence has been significantly reduced by eliminating its alternate host (barberry species) particularly in North America and Western Europe, which assisted in reducing early infection of the wheat plant. Distribution of semidwarf, high yielding, and stem rust resistant varieties further controlled the adverse effect of the disease [25]. Moreover, the use of CIMMYT derived varieties of wheat triple rust resistant genes (*Lr26, Yr9, Sr31*, and *Pm8*) seemed to wiped out stem rust epidemics by 1990s [25].

However, the detection of a virulent race named *Ug99* in Kalengyere Research station, Uganda [31] signaled the return of this devastating disease after about 50 years of successful control [25]. To date, seven variants of *Ug99* are known to be distributed to many wheat-growing countries in the eastern African highlands, Zimbabwe, South Africa, Sudan, Yemen, and Iran. The *Ug99* race is considered as precarious to the world wheat production as 90% of commercial cultivars have succumbed to it [22].

Stem rust is caused by the fungus *P. graminis* f. sp. *tritici*, which is heteroecious, alternating between a telial host in the Gramineae and an aecial host in the Berberidaceae families of plants. Like all rust fungal species, it is macrocyclic with five spore stages that have specific functions and distinct morphology [17]. Stem rust parasitizes mainly on the surface of the leaf and stem, and can attack even the leaf sheaths, spikes, glumes, awns, and grains in susceptible cultivars [16]. It usually causes damage to the above ground parts of the wheat plant, and contaminated plants frequently produce smaller number of tillers and fewer kernels per spike, and the kernels become inferior in size, usually shrunken, and of reduced milling and food quality [19]. According to Roelfs et al. [16], the spores of stem rust can germinate from 2°C as the minimum temperature, while the optimum and maximum temperatures are 15–24°C, and 30°C. Formation of spores starts from 5°C, however, sporulation optimizes at 30°C, and can occur up to 40°C as the maximum temperature.

2.2.1. Geographical Distribution of Stem Rust. Historically, stem rust was the major threat to the wheat crop to all parts of the world before the use of resistant cultivars. However, currently it is a major concern in East African highlands, and has only minor importance in North America, Europe and Asia. It is only locally important in North and South Africa, Far East and West Asia, Australia, and New Zealand, and South America [16].

2.2.2. Economic Importance. In the first half of the 20th century, stem rust damaged 20% of America's wheat produce in a cyclic epidemics occurred between 1920 and 1960s. In Scandinavian countries, in the 1951 cropping season, yield loss ranged from 9% to 33% was recorded; in eastern and central Europe 5–20% loss was exhibited in the 1932 crop season [25]. Severe rust epidemics were reported in northern China and Inner Mongolia in the 1948, 1951, 1952, and 1956 cropping seasons where spring wheat is extensively grown [25]. In Australia, intermittent epidemics of stem rust caused losses of £2-3million in 1889, £400,000 in 1903, £2million in 1916, £7million in 1947, and the most severe loss occurred in New South Wales that costed $200–300million in 1973 alone which led to the establishment of the National Rust Control Program [32]. A recent study [33] estimated global annual yield losses of wheat due to stem rust could reach 6.2 million tons, which is equivalent to $1.12 billion.

2.2.3. Life Cycle of Wheat Stem Rust. Bread and durum wheat, barley, and triticale are considered as the primary hosts among crop species for *Puccinia graminis* f. sp. *tritici*. Many species of the genera *Berberis* and *Mahonia* are known to be vulnerable to stem rust; however, *Berberis vulgaris* (common barberry) is the most important aecial host [25].

In the maturing host crop plant, teliospores (dikaryotic cells) fuse their nuclei and start to germinate and undergo meiotic cell division that gives rise to single celled, hyaline haploid basidiospores. Then, the basidiospores carried by wind will land on the upper leaf surface of alternate host plants species and cause infection. Consequently, haploid single celled pycniospores and receptive hyphae are produced by the flask shaped pycnia that function as two opposite gametes. Fusion of the pycniospores and receptive hyphae (fertilization) results in the formation of dikaryotic hyphae, which eventually develop into aecia in the underside of the leaf area [17].

The aecia yield aeciospores that will be taken by wind to infect only the telial hosts (wheat, barley, and triticale) to develop uredinia that eventually start to develop urediniospores for several weeks after infection. Finally, when the crop reaches close to maturity stage, teliospores are produced [17].

2.3. Stripe Rust of Wheat. *Puccinia striiformis* f. sp. *tritici*, a causal agent of stripe rust of wheat, has a potential to be equally destructive as stem rust of wheat, though its low temperature requirement restricts its widespread attack across all wheat growing regions of the world [16, 17, 34]. Nonetheless, past evidence confirmed that stripe rust epidemics could be an important threat to the major wheat growing areas of the world

such as China, USA, Southern Asia, and Northern Europe [34, 35].

The disease infects the wheat plant at any of the growth stages starting from a single leaf stage up to maturity as long as the plant is green and causes chlorotic spots that produce yellow coloured stripes of uredinia [17, 34]. The uredinia of stripe rust are smaller in size than uredinia of both stem and leaf rusts, and they grow mostly in the upper surface of the leaf. To some extent particularly in susceptible plants, they can parasitize on the lower surface of the leaf, leaf sheaths, glumes, awns, and even on immature green kernels [17, 34]. The uredinial spores can germinate on the surface of the leaf with minimum requirement of 3 hours dew formation and 0°C as the minimum, 10–12°C the optimum, and 20°C maximum temperature [17, 34].

Stripe rust causes loss of quality and yield of grain by reducing the size, number, and weight of kernels per spike [34, 35]. It also reduces the amount of dry matter of the plant by decreasing plant height, root growth, size, and number of flowering spikes [34, 35]. Moreover, seeds obtained from stripe rust attacked plants show reduced plant vigour and poor emergence [36]. In Australia, stripe rust pathogen was first spotted in New South Wales in 1979, and occurred every season making subsequent mutations as a means of adaptation to the warm temperatures prevalent in the country [37]. A recent introduction of a new pathotype in Western Australia in 2003 and its successive spread to eastern Australia modified the pathogen population of stripe rust to be dominated by the new race, which necessitated the use of fungicides to control it in commercial wheat varieties [37].

2.3.1. Geographical Distribution of Stripe Rust. According to Wellings [35], the major wheat growing regions of the world in which stripe rust is currently causing significant damage in: East Asia (China north-west and southwest), the USA (particularly Pacific North West), South Asia (India, Pakistan, and Nepal), the Arabian Peninsula (Yemen) and Western Europe (East England), Oceania (Australia, New Zealand), and East Africa (Ethiopia, Kenya). Carver [17] also indicated that the importance of stripe rust has been reported from over 60 countries in the world representing all continents except Antarctica and has caused significant yield losses.

2.3.2. Economic Importance. Chen [35] reported 100% yield losses in an experiment station near Mount Vernon, Washington on susceptible cultivars such as PS 279. Depending on the vulnerability of the cultivar, earliness of the initial infection, and degree of disease progress, yield losses due to stripe rust could range from 10% to 70%. In USA, stripe rust caused significant damage in four cycles from 1958 up to 2005 (1958–1961, 1974–1978, 1980–1984, and 1999–2005) of which the highest record occurred in 2003 and was estimated at $300million. In South Africa, it caused $2.25million loss in 1998 which is after two years of its introduction. In 2002 China incurred a loss of 1.3 million tons of wheat grain due to stripe rust. Central Asian countries (part of former USSR) incurred a 20–40% yield loss between 1990s and early 2000s [35]. Australia has also experienced an epidemic of stripe rust damage that caused a loss amounting to AUD$40 million in the 2003 cropping season alone [36].

2.3.3. Life Cycle of Wheat Stripe Rust. Until 2010, it was believed that *P. striiformis* f. sp. *tritici* has only dikaryotic uredial and telial stages as there were no known alternate hosts [36]. However, Jin et al. [38] identified *Berberis* spp. as the alternate host of stripe rust,they demonstrated that *B. chinensis, B. holstii, B. koreana*, and *B. vulgaris* were able to produce pycnia and aecia after being inoculated with germinating telia of *P. striiformis* f. sp. *tritici*, the wheat plant infected by aeciospores from *B. chinensis* produced uredinia, which confirmed that *Berberis* spp. can serve as alternate host for stripe rust.

3. Virulence Variations of Wheat Rust Diseases

The discovery of physiological races in wheat stem rust pathogen *P. graminis* f. sp. *tritici* by Stakman and coresearchers in USA paved the way for many countries (such as USA, Canada, France, and Australia) to establish an annual pathotype surveillance program [15, 39]. Pathotype surveillance is the basis for information on the virulence or pathogenic variations, particularly in regions or countries which have actual knowledge of the resistance genes deployed in the commercial cultivars [39]. However, the major goal of pathotype surveillance is to keep track on the occurrence of new virulent cereal rust pathotypes and control the same before it cause damage to the cereal industry [29]. Studies in pathotype variation are conducted in controlled environments using definite groups of host genotypes inoculated with pathogen isolates of interest [37]. Each race of rust is identified depending on the qualitative infection type score of the isolate on each differential line that is categorized as avirulent or virulent [29].

3.1. Virulence Variation of Leaf Rust of Wheat in Australia. The continual use of race specific leaf rust resistance genes triggered high degree of genetic variation in *P. triticina* population through mutation particularly in North America since large populations of susceptible winter wheat cultivars are grown frequently [17]. In the early 1920s and 1930s, the variation in the cereal rust fungi was usually assessed by testing the different pathotypes (isolates) on the wheat varieties that possess different types and numbers of resistant genes [29]. Following Flor's conception of the gene-for-gene hypothesis and better understanding of rust resistance genetics in wheat, about 20 near isogenic lines of "Thatcher" wheat variety, each containing known single leaf rust resistant genes, were developed to assess the virulence variations of leaf rust [17]. To date, about 79 leaf rust resistance genes of wheat are recognized with known chromosomal location, of which *Lr12, Lr13, Lr22a, Lr34, Lr35, Lr37, Lr46, Lr48, Lr49, Lr67, Lr68, Lr74, Lr75, Lr77*, and *Lr78* are adult plant resistant (slow rusting) genes [17, 29, 40–45].

In Australia, leaf rust of wheat is common in every wheat growing region of the country and may cause significant yield losses if susceptible cultivars are used for production [46]. Initially leaf rust was important in Queensland and New South Wales, and it was controlled using resistant cultivars. However, irregular incidences of the disease were observed from 1990 to 2000 in Western Australia and in 1999 in the Southern Australia and Victoria States [46]. Commercial wheat varieties

of Australia possess the following resistant genes: *Lr1, Lr3a, Lr13, Lr13+, Lr14a, Lr17a, Lr17b, Lr20, Lr23, Lr24, Lr26, Lr27, Lr31, Lr34, Lr37*, and *Lr46* mostly in combination (2 or 3 genes) and significant number of cultivars possess *Lr34* [47]. The corresponding virulent genes of the pathogen were also detected in the pathogen population for the series of cultivars released [46]. The dominant pathotype population of Australian wheat leaf rust is 104-2,3,(6),(7),11 first detected in 1984 in Victoria, since then it undergoes a dozen of single step mutations to produce its clonal lineages, and the other less frequent pathotype with only three clonal lineages is 122-1,(2),3,(6),(7),11 [48].

3.2. Virulence Variation of Stem Rust of Wheat in Australia. Annual pathogenicity surveys of *P. graminis* f. sp. *tritici* began in 1919 both in USA and Australia using 12 cultivars: i.e. four from bread wheat (Little Club, Marquis, Kanred and Kota); five from durum cultivars (Arnautka, Speltz Marz, Mindum, Kubanka, and Acme); two from emmer wheat ("White Spring" and "Khapli"); and one diploid einkorn wheat cultivar [17, 32]. However, it was later revealed that these widely adapted stem rust differential sets were not useful for practical breeding application as they possessed more than one resistant gene and hence, were replaced by single gene containing differentials [15]. Currently, about 15 single resistant genes containing differentials (*Sr5, Sr6, Sr7b, Sr8a, Sr9a, Sr9b, Sr9d, Sr9e, Sr9g, Sr10, Sr11, Sr17, Sr21, Sr30, Sr36*, and *SrTmp*) are being used for pathotype test analyses in North America [17], however, a greater number of differential sets are used in Australia since new strains of some races were generated due to step wise mutations [25, 32].

The stem rust population of Australia were intermingled with exotic introductions of new pathotypes designated as race 126, race 21 and races 194, and 326, which were introduced in 1925, 1954, and 1969, respectively [32]. In order to reduce or avoid the significant yield losses caused by *Puccinia graminis* f. sp *tritici*, cultivars containing multiple resistant genes were released and as a result the overall inoculum of stem rust population and pathogen diversity reduced across the wheat growing regions of Australia [32].

Australian Commercial wheat varieties possess about 17 stem rust resistant genes *Sr2, Sr5, Sr8a, Sr8b, Sr9b, Sr9g, Sr11, Sr12, Sr13, Sr15, Sr17, Sr22, Sr24, Sr26, Sr30, Sr36, Sr38*, and *Sr57* singly or mostly in combination of 2 , 3 or 4 genes where the APR genes *Sr2* and *Sr57* are more frequent [23, 32, 47]. About 12 pathotypes of stem rust have been identified in Australia through annual pathogenicity surveys, which are supposed to be mutational derivatives of the pathotype 326-1,2,3,5,6 [32]. So far, over 59 stem rust resistance genes have been recognized with their respective chromosomal locations among which, *Sr2, Sr55, Sr56, Sr57*, and *Sr58* are APR genes [15, 49], McIntosh et al. 2017, [50].

3.3. Virulence Variation of Stripe Rust of Wheat in Australia. Pathotypes of *P. striiformis* were first reported in the genera of wheat and grasses in 1923 in North America, and races of *P. striiformis* f. sp. *tritici* specific to wheat cultivars were recognized in 1930 in Europe [36, 51]. Few years later, a set of differential cultivars were developed in Germany and subsequently, an international pathotype survey was initiated [36, 51]. In the 1930s a set of differentials were developed for race identification,the first "world differential sets" include, Chinese 166 (*Yr1*), Lee (*Yr7*), Heines Kolben (*Yr2, Yr6*), Vilmorin23 (*Yr3*), Moro (*Yr10*), Strubes Dickkopf (*YrSD*), and Suwon 92 x Omar (*YrSU*), and the European differentials set includes Hybrid 46 (*Yr4+*), Reichersberg 42 (*Yr7+*), Heines Peko (*Yr2, Yr6+*), Nord Desprez (*Yr3*), Compair (*Yr8,Yr19*), Carstens V (*YrCV*), Spaldings Prolific (*YrSP*), and Heines VII (*Yr2, YrHVII*) [36, 51].

Stripe rust was first noticed in Australia in October 1979 and further expanded to New Zealand in 1980 as a single race [36, 52]. Annual pathotype surveys in Australia started since 1979 [52] using the international (world) differential set [37]. Later additional differential cultivars [Avocet R (*YrA*), Selkirk (*Yr27*), and Trident (*Yr17*)] were developed to accommodate the new mutant races appeared in Australia [37]. A new set of differentials containing single resistance genes (near-isogenic lines) derived from "Avocet susceptible cultivar" were also developed at the Plant Breeding Institute, University of Sydney, which are currently gaining importance worldwide for pathotype surveillance of stripe rust of wheat [51].

Since its first introduction to Australia, the stripe rust pathotype 104 E137A- has undergone several single gene mutations for increased virulence which finally became ancestor of 20 closely associated pathotypes till 2006 [37]. Another exotic introduction of new pathotype designated as 64 E0 A- occurred in 1999, however, it was not important to the commercial agriculture due to its high level of avirulence [37]. The third arrival of a new pathotype designated as 134 E16A+ to Western Australia in 2002 is currently the most important one in commercial wheat production as this pathotype is dominating the stripe rust population in the country,this further gave rise to pathotypes 150 E16A+ and E16A+Yr17+ which become virulent on *Yr10* and *Yr17* genes, respectively [37].

The currently cultivated commercial wheat cultivars of Australia possess only seven stripe rust resistance genes (*Yr4, Yr9, Yr17, Yr18, Yr27*, and *Yr33*) most commonly singly (*Yr17, Yr18* or *Yr29*), significant number of paired genes and few in combination of three or four genes [47]. Up to now over 81 stripe rust resistance genes [52] have been recognized with known chromosomal locations among which, *Yr11, Yr12, Yr13, Yr14, Yr16, Yr18, Yr29, Yr30, Yr36, Yr39* (high temperature), *Yr46, Yr48, Yr49, Yr52, Yr54, Yr58, Yr59, Yr79* (high temperature), and *Yr62, Yr68, Yr71, Yr75, Yr77, Yr78*, and *Yr80* are APR genes, and pyramiding of these APR genes in a cultivar could confer an enhanced level of durable resistance to stripe rust of wheat [9, 54–64].

Conflicts of Interest

The author declares that they have no conflicts of interest regarding the publication of this paper.

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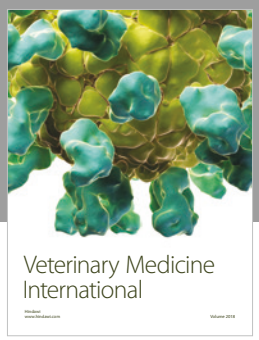

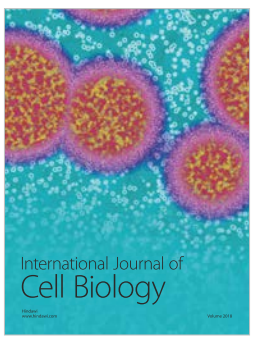

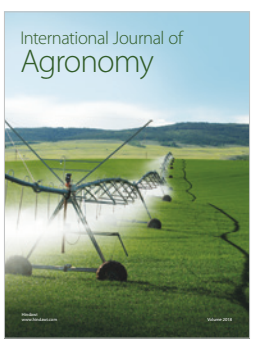

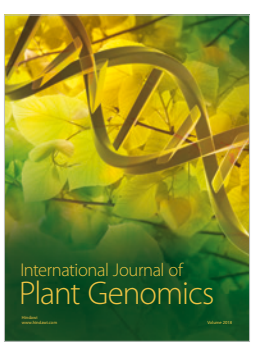

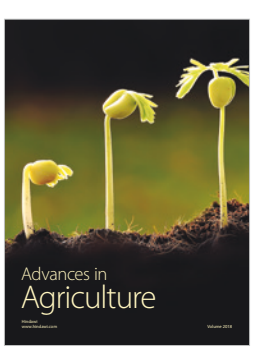

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