



The Rapid Apple Decline Phenomenon: Current Status and Expected Associated Factors in Korea

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Rapid apple decline (RAD) is a complex phenomenon affecting cultivated apple trees and particularly dwarf rootstocks on grafted young apple trees. Since its first appearance in the United States, RAD has been reported worldwide, for example in Canada, South America, Africa, and Asia. The phenomenon has also been observed in apple orchards in Korea, and it presented similar symptoms regardless of apple cultivar and cultivation period. Most previous reports have suggested that RAD may be associated with multiple factors, including plant pathogenic infections, abiotic stresses, environmental conditions, and the susceptibility of trees to cold injury during winter. However, RAD was observed to be more severe and affect more frequently apple trees on the Malling series dwarf rootstock. In this study, we reviewed the current status of RAD worldwide and surveyed biotic and abiotic factors that are potentially closely related to it in Korea.

Keywords : dwarf rootstocks, *Malus domestica*, rapid apple decline

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Apples, which grow in temperate regions, are one of the most important fruits worldwide, both economically and culturally. A total of 62 pathogens capable of infecting the fruit, trunks, and roots of apple trees, have been reported in Korea so far (Korean Society of Plant Pathology, 2023). To prevent economic losses, the Korean apple fungicide spray program was developed by prof. Emeritus Jae-Youl Uhm (Lee et al., 2009). However, due to climate change and newly emerged pathogens, it is difficult to maintain tree vigor and produce high-quality fruit (Das et al., 2020; Kim et al., 2018; Lee et al., 2017, 2021a, 2021b; Park et al., 2018). Recently, it has been shown that apple trees can be affected by unexpected decline, a worldwide phenomenon referred to as rapid apple decline (RAD). It was firstly reported in the United States, but the specific causative agent responsible for it has not been identified yet (Peter, 2018; Rosenberger, 2018; Singh et al., 2019; Stokstad, 2019). Reports have shown that RAD occurs mainly in young trees (2-8 years old) on Malling 9 (M.9) dwarf rootstocks and is characterized by various symptoms, such as stunted growth, pale yellow to reddish leaves, rolled and spindle leaves, peeling bark, necrosis around and above the rootstock-scion graft union, canker, and eventually decline within a weeks after the onset of symptoms (MacDonald et al., 2019; Peter, 2018; Rosenberger, 2018). Another common characteristic observed in affected orchards is the lack of a specific pattern in the distribution of infected trees, which appear to be evenly scattered among the healthy ones across the orchard (Peter, 2018; Singh et al., 2019). Several factors have been associated with RAD, and it is believed that multiple causes may contribute to its occurrence (Rosenberger, 2018; Singh et al., 2019).

Recently, RAD has been observed in apple orchards in Korea regardless of cultivar, cultivation period, or region.

Such a widespread occurrence has led to misdiagnosis and confusion among farmers in regard to its causes. Several studies have been conducted to determine the factors that can be associated with RAD or apple decline more generally (Avalos-Ruiz et al., 2022b; Lee et al., 2016, 2020b, 2021a, 2023). However, due to the complex nature of RAD, it is difficult to establish the causative agents and what triggers this phenomenon. This review aims to summarize the current research into apple decline, including RAD worldwide, and suggest potential causal factors. In addition, the results of a survey conducted in apple orchards in Korea were presented in order to gain a further understanding of RAD.

Current Status of RAD Worldwide and Contributing Factors

RAD has been recently observed and studied in the United States and Canada, and it has similarities with a phenomenon known as quick decline (QD) in Japan (Fujikawa et al., 2019; Peter, 2018; Rosenberger, 2018). Currently, several factors, both biotic and abiotic, have been proposed to cause RAD worldwide (Table 1). Most studies have isolated opportunistic fungal pathogens from trees affected by stem canker, dieback, or decline. However, apple decline cannot be explained by a single factor (such as infection by fungal pathogens), and more studies are being conducted into more complex factors related to this phenomenon,

Table 1. Current status of apple decline, canker, dieback, and associated factors worldwide

No.	Region	Country	Observed symptoms/ Phenomenon	Type of suggested agents	Suggested agent could be associated	Reference
1	North America	USA	Stem canker and dieback	Fungi	<i>Neofusicoccum nonquasitum</i>	Rooney-Latham et al. (2012)
2		USA	Decline	Insects	Ambrosia beetle	Agnello et al. (2017)
3		USA	Sudden apple decline	Complexed factors	Fire blight in the rootstock, herbicide injury, boring insects, winter injury etc.	Rosenberger (2018)
4		USA	Rapid apple decline	Complexed factors	Winter injury, fire blight, <i>Phytophthora</i> spp., fungal pathogens etc.	Peter (2018)
5		USA	Rapid apple decline	Virus	Apple luteovirus 1	Liu et al. (2018)
6		USA	Decline	Virus	Virome analysis (including Apple rubbery wood-associated viruses, Citrus concave gum-associated virus)	Wright et al. (2018)
7		USA	Rapid apple decline	Complexed factors	Biotic and abiotic factors	Singh et al. (2019)
8		Canada	Stem canker and death	Fungi	<i>Diaporthe eres</i>	Ali et al. (2020)
9		USA	Rapid apple decline	Virus	Virome analysis (including Apple ilarvirus, Apple barna-like virus, Apple tombus-like virus, etc.)	Wright et al. (2020)
10		Canada	Stem canker and dieback	Fungi	<i>Botryosphaeria dothidea</i>	Ilyukhin et al. (2022)
11		Canada	Rapid apple decline	Virus	Virome analysis (including Apple ilarvirus 2, Apple rubbery wood virus 1 and 2, Apple luteovirus 1)	Xiao et al. (2022)
12	South America	Uruguay	Stem canker and dieback	Fungi	<i>Botryosphaeria dothidea</i> , <i>Neofusicoccum parvum</i> , <i>N. luteum</i> , <i>N. australe</i> , <i>Diplodia seriata</i> , <i>D. intermedia</i> , <i>D. pseudoseriata</i> , <i>Lasiodiplodia theobromae</i>	Delgado-Cerrone et al. (2016)

(Continued)

Table 1. Continued

No.	Region	Country	Observed symptoms/ Phenomenon	Type of suggested agents	Suggested agent could be associated	Reference
13		Chile	Stem canker and dieback	Fungi	<i>Diplodia</i> spp., <i>Lasiodiplodia</i> , <i>Neofusicoccum</i>	Díaz et al. (2022)
14		Argentina	Stem canker and dieback	Fungi	<i>Diplodia seriata</i> , <i>D. mutila</i> , <i>Dothiorella omnivora</i>	Lódolo et al. (2022)
15	Africa	Tunisia	Dieback	Fungi	<i>Phytophthora</i> spp., <i>Pythium</i> spp.	Souli et al. (2014)
16		Tunisia	Decline	Fungi	<i>Fusarium oxysporum</i> , <i>F. solani</i> , <i>F. equiseti</i> , <i>F. proliferatum</i>	Mannai et al. (2018)
17		Morocco	Decline	Fungi	<i>Phytophthora vexans</i>	Jabiri et al. (2021)
18		Ethiopia	Canker and dieback	Fungi	<i>Didymosphaeria rubi-lulmifolli</i>	Yirgu et al. (2021)
19	Europe/ Asia	Turkey	Stem canker and dieback	Fungi	<i>Neoscytalidium dimidiatum</i>	Ören et al. (2022)
20	Central Asia	Iran	Cytospora canker	Fungi	<i>Cytospora</i> spp.	Mehrabi et al. (2011)
21		Iran	Decline	Fungi	<i>Cytospora chrysosperma</i> , <i>C. germanica</i> , <i>C. paratruncata</i> , <i>C. salicina</i>	Azizi et al. (2020)
22	East Asia	China	Stem canker	Fungi	<i>Cytospora parasitica</i>	Ma et al. (2018)
23		Japan	Quick decline	Bacteria	<i>Dickeya dadantii</i>	Fujikawa et al. (2019)
24		Korea	Dieback	Fungi	<i>Phytophthora</i> sp., <i>Helicobasidium mompa</i> , <i>Rosellinia necatrix</i>	Lee et al. (2020b)
25		Korea	Decline	Fungi	<i>Botryosphaeria sinensis</i>	Lee et al. (2021a)
26		China	Stem canker and dieback	Fungi	<i>Diplodia mutila</i>	Sha et al. (2022)
27		China	Dieback	Fungi	<i>Fusarium tricinctum</i>	Zhang et al. (2022)
28		Korea	Cold injury	Fungi	<i>Fusarium tricinctum</i> (ice nucleation active fungi)	Avalos-Ruiz et al. (2022b)
29		Korea	Canker	Bacteria	<i>Pseudomonas syringae</i> pv. <i>syringae</i>	Lee et al. (2023)

such as fungal, bacterial, and viral infections (biotic factors) and extreme cold, insufficient soil moisture, drought, injuries caused by insects or rodents, and water stress (abiotic factors).

Abiotic factors. Environmental stressors, such as extreme temperature fluctuations, drought, or excessive moisture, may play a significant role in RAD development. These stressors can weaken apple trees, making them more susceptible to diseases. The occurrence of RAD could be attributed to variations in abiotic factors, including moisture levels in deteriorating roots, coupled with extreme weather conditions (Singh et al., 2019). In regard to drought stress, apple trees that experience drought in summer are susceptible to the opportunistic fungus *Botryosphaeria dothidea*, which resides in older bark and can potentially infect both

the bark and cambium of water-stressed trees (Rosenberger, 2018). Moreover, trunk damage can manifest on the southwest-facing side of trees during winter due to heating-cooling cycles. Specifically, this occurs when solar radiation, sometimes amplified by reflection on the snow cover, heats the trunks on the southwest-facing sides during the day, and rapid cooling to sub-freezing temperatures follows at night. Factors such as excessive nitrogen fertilizer and drought conditions can make young trees more susceptible to winter damage by stimulating late-season growth (Rosenberger, 2018). Exposure to freezing conditions can lead to frost injuries, weakening trees and making them susceptible to pathogen infection and canker (Kennelly et al., 2007; Sobiczewski and Jones, 1992; Weaver, 1978). Overall, environmental stressors, like extreme temperature fluctuations or drought, can significantly contribute to

RAD development in apple trees. Weakened trees become more vulnerable to diseases and pests, necessitating proper management to maintain tree health and productivity.

Biotic Factors

Bacteria. The plant pathogenic bacteria *Dickeya dadantii* and *Pseudomonas syringae* pv. *syringae* have been reported as the causative agents of apple QD and stem canker (Fujikawa et al., 2019; Lee et al., 2023). Specifically, QD was associated with infection by *D. dadantii* (formerly known as *Erwinia chrysanthemi*), which was isolated from the necrotic tissues and exudates of apple trees growing in some areas of Iwate Prefecture, Japan, and showing acute defoliation, red exudates from the trunk near the ground, and necrosis of leaves and branches (Fujikawa et al., 2019). In contrast, *P. syringae* pv. *syringae* (PSS) was isolated from apple trees affected by canker on the stems in various orchards located in Gyeongbuk province (Yeongju, Yeongyang, Cheongsong, Mungyeong, Andong, and Yechone), Korea (Lee et al., 2023). Interestingly, this pathogen not only causes disease in apple trees but also shows ice nucleation activity (INA), which can induce cold injury (Lee et al., 2023; Lim et al., 2019b).

Viruses. The common latent viruses in apple trees are the Apple stem pitting virus, Apple stem grooving virus, Apple chlorotic leaf spot virus, and Apple mosaic virus (Lee et al., 2020a; Rosenberger, 2018). However, these virus types are generally not directly associated to apple decline (Rosenberger, 2018). Recently, in addition to them, a new virus, known as Apple luteovirus 1 (ALV-1), has been identified in declined trees in the United States (Liu et al., 2018) as well as in Korea, Belgium, and Greece (Fontdevila Pareta et al., 2022; Lim et al., 2019a; Malandraki et al., 2020). Luteoviruses target only the phloem tissue, affecting sieve elements, companion cells, and the phloem parenchyma (Ali et al., 2020). The effects produced on these components are suspected to contribute to apple decline, however, further studies are needed to confirm this hypothesis. Recently, twenty previously described plant viruses and one viroid, as well as a new ilarvirus named Apple ilarvirus 2 (AIV2), have been identified from apple orchards affected by rapid decline in the Okanagan and Similkameen Valleys of British Columbia, Canada (Xiao et al., 2022). Among these viruses, none has been definitively confirmed as the primary causative agent of RAD. Therefore, it is important to conduct further extensive research to clarify the etiology of this disease.

Fungi. Numerous pathogens have been reported to cause stem canker, dieback, or decline in apple trees in several countries worldwide (Table 1). The frequently isolated fungal pathogens that may be associated with RAD belong mostly to genera *Botryosphaeria*, *Diaporthe*, *Diplodia*, *Cytospora*, and *Neofusicoccum*. Various infections have been reported in apple trees, however, the responsible fungi were known to be typical opportunistic pathogens. For this reason, while it is simple to isolate fungal pathogens from declined trees, it remains difficult to conclude that they cannot be major contributors to RAD, except for soil-borne fungal pathogens like *Helicobasidium mompa*, *Phytophthora* spp., *Pythium* spp., *Rosellinia necatrix*, or *Athelia rolfsii*. Recently, *Fusarium tricinctum* has been reported as the causal agent of apple decline in China (Zhang et al., 2022). In addition, studies have shown that the ice nucleation-active *F. tricinctum* and *Fusarium diversisporum* isolated from declined apple trees in Korea may be linked to RAD (Avalos-Ruiz et al., 2022a, 2022b). Thus, further research is needed for a comprehensive understanding of RAD as well as the identification of causal agents, which will contribute to combating this disease worldwide.

Factors Linked to RAD: Cold Stress Accelerated by Ice Nucleation-Active Microorganisms

Ice nucleation is the process by which ice crystals form, and INA refers to the capability of external particles to induce the freezing of water at temperatures higher than approximately -38°C , the freezing point of ultra-pure water (Failor et al., 2021; Kunert et al., 2019). Certain biological particles, including bacteria and fungi, have demonstrated their significance as ice nuclei, facilitating ice formation at temperatures ranging from -15°C to 0°C (Kunert et al., 2019; Lagzian et al., 2014; Pouleur et al., 1992). However, INA can play a role in ice formation within plants, potentially influencing the severity of frost damage. Previous studies have indicated that *Pseudomonas syringae* showed INA, which can cause frost damage to susceptible plants (Lindow et al., 1978). In Korea, PSS WSP007 was isolated from apple stem canker, and draft genomic analysis shed light on its life cycle, revealing that it exhibited INA (Lee et al., 2023; Lim et al., 2019b). At the same time, *Fusarium* strains obtained from declining apple trees in Korea have also been reported to show INA (Avalos-Ruiz et al., 2022a, 2022b). However, our understanding of the specific effects of INA caused by PSS or *Fusarium* species on different apple rootstocks depending on climatic conditions and geographic regions is still limited. Further research is nec-

essary to increase our knowledge of the prevalence and significance of INA in apple orchards and to explore potential strategies for mitigating the detrimental effects of RAD.

Status of RAD in Korea

During the past decades, apple decline has been continuously observed in apple orchards in Korea. A variety of symptoms have been reported, including wilted flower and

leaves, poor growth with small, spindle and curled leaves, yellowing, necrosis of the grafted union, and eventual decline regardless of cultivar or cultivation period (Fig. 1). Until now several fungal pathogens have been shown to affect the vigor of apple trees in Korea, including *Botryosphaeria* spp., *Phytophthora* spp., *Cytospora mali* (= *Valsa mali*), *Diaporthe eres* (= *Phomopsis mali*), *Rosellinia necatrix*, and *Helicobasidium mompa*, among others (Korean Society of Plant Pathology, 2023). Previous studies focused



Fig. 1. Typical symptoms of rapid apple decline (RAD) observed in Korea. (A-C) Wilted flowers and leaves observed on cv. Fuji. (D-F) Poor growth with small, spindle, and curled leaves on cv. Fuji (D, F) and cv. Shinano Gold (E). (G-I) Leaves turning yellow and drooping on cv. Fuji (G, H) and cv. Shinano Gold (I). (J-L) Damaged part observed around the M.9 grafted union.

on isolating and identifying pathogens from declined apple trees. For instance, *Valsa ceratosperma*, *P. mali*, *B. dothidea*, and *R. necatrix* have been identified from diseased apple trees during a survey conducted from 1992 to 2000 in seven regions of Korea (Lee et al., 2006). Other studies isolated *B. sinensis* and *B. kuwatsukai* from apple trees experiencing decline (Lee et al., 2021a; Lim et al., 2023). Based on research conducted in various provinces of Korea, the most prevalent causal agents associated with apple decline symptoms were Phytophthora rot and violet root rot. Rodents, white root rot, and freezing injury were also found to be associated with apple dieback in 27 orchards between 2013 and 2019 (Lee et al., 2016, 2020b).

Between 2020 and 2022, we surveyed RAD-associated fungal pathogens on 91 declined apple trees from 48 orchards across seven Korean provinces. The most predominant infections observed were Botryosphaeria canker (63%) caused by *Botryosphaeria* spp., followed by Phomopsis canker (20%) caused by *Diaporthe eres*, Cytospora canker (9%) caused by *Cytospora mali*, white root rot (6%) caused by *Rosellinia necatrix*, and violet root rot (4%) caused by *Helicobasidium mompa* (data not shown). The findings highlighted the frequent presence of pathogenic fungi, especially *Botryosphaeria* spp., that can be associated with apple decline, which was in line Rosenberger (2018). Moreover, samples with a suspected Phytophthora root rot infection were assessed using the Agdia ImmunoStrip kit for Phytophthora, and 8 out of 27 of them resulted positive to the disease (data not shown). *Phytophthora* spp. are

considered as potentially associated with apple decline but cannot be the sole factor explaining RAD.

Cultivation techniques are important in the cultivation of apple trees. To examine the conditions of apple orchards affected by RAD, we assessed cultivation methods in 112 apple orchards between 2021 and 2022. Specifically, we examined the presence of drainage pipes under the orchards, type of irrigation, presence of beetles, application of white paint on trees, weed control methods, and kinds of rootstocks and apple cultivars (Fig. 2). The results showed that in about 85% of the RAD-affected apple orchards drainage pipes were used, and in 71% of them herbicides were applied to control the weeds under the trees. Extreme cold followed by drought/water stress, or either abiotic factor acting individually, may not have directly caused RAD but may have debilitated the trees and facilitated the proliferation of insects and infection by opportunistic pathogens (Singh et al., 2019). As for the irrigation types, it was found that dropping irrigation and mini-sprinkler irrigation were used in 56% and 44% of apple orchards, respectively, during two consecutive years. Dropping irrigation was slightly more used than mini-sprinkler irrigation; however, these could be hardly considered as direct causes of RAD. The presence of beetles was observed in only 2% of the RAD-affected orchards, and the application of white paint on trees, which is known to prevent cold injuries, showed similar incidence (49% vs. 51%) of RAD. The choice of rootstocks was also found to be important, with the rates of M.9 and M.26 rootstocks being 63% and 36%, respectively, in

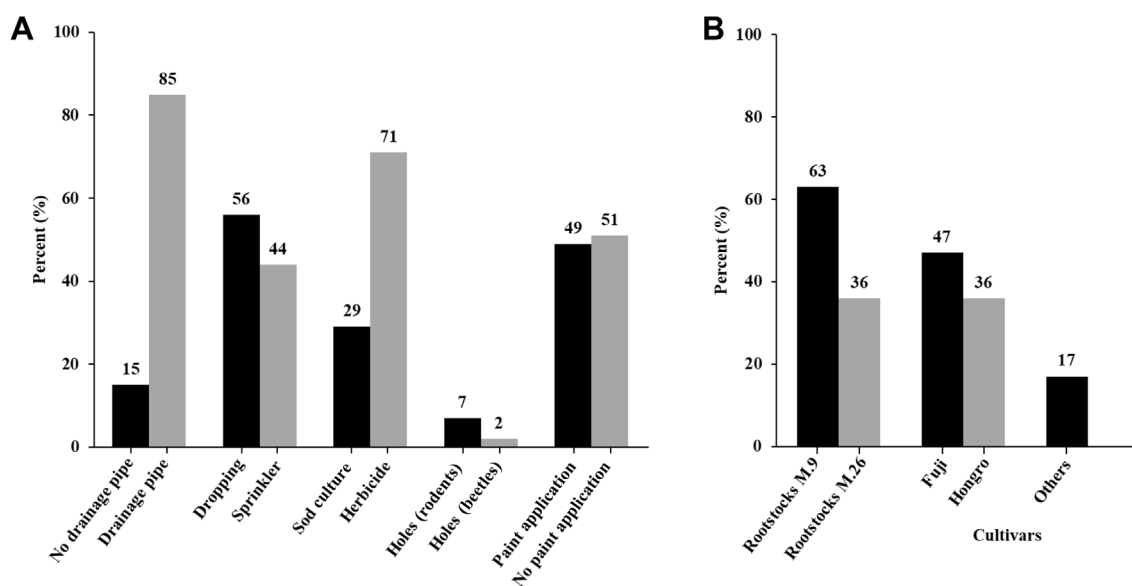


Fig. 2. Screening of abiotic factors in apple orchards between 2021 and 2022. (A) Drainage systems, irrigation type, holes made by rodents, presence of beetles, grass control, and paint application. (B) Rootstocks and commonly used apple cultivars in Korean orchards.

the RAD-affected orchards. RAD was observed regardless of apple cultivar; however, more than 80% of trees belonging to cvs. ‘Fuji’ and ‘Hongro’ were infected, and these are the dominant cultivars used for apple cultivation in Korea. The results here reported suggested that rootstock vigor and tree water use strategies influenced scion stress responses. This implies the need for vigor-specific irrigation management to alleviate stresses and achieve production objectives for various rootstocks (Xu and Ediger, 2021).

Conclusions and Future Perspectives

RAD is a complex syndrome with unclear etiology that poses significant challenges to the apple industry, particularly affecting young apple trees grafted on dwarf rootstocks. While extensive research has shed some light on the factors contributing to RAD, there is still much to be elucidated in relation to its underlying causes, prevention, and management. RAD appears to be influenced by both biotic and abiotic factors, rootstock interactions, and environmental conditions (Fig. 3), whose interplay is likely to contribute to the manifestation and severity of RAD symptoms. It is evident that the combination of different factors can have synergistic effects, exacerbating the decline of apple trees.

Recently, the average winter temperature has been rising not only in Korea but also globally, and the frequency of cold waves has increased (Jeon and Cho, 2015; Laing and Binyamin, 2013). In Korea, dormancy breaking in apple

trees occurs between January and early February (Kweon et al., 2013). After this period, cold injury is likely to affect the trees if they experience a cold wave. At present, the most commonly used rootstocks for apple cultivation are M.9 and M.26, and, in terms of their cold hardiness, M.9 rootstocks are known to be more vulnerable to cold injury than M.26 (Moran et al., 2011; Westwood and Bjornstad, 1981). Therefore, the above-mentioned factors may contribute to the susceptibility of M.9 to RAD and may explain the higher incidence of the disease observed in these rootstocks than in M.26 trees (Fig. 2). Furthermore, INA can be a factor of RAD, highlighting the potential role of ice nucleation-active microorganisms in the decline of apple trees. Research suggests that elevated INA levels may increase the susceptibility to cold injury (Avalos-Ruiz et al., 2022a, 2022b; Lee et al., 2023; Lim et al., 2019b), leading to rapid decline due to infection by opportunistic fungi. However, further research is needed to fully understand the complex interactions between INA and other contributing factors like opportunistic pathogens.

In conclusion, RAD remains a complex syndrome requiring further research efforts to unravel its underlying causes, develop effective management strategies, and mitigate its impact on the apple industry. Collaboration between researchers, growers, and industry stakeholders is essential to address these knowledge gaps and safeguard the sustainability of apple orchards in the face of RAD.

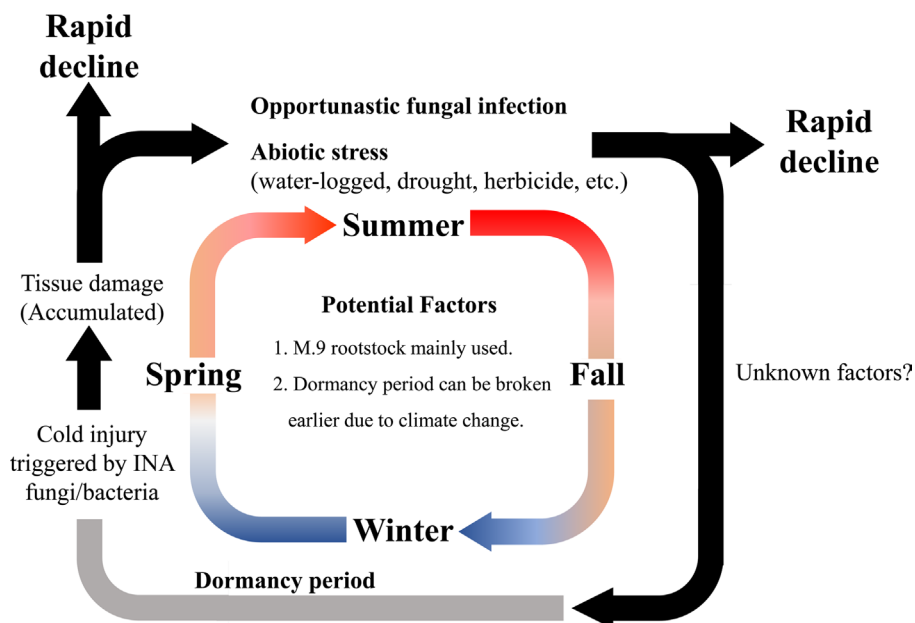


Fig. 3. Schematic diagram of rapid apple decline (RAD)-associated factors including potential links to the syndrome.

Conflicts of Interests

No potential conflict of interest relevant to this article was reported.

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