Imperata cylindrica: reproduction, dispersal, and controls

Muhammad Rusdy*

Address: Laboratory of Forage Crops and Grassland Management, Faculty of Animal Sciences, Hasanuddin University, Makassar 90245, Indonesia.

ORCID information: Muhammad Rusdy (orcid: 0000-0002-2731-9383)

***Correspondence:** Muhammad Rusdy. Email: muhrusdy79@yahoo.co.id

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Abstract

Imperata cylindrica is one of the 10 worst weeds in the tropics and subtropics. Although it has many beneficial uses, the problems related to its invasiveness far outweigh its positive benefits. *I. cylindrica* negatively affects production of annual, perennial, plantation, and forest crops. Its mode of reproduction fosters its extensive growth and very persistent nature because of its high competitive ability in a wide range of habitats. Control efforts for *I. cylindrica* consist of prevention, cultural, mechanical, biological, and integrated approach. All control methods are not cost effective and require careful planning to achieve the desired outcome. Currently, good control can be achieved by integrating cultural, mechanical, and chemical methods, but long term of management control must involve sustainable strategies such as biological control and revegetation practices.

Keywords: *Imperata*, reproduction, dispersal, control

Review methodology: Recently, published literature in Google Scholar, CAB Abstracts, Scopus, PubMed, Crossref, and Web of Science using the keywords *Imperata*, distribution, reproduction, dispersal, and management was searched from March 2019 to January 2020. We also used the synonym and antonym of these words for searching other relevant literature. Of about 200 articles read, we selected 85 for review. We also observed the growth of *Imperata* in the field at different environmental conditions and asked the farmers and colleagues for their knowledge concerning the subject.

Introduction

Imperata cylindrica (hereafter is called *Imperata*) is an aggressive, rhizomatous tropical grass native to southeast Asia, Australia, China, Japan, the Philippines, and the East Africa [1]. It consists of five varieties, that is, var. *major* is found in tropical Asia, var. *africana* is from Africa, var. *europaea* is found in Mediterranean region, var. *condensata* is native to coastal region of Chile/Argentina, and var. *latifolia* occurs in India [2]. Chromosome number varied with variety; 2n = 20 for var. *major*, 2n = 40 for var. *europaea*, and 2n = 60 for var. *africana* [3].

Imperata is widely distributed throughout the tropics and subtropics and has spread to some warm parts of the temperate regions of the world, except Antarctica [4, 5], at altitude from sea level to 2700 m and rainfall from 500 to 5000 mm/year [6]. It is found in wide range of habitats, such as cultivated crops, plantations, deforested areas, abandoned farm lands, and recreational areas, but it mostly invades grassland where slash and burn agriculture are widely practiced [7].

Imperata grasslands are common in Asia; it occupies about 35 million ha, the largest area was occurring in Indonesia (8.5 million ha), followed by India (8 million ha) that occupies both fertile and infertile soils [8]. In the southeastern of USA, this grass has invaded nearly 500,000 ha of land [5].

Imperata can be used for many purposes. In many developing countries, the leaves and stems are widely used as thatch, for making hats, basket, rope, paper; energy sources; and medicinal purposes. It also is used for mulching, livestock bedding, erosion control, and stabilizing slopes. In many parts of the tropics, *Imperata* is commonly used as animal feed. However, its nutritive value is only high when it is young, and productivity of animals grazing on solely *Imperata* stand is commonly low [9].

Although *Imperata* has many beneficial uses, its harmful effects far outweigh its positive attributes. It is generally recognized as a weed, and for this reason, the main emphasis of research has been on its control or eradication [7]. *Imperata* is classified as noxious weed in more than 70 countries [4] due to its ability to successfully disperse, colonize, compete with, and displace desirable vegetation and disrupt ecosystem over a wide range of environmental conditions. It constitutes a significant threat to global diversity and sustainable agriculture [10]. *Imperata* is rated as the world's seventh worst weed [6, 11].

The negative effects of *Imperata* on plantation crops have been reported elsewhere. It retards the growth of plantation crops such as teak, cocoa, coffee, oil palm, cocoa, rubber [6, 12], and *Pinus taeda* [13]. Yields of annual crops are also severely reduced by *Imperata* infestations. Its harmful effects have been documented in upland rice [14], cassava [15], maize [16], soybean [17], and so on. These losses are due to its higher competitive ability for plant growth resources and its allelopathic properties [18, 19].

Besides reducing crop yields, *Imperata* infestation also increases cost of control and decreases market value of tuber crops due to physical injury when rhizome tips penetrate the roots of tuber crops. Because of its inflammability, *Imperata* increases the risk of fire in perennial crops, plantation, and forest plants. Recurrent burning has converted million hectares of tropical forest to *Imperata* dominated grassland [20] and causes considerable losses of organic matter and soil nutrients, which result in soil degradation [21].

Imperata control has been the subject to several reviews [4, 12, 20, 21]. In general, *Imperata* is pernicious weed that is difficult to control, but there have been several recent advances on its control. The objective of this paper was to review the literatures concerning reproduction and dispersal of *Imperata* and examine the latest research efforts to control it.

Reproduction and dispersal

Imperata reproduces sexually by seeds and asexually by living rhizome extension fragment propagation. Seed reproduction enhances long-distance dispersal and colonization, while rhizome extension promotes short distance spread and population expansion [22]. Transportation of rhizome fragments to other places contributes to long-distance dispersal. Rhizomes are the main organ, which enable *Imperata* to be an aggressive and invasive weed. Several characteristics that make this plant extremely invasive are: (1) it can produce up to 3000 seeds per plant; (2) it has very light seeds that can disperse over long distances; and (3) it has very rigorous rhizomes that allow it to survive during adverse environmental conditions and aid its rapid spread within short distances [23].

In the tropics and subtropics, flowering occurs throughout the year after *Imperata* is exposed to stress such as burning, overgrazing, or frequent slashing [21], and these may encourage the spread of the plant. *Imperata* can only produce viable seeds through cross-pollination [24]. It is a prolific seed producer, one panicle can produce about 700 [25] to 3000 seeds per plant [6]. Seeds have no dormancy and can remain viable for over 1 year [26]. They spread by wind, animals, and agricultural equipment. The seeds are small and light, with long and hairy plumes, aiding long wind dispersal. The wind can disperse the spikelet up to 110 m from the parent plant [27]. Because seeds lack dormancy, suitable site conditions during the period of early seedling establishment are critical for successful dispersal. Seedlings tend to emerge in groups and establish best in open with high-nutrient soils [28] and in tilled and well-drained soils. Because it needs well-drained soil, *Imperata* dispersal by seeds may be limited by excessive moisture during the rainy season [29]. In general, seedling mortality is high, with only about 20% of emergent surviving to produce healthy seedling [27].

For established populations, asexual reproduction by rhizomes is the main method of plant propagation. Rhizomes are whitish in color, branched, scaly, and sharp at the tips, which enable the plant to perforate underground parts of other plants. These organs contain 2,4-di-tert-butylphenol, isoeugenol, and 4-acetyl-2-methoxyphenol, which play an important role in the invasiveness of this plant [30]. The ecological resiliency of *Imperata* and its ability to regenerate from man-made or natural disturbance is primarily due to its well-protected rhizome network. Seeds and rhizome fragments are easily dispersed by people through road construction, trade, and soil movement [31].

Rhizomes are normally concentrated in the upper 15–20 cm of soil where they can remain dormant but viable for a long time [32]. Compared with most nonrhizomatous plants, *Imperata* has high root rhizome to shoot ratios. The belowground biomass of *Imperata* on average was seven times higher than many other native species [33]. *Imperata* rhizomes can comprise more than 60% of the total plant biomass [34]. A high root rhizome to shoot ratio provides a substantial amount of nutrients needed for growth and regrowth of the plant following the slashing, tillage, and other human disturbances. *Imperata* can produce average 16 ton/ha dry matter and rhizomes contributing 56% of this [16]. Rhizomes are resistant to heat and breakage and can penetrate soil up to 1.2 m deep but generally can only reach up to 0.15 m in heavy clay soil and up to 0.40 m in sandy soils [35]. Because of its high belowground biomasses, *Imperata* can retain more N per hectare than native vegetation [33]. Rhizomes have millions of buds with the potential to reestablish the plant after surviving adverse growing conditions.

Rhizomes have a high regenerative ability due to numerous buds that are readily sprouted into new shoots after fragmentation by soil disturbance [21]. The lateral buds can remain dormant for long period and give *Imperata* a perennating habit. Regrowth ability increased with rhizome age, weight [36], and length. Longer rhizomes have a better chance of sprouting because they have more carbohydrate reserves than short fragments [32]. Mature buds near the rhizome apex are the first to sprout when rhizomes are fragmented from the parent plant. *Imperata* does not produce axillary buds along most of the rhizomes nor regenerate when the apical six-node-long rhizome segments are buried deeper than 8 cm [37].

To control *Imperata*, it is important to reduce the number of viable buds and prevent them forming a new shoot. Bud germination of rhizomes is favored by dry season, light, and oxygen and decreases with increasing depth of burial [32]. The rhizome extends in the soil by means of expansion of intercalary meristems between nodes. A single *Imperata* plant at 24 weeks of age was found to have 2.34 m of rhizome length [38].

Rhizome fragments can spread when they attached to agricultural equipment or transportation of soil containing rhizome fragments [39]. *Imperata* is tolerant to wide range of soil conditions, including variations in soil fertility, organic matter, and moisture content but appears to grow best in the acid soil. Once established, *Imperata* will continue to persist even when there is environmental stress such as drought, flooding, or fire. *Imperata* can persist because many other plant species have difficulty competing with this plant for water, nutrients, and light [40].

Controls

Prevention

The most effective and efficient method of *Imperata* control is to prevent its spread. Preventing the introduction of *Imperata* into new area should be given priority, but as *Imperata* is so widespread, this may impossibly conducted in many instances. Uninvaded places should be periodically surveyed to detect a new invasion. Sanitation of the equipment that may be contaminated with by seed or rhizome fragments is necessary. If prevention is no longer possible, early detection and eradication are very important. A young infestation is much easier to control and eradicate than established infestation.

Cultural control

Imperata has C_4 pathway of CO_2 fixation, and therefore, it is intolerant to shade and usually dies when subjected to shade for a long time [21, 41]; however, it can also thrive under moderate shade conditions [22]. Shading on *Imperata* results in reduced carbohydrate storage, rhizome, and shoot dry weight; increased susceptibility to competition and herbicides; and decreased vigor and rhizome to shoot ratio [42]. Moosavi-Nia and Dore [43] found that increasing shade levels to more than 50% reduced both rhizome length and dry weight and increased shoot to rhizome ratios. Lojka *et al.* [41] noted that aboveground and belowground biomass of *Imperata* decreased by 9.6% and 78%, respectively, by shading at light intensity of 15,000 lux for 6 months. Hairiah *et al.* [40] reported that ability of rhizomes to resprout after shoots has been slashed declined when the slashed stand was subjected to 88% shade for more than 2 months.

Leaf area increased with shading, the plants grown in 11% full light had leaf area ratios about 2.5 times greater than those grown in full light. Reduction in dry matter production with shading is due to significant reductions in both net assimilation rate and leaf area duration or total amount of leaf area produced [44].

Herbaceous cover crops of the genera *Calopogonium*, *Crotalaria*, *Mucuna,* and *Pueraria* can effectively suppress *Imperata* growth and can be used to prevent and in some cases eradicate the plant. Fast growing tree legume species such as *Sesbania sesban*, *Acacia nilotica* and *Leucaena leucocephala* can improve soil fertility and suppress *Imperata* growth [42]. However, *Imperata* control methods based on cover crop, shade shrubs, or trees need a long time to give effective results. In Nigeria, *Mucuna pruriens* requires nearly 2 years to eliminate rhizomes of *Imperata*. Rhizome dry matter was reduced to zero after 97 weeks in velvet bean (*Mucuna pruriens*) plots and 105 weeks in tropical kudzu (*Pueraria phaseoloides*) plots [45]. Also in Nigeria, Anoka *et al*. [46] reported that shading by uncut *Leucaena leucocephala* and *Gliricidia sepium* hedgerows for 10 months only reduced density of *Imperata* by 51% and 67% and shoot biomass by 78% and 81%, respectively, while reduction in *Imperata* rhizome biomass in *Leucaena* plot was nearly 90% and in *Gliricidia* plot 96%.

Mature plantation crops such as coconut and oil palm that their canopy has closed can control *Imperata,* but at early stage of development, these crops are susceptible to *Imperata* invasion because they do not develop sufficient dense rapid canopy rapidly enough to shade out the grass [40].

Besides legume species, some other grass species can be used to control *Imperata*. For example, intercropping with switch grass (*Panicum virgatum*), *Panicum hemitomon,* and *Muhlenbergia capillaries* reduced shoot and roots of *Imperata*, but the greatest reduction of *Imperata* occurred in combination with *Panicum hemitomon* [47]. Bahia grass (*Paspalum notatum*), *Cynodon dactylon,* and *Indigofera hirsuta* also have been reported to be effective in managing *Imperata* infestation [27, 48, 49].

Slash and burn agriculture have transformed a vast forest areas to *Imperata* dominated grasslands. *Imperata* is very successful in areas that are frequently burnt, slashed, or overgrazed and results in the extension of *Imperata* grassland [50]. *Imperata* burns readily, even when still green, and the fire destroys nearby vegetation. Compared to many other plant species, *Imperata* produces more persistent standing biomass, resulting in a greater fuel load on invaded sites. Average fire temperatures are higher on invaded *Imperata* sites than uninvaded sites [51]. Its fire burns so hot that it can exclude nearly all native vegetation.

Burning destroys the leaves of *Imperata* but not the rhizomes because they are belowground. After burning, these rhizomes sprout again and produce new shoots and flowers [21]. Regrowth from rhizomes is rapid, and frequent fire favors *Imperata* growth over associated species [52]. In Florida, areas that were burned or had greater biomass removal following the hurricane had greater number of *Imperata* patches and larger patch size [53]. Thus, burning creates a noncompetitive situation in which *Imperata* can persist and quickly dominate the invaded areas.

Burning increases soil fertility for short period of time. Soil organic carbon, total N, and available P increased soon after fire. Conventional practice of annual burning can increase soil nutrients in soil surface and support higher biomass production in *Imperata* covered degraded lands [54]. However, in the long term, repeated short cutting intervals or fire on *Imperata* increases its abundance, reduces soil fertility, and increases soil erosion [55].

Mechanical control

The main mechanical control method practiced by smallholder farmers in developing countries is slashing or handweeding. Slashing interval affects sprouting ability of *Imperata*. Slashing at short intervals results in better control of *Imperata*; however, slashing at long intervals can increase sprouting. Plants slashed every 2 months produced more sprouts than plants slashed monthly [34]. Killing *Imperata* needs very short slashing interval for a long time. Slashing every 10 days over a 3-year period still left a small number of rhizomes in the soil, but reserve carbohydrates in the rhizome were severely reduced [56]. In general, slashing at long interval only suppresses the shoots with little effect on rhizomes.

To achieve more effective results, slashing should be followed by tilling to destroy the rhizomes. On small-scale farms, most tillage operations are performed using crowbar, hoes, or draft animal driven plows, whereas on commercial farms, tractor-driven plows are generally used.

Tillage damages the rhizomes and prevents their regrowth into new shoots by fragmentation, desiccation, or deep burial. Ivens [32] reported that most rhizome fragments of two nodes mostly could not sprout, and 77%–84% of these nodes rotted within 2 months when buried at a depth of 7.5 cm. Lee [57] found that rhizome fragments buried at 10 cm or more did not germinate.

Tillage is most effective when it is conducted during the dry season that is when plant biomass is concentrated in the rhizomes and their desiccation is enhanced [58]. If it is done in wet season, not only it is difficult, but also there is insufficient sunlight to kill the exposed rhizomes. Sometimes tillage extends into the wet season when the soil is easier to work. Deep tillage should be to a depth of about 30–40 cm because most rhizomes are found above this depth. Rhizomes should be broken into short fragments and buried as deeply as possible [21] or exposed to desiccation by sun light. Wilcut *et al.* [37] reported that burying of *Imperata* rhizome fragments to depth of 5–8 cm greatly reduced sprouting. If left on the soil surface during the dry season, rhizomes will desiccate and lose their ability to sprout if dried to 70%–75% of their fresh weight [56]. Akobundu and Ekeleme [16] reported that maize grain yield reduction was 51% in plots where rhizomes were fragmented by hoe tillage and the crop was weeded twice, whereas grain yield reduction was 62% less when the crop was grown in slashed plots with intact rhizomes and was weeded four times.

One of the most successful methods to control *Imperata* by subsistence farmers in Indonesia is to slash or burn the grass then till the soil. After several weeks, the soil clods are broken into small pieces, and rhizomes are separated from the soil for baking in the sun. For intensive agricultural practices, repeated disking and deep plowing are effective in suppressing and eradicating *Imperata*, but these practices are costly and impractical by most subsistence farmers. In oil palm plantation areas, *Imperata* control is mainly conducted through integrated cultural (slashing), mechanical (rolling), chemical methods (glyphosate application) [59].

Results of many studies indicate that mechanical control of *Imperata* is not cost effective. Slashing is labor intensive, requiring as many as 75 man-days/ha [20]. It is possible to clear *Imperata* grasslands manually and plant crops or trees, but this may take up to 200 man-days/ha, which is far more than it takes to open a new area of secondary forest using slash and burn methods [40]. In Nigeria, it is cheaper to use glyphosate than handweeding for *Imperata* control [60].

Another low-cost technique that can be used to control the growth of *Imperata* is pressing (lodging or rolling). It is conducted by bending the culm of *Imperata* to ground level [21] by trampling or rolling a weight like old drum over the grass. Pressing can be used to clear areas for planting and as part of an integrated approach to enable the establishment of legume ground cover [58, 61]. With pressing, dense stands of *Imperata* regrowth can be decreased by 40%–80%. About 90% of pressed *Imperata* decomposes or dries up within 1 month, and it can take more than 6 months for the regrowth to reach its previous population density [62]. The best growth stage to press *Imperata* is when it is about 1 m high because stems usually remain permanently bent after being pressed. It is better to press the grass during the rainy season when cover crop species grow rapidly, thereby helping to accelerate biological succession from the grass stage to cover crop stage [63, 64].

Chemical control

Several herbicides have been tested alone (paraquat, dalapon, imazapyr, glyphosate, sulfometuron, nicosulfuron, rimsulfuron, etc.) or in mixture for the control of *Imperata*. Glyphosate and imazapyr appear to be the most promising herbicides for control of *Imperata* because of their ability to translocate to the underground rhizomes [21], although short-term control is rarely achieved. At high rates, these herbicides give partial control of *Imperata* up to 1-year application [65]. Glyphosate, a broad spectrum, systemic, and nonselective herbicide, has the potential for the control of *Imperata* and has become the market leader in the tropics and subtropics. The popularity of glyphosate is attributed to its low mammalian toxicity [66], little, or no phytotoxic residue in the soil [67] and primarily its efficacy against *Imperata*. Its negative attributes are its requirement for several rain-free periods after application [68].

Because glyphosate has very little to no soil activity, it needs only a short time for weeds to reinfest the treated areas. *Imperata* will likely reinfest the area if only one application of glyphosate is done during the same year. Research revealed that it takes about 3 years of two applications of glyphosate per year to reduce *Imperata* rhizome biomass by 90% [69]. Due to its little or no residual soil activity, glyphosate may be attractive to subsistence farmers because following application, crops can be planted immediately.

Imazapyr also is an effective herbicide for control of *Imperata*; one or two applications of imazapyr (0.75 lb/acre) can effectively control *Imperata* for 18–24 months [69]. Glyphosate at 1.0–1.8 kg/ha and imazapyr at 0.5–1.0 kg/ha provide good control lasting up to 12 months, depending on soil type, rates of application, and environmental conditions [70]. With glyphosate at 4.48 kg ai/ha, imazapyr at 0.84 kg ai/ha, and mixture of glyphosate and imazapyr at the same rates applied three times a year, the entire rhizome biomass of *Imperata* can be eliminated within 3 years [71]. Like glyphosate and other broad-spectrum herbicides, imazapyr will severely injure or kill forage grasses, broadleaved herbs, and annual and perennial crops. It has a long soil half-life and will remain in the soil for several months after application. Since its lasting effect, effectiveness of imazapyr on *Imperata* may continue up to 1–2 years after application. One or two applications (0.75 lb/acre) will often effectively control *Imperata* for 18–24 months. However, imazapyr applications often lead to "bare ground" for up to 6 months post-treatment because of its residual effect and nonselective nature of this herbicide [69]. Therefore, imazapyr may be appropriate for plantation and grassland areas but not in arable farming situations where it inhibits the establishment of arable crops [21]. The soil activity of imazapyr also has the potential to move down slopes during periods of rainfall, killing or injuring other species in the runoff area. In pasture areas, imazapyr can only be used as a "spot treatment" with no more than 10% of the area treated per year [69].

Used alone, imazapyr is more effective than glyphosate. Richardson [72] reported that application of imazapyr on shaded *Imperata* plots resulted in nearly bare soil, but in glyphosate-treated shaded *Imperata* plots, some *Imperata* was still growing.

Efficacy of glyphosate and imazapyr at the rates of 8.96 and 1.12 kg ai/ha, respectively, measured 24 months after treatment increased linearly with increasing rates of both herbicides, but eradication of *Imperata* was not achieved. *Imperata* recovered after imazapyr was applied at 2.24 kg ai/ha in a 2-year-old loblolly pine plantation [73].

A combination or tank mix of glyphosate and imazapyr provided greater control than similar rates of the either herbicide alone on new infestations [74]. However, Willard *et al.* [75] reported that combinations of glyphosate and imazapyr at various proportions were equally effective as the highest rate tested for these herbicides used alone. Glyphosate at 0 54 kg ae/ha improved control when mixed with imazapyr at 0 3 kg ae/ha, while comparable control was obtained when glyphosate at 1 08 kg ae/ha was mixed with imazapyr at 0.15 kg ae/ha [76], but combination of glyphosate and imazapyr did not give complete eradication of *Imperata* 24 hours after treatment [74]. Complete eradication of *Imperata* using a mixture of glyphosate and imazapyr obtained only after multiple applications over a 3-year period [71].

Rice husk burning has also been reported more effective to control *Imperata* than herbicide application. Isah *et al.* [77] reported that in the second year of study, rice husk burning and glyphosate caused delay of 84.1 and 28.2 days in *Imperata* first emergence, respectively.

Biological control

Although the problems caused by *Imperata*, biological control efforts have been few and rather piecemeal [78]. A review of biological agents related to *Imperata* has been conducted in the southeastern US. Literature records suggest an extensive number of its potential natural enemies. These include 90 pathogens, 92 insects, and several nematodes and mites that have been found on *Imperata* [35]. Of the arthropods recorded on *Imperata*, only one is reported to be specific to *Imperata*, that is, the gall midge (*Orseolia javanica*). This insect destroys the shoot meristem, but only after the grass is cut and the rhizome system has been debilitated. This requirement along with the presence of natural enemies of this insect significantly reduces its potential for control option [56, 79]. However, recent surveys in Asia and East Africa have identified several insect herbivores, including several genera of stem borer and gall-forming midges such as *Emmalocera* sp., *Chilo* sp., and *Contarinia* sp. that show some promise as biological control agents for *Imperata* [80]. Two fungal pathogens, *Bipolaris sacchari* and *Drechslera gigantea*, have also been identified as promising biological control agents for *Imperata* [81].

Integrated control

Herbicide applications alone are rarely successful in eradicating *Imperata*. Integrated control that combines cultural, mechanical, chemical, and perhaps biological methods provides the best option for *Imperata* control. In grassland and plantation areas, *Imperata* may be first burned or slashed to remove aboveground plant parts. The soil then can be tilled and sown with herbaceous or tree cover species to control this grass. The species that have good characteristics as cover crops are grow fast, can climb over and smother the grass, provide fodder for animals, and can fix atmospheric N. However, eradicating *Imperata* by cover crops alone is a long-term process.

To speed up *Imperata* control, the shaded grass should be sprayed with herbicides. Lojka *et al.* [41] reported that after 1 year of shading, glyphosate application and weeding significantly reduced aboveground biomass by 94.67% and 45%, and belowground by 76.5% and 58%, respectively. This is in line with Weng [82] that in shaded conditions, glyphosate at 2.2 kg/ha gave over 95% control of *Imperata* for 6 months, while in open conditions, 4.4 kg/ha was required to give the same level of control. Ogogo *et al.* [15] reported that in *Imperata* infested cassava, *Imperata* rhizome dry weight was the lowest in plots treated with glyphosate plus *Mucuna pruriens* cover crop, followed by handweeding plus *Mucuna pruriens* cover crop, followed by glyphosate application or handweeding alone.

If burned, *Imperata* should be left to grow for several months before spraying with herbicide or tilling. Regrowth of the plant for 1–4 months after burning will deplete food reserves as more leaves are produced. With more leaves, a larger surface area can intercept more droplets by herbicide spray. This allows herbicides to kill actively growing leaves, which maximizes effectiveness. Glyphosate as a 2% solution appeared to control *Imperata* satisfactorily for at least 2 years (91% mortality) [83]. If tillage can be incorporated, then a disking treatment following a burn is the best approach. This will kill rhizomes through desiccation. However, these practices may be impractical in many habitats such as forest and plantation areas.

In cropping areas, burning should not be conducted because it will harm the crops. Handweeding, herbicide, and cover crops are the methods that commonly used by smallholder farmers to control *Imperata*. In Nigeria, Chikoye *et al.* [60] reported that handweeding five times or applying glyphosate was more effective than handweeding twice in preventing maize yield losses and suppressing *Imperata*. *Imperata* was more effectively suppressed by handweeding and planting cover crops such as *Mucuna pruriens* than without cover crops. *Mucuna pruriens* nearly eliminated rhizomes of *Imperata* within 2 years of treatment application. Further, Chikoye *et al.* [84] reported that besides *Mucuna pruriens* and glyphosate application, narrow corn spacing and the use of competitive corn cultivar may be a sustainable approach to the control of *Imperata* in cropping areas. In soybean, Avav [17] reported that in *Imperata* infested soybean, glyphosate controlled 57%–85% of *Imperata* compared with 64%–67% by traditional hoe-weeding. The highest soybean grain yield (1.88 t/ha) was obtained from plots treated with glyphosate (1.44 kg/ha) followed by one hoe weeding. For the small-scale farmer who has no interest to use legume ground covers, intensive agricultural land use will prevent reestablishment of *Imperata.*

Once good control has been achieved, it is desirable to establish useful cover plant species, which can suppress regrowth of *Imperata* and conserve soil fertility. This is because the eradication of *Imperata* without planting of cover plant can led to the succession by other pernicious weed such as *Mikania cordata, Melastoma malabathricum*, and *Eupatorium odoratum* [85].

Conclusion

The extensive rhizome system and the large number of seed production capable of both short and long dispersal make *Imperata* to be dispersed far from its native habitats. In new habitats, *Imperata* can be a pernicious weed because of its higher competitive ability than many crop species. The best management practice is prevention; however, it is very difficult to achieve once the plant is established. Cultural control using fire is not recommended because it can increase dominance of the grass. Mechanical control is labor intensive and is only suitable where cheap labor is available. Using herbicides alone also is not cost effective and needs repeated application to achieve control. Leguminous plant cover can increase soil fertility, but it needs a long time for eradication. Integrating cultural, mechanical, chemical, and perhaps biological control methods may be the best approach because it is cheaper and can provide sustainable control.

References

1. McDonald SK, Chandler IE. Element of stewardship abstract for *Imperata cylindrica cf var*. major. Arlington (VA): Nature Conservancy; 1994.
2. Hubbard CE, Whyte RO, Brown D, Gray AP. *Imperata cylindrica*: taxonomy, distribution, economic significance and control. Aberystwyth, UK: Imperial Agricultural Bureaux; 1944.
3. Santiago A. Genocological aspect of the *Imperata* weeds and its practical implication. In: Proceedings of the BIOTROP Workshop of Alang-alang, Bogot, Indonesia, 27–29 July 1976. p. 23–34.
4. MacDonald GE. Cogongrass (*Imperata cylindrica*) – biology, ecology and management. Critical Reviews in Plant Sciences 2004;23:367–80.
5. MacDonald GE. Cogongrass: the plant's biology, distribution and impact in the southern US. In: Loewenstein NJ, Miller JH, editors. Proceedings of the regional cogongrass conference: a cogongrass management guide. Mobile, AL: Alabama Cooperative Extension System, Auburn University; 2007. p. 10–23.
6. Holm LG, Plucknet DL, Pancho JB, Herberger JP. The world's worst weeds, distribution and ecology. Honolulu, USA: University Press of Hawaii; 1977. p. 609.

7. Falvey JL. *Imperata cylindrica* and animal production in South East Asia; a review. Tropical Grassland 1981;15:52–6.
8. Garrity DP, Soekardi M, Van Noordwijk M, De La Cruz R, Pathak PS, Gunasena HPM, et al. The *Imperata* grassland in tropical Asia: area, distribution and ecology. Agroforestry Systems 1996;36(1–3):3–29.
9. Rusdy M. A review of the potential of *Imperata cylindrica* (L.) Raeusch. as feed for ruminant animals. Tropical Agriculture 2017;94(1):99–106.
10. Burrell AM, Pepper AE, Hodnett G, Goolsby JA, Overholt WA, Racelis AE, et al. Exploring origins, invasion history and genetic diversity of *Imperata cylindrica* (L.) Beauv. (cogongrass) in the United States using genotyping by sequencing. Molecular Ecology 2015;24(9):2177–93.
11. Bryson CT, Carter R. Cogongrass, *Imperata cylindrica* in the United States. Weed Technology 1993;7:1005–9.
12. Townson JK. *Imperata cylindrica* and its control. Weed Abstracts 1991;40:457–68.
13. Trautwigt A, Loewenstein NJ, Eckhardt LG, Hoeksema JD. Cogongras (*Imperata cylindrica*) affects above and belowground processes in commercial Loblolly pine (*Pinus taeda*) stands. Forest Science 2016;63(1):10–6.
14. Amadou T, Sogbedji J, Yawovi MD. The critical period of weed interference in upland rice in northern Guinea savanna: field measurement and model prediction. African Journal of Agricultural Science 2013;8(17):1748–59.
15. Ogogo AU, Oko BFD, Odey JO. Eco-friendly methods of speargrass (*Imperata cylindrica* L.) control in the derived savanna zone of Nigeria. Ethiopian Journal of Environmental Studies and Management 2008;1(1):64–9.
16. Akobundu IO, Ekeleme F. Effects of method of *Imperata* management on maize grain yield in the derived savanna of south-western Nigeria. Weed Research 2002;40:335–41.
17. Avav T. Weed management in soybean (*Glicine max* (L.) Merr) in southern savanna agroecology. PhD thesis. University of Nigeria; 1997.
18. Estrada JA, Flory SL. Cogongrass (*Imperata cylindrica*) invasions in the US: mechanisms, impacts, and threats to biodiversity. Global Ecology and Conservation 2015;3:1–10.
19. Hagan DL, Jose S, Lin CH. Allelophatic exudate of cogongrass (*Imperata cylindrica*): implication for the performance of native pine savanna plant species in southeastern US. Journal of Chemical Ecology 2013;39(2):312–22.
20. Brook RM. Review of literature on *Imperata cylindrica* (L.) Raeuschel with particular reference to South East Asia. Tropical Pest Management 1989;35(1):12–25.
21. Chikoye D. Characteristics and management of *Imperata cylindrica* (L.) Raeuschel in smallholder farms in developing countries. In: Labrada R, editor. Weed management for developing countries. Rome: FAO of the United Nations; 2003. p. 290.
22. Hubbard CE. *Imperata cylindrica*: taxonomy, distribution, economic significance and control. Oxford, UK/Aberystwyth, UK: Imperial Forestry Bureau/Imperial Bureau of Pastures and Forage Crops; 1984. p. 63.
23. Divate N, Solis D, Thomas MH, Alvares S. The economic impact of cogongrass among non-industrial private landowners in Florida. Selected paper for presentation at the Southern Agricultural Economics Association's 2016 Annual Meeting, San Antonio, TX. 2016.
24. McDonald SK, Shilling DG, Bewick TA, Okoli CAN, Smith R. Sexual reproduction by cogongrass, *Imperata cylindrica*. Proceedings of the Southern Weed Science Society 1996;48:185–6.
25. Sajise PE. Evaluation of cogon (*Imperata cylindrica* (L.) Beauv.) as a seral stage in Philippine vegetational succession: I. The cogonal seral stage and plant succession; II. Autecological studies on cogon. Dissertation. Ithaca (NY): Cornell University; 1972. p. 152.
26. Santiago A. Studies on the autoecology of *Imperata cylindrica* (L.) Beauv. In: Proceedings of the 9th International Grassland Congress, Sau Paulo, Brazil. 1965. p. 499–502.
27. Shilling DG, Bewick TA, Gaffney JF, McDonald SK, Chase CA, Johnson ERRL. Ecology, physiology, and management of cogongrass (*Imperata cylindrica*). Gainesville (FL): University of Florida; 1997. p. 128.
28. Holly DC, Ervin GN. Effects if intraspecific seedling density, soil type, and light availability upon growth and biomass allocation in cogongrass (*Imperata cylindrica*). Weed Technology 2007;21(3):812–20.
29. King SE, Grace JB. The effects of gap size and disturbance type on invasion of wet pine savanna by cogongrass (*Imperata cylindrica*) (Poaceae). American Journal of Botany 2000;87(9):1279–86.
30. Xuan TD, Toyama T, Fukuta M, Khahn TD, Tawata S. Chemical interaction in the invasiness of cogongrass (*Imperata cylindrica* (L.) Beauv). Journal of Agricultural and Food Chemistry 2009;57(20):9448–53.
31. AQAS. Agriculture Quarantine Activity System (AQAS) database. USA: United States Department of Agriculture, Plant Protection and Quarantine; 2018. Available from: URL: https://aqas,aphis.usda.gov/aqas/ [accessed: 5 August 2019].
32. Ivens GW. *Imperata cylindrica* (L.) Beauv. in west African agriculture. Indonesia: BIOTROP Special Publication; 1980. p. 149–56.
33. Daneshgar P, Jose S. *Imperata cylindrica*, an alien invasive grass, maintains control over nitrogen availability in establishing pine forest. Plant and Soil 2009;320(1):209–18.
34. Sajise PE. Evaluation of cogon (*Imperata cylindrica* (L.) Beauv.) as a serial stage in Philippine vegetational succession. 1. The cogonal seral stage and plant succession. 2. Autecological studies on cogon. Dissertation Abstracts International B 1973;3040–1. Weed Abstracts 1976, No. 1339.
35. Van Loan A, Meeker J, Minno M. Cogongrass, biological control of invasive plants in the Eastern United States. Morgantown, USA: USDA Forest Service Publication, Forest Health Technology Enterprise Team; 2002. p. 361–72.
36. Ayeni AO, Duke WB. The influence of rhizome features on subsequent regenerative capacity in speargrass (*Imperata cylindrica* (L.) Beuv.). Agriculture, Ecosystems and Environment 1985;13(3–4):309–17.
37. Wilcut JW, Dute RR, Truelove B, Davis DE. Factors limiting the distribution of cogongrass, *Imperata cylindrica*, and torpedograss, *Panicum repens*. Weed Science 1988;36(5):577–82.
38. Muchovej JJ, Onokpise OU, Bambo SK. Characteristics of cogongrass rhizome and its perforation of a Maiden cane rhizome. International Journal of Botany 2009;5:314–6.

39. Patterson DT, McWhorter CG. Distribution and control of cogongrass (*Imperata cylindrica*) in Mississippi savanna zone. USA: US Department of Agriculture, Agricultural Research Service, Southern Weed Science Laboratory; 1983.
40. Hairiah K, Noordwijk M, Purnomosidhi P. Reclamation of grassland using agroforestry. Bogor, Indonesia: International Centre for Research in Agroforestry, Southeast Asian Regional Research Programme; 2000.
41. Lojka B, Cepkova PH, Navratilova L, Damme PV, Banou J, Polesny Z, et al. Methods for short-term control of *Imperata* grass in Peruvian Amazon. Journal of Agriculture and Rural Development in the Tropics and Subtropics 2011;112(1):37–43.
42. Mcdicken KG, Hairiah K, Otsamo A, Duguma B, Majid NM. Shaded-based control of *Imperata cylindrica*: tree fallows and cover crops. Agroforestry Systems 1996;36(1–3):131–49.
43. Moosavi-Nia H, Dore J. Factors affecting glyphosate activity in *Imperata cylindrica* (L.) Beauv. and *Cyperus rotundus* L. II. Effect of shade. Weed Research 1979;5:321–7.
44. Patterson DT. Shading effects on growth and partitioning of plant biomass in cogongrass (*Imperata cylindrica*) from shaded and exposed habitats. Weed Science 1980;28(6):735–40.
45. Chikoye D, Ekeleme F. Cover crops for cogongrass (*Imperata cylindrica*) management and effect on subsequent corn yield. Weed Science 2003;5(5):792–97.
46. Anoka UA, Akobundu IO, Okonkwo SNC. Effects of *Gliricidia sepium* (Jacq.) Steud and *Leucaena leucocephala* (Lam.) de Wit on growth and development of *Imperata cylindrica* (L.). Agroforestry Systems 1991;16(1):1–12.
47. Onokpise OU, Muchovej JJ, Bambo SK, Grabowski JM, Louime CJ. Parameters of plant growth in competition of *Imperata cylindrica* with native grass species under greenhouse conditions. American-Eurasian Journal Agricultural and Environmental Sciences 2010;8(12):116–23.
48. Gaffney JF. Ecophysiological and technical factors influencing the management of cogongrass (*Imperata cylindrica*). PhD dissertation. Gainesville (FL): University of Florida; 1996.
49. Rasyid T, Rusdy M. Effect of cutting interval on dry matter yield, nutritive value and competitive ability of *Imperata cylindrica* and *Paspalum notatum* intercropping. Transylvanian Review 2018;26(34):8769–73.
50. Wibowo A, Suharti M, Stewart PG. Fuel characteristics and fire behaviour in alang-alang under *Acacia mangium* plantation in Depok, West Java, Indonesia. Forestry Research Bulletin 1991;544:1–7.
51. Lippincott CL. Ecological consequences of *Imperata cylindrica* (cogongrass) invasion in Florida sandhill. Dissertation. Gainesville (FL): University of Florida; 1997. p. 165.
52. Wibowo A, Suharti M, Sagala APS, Hibanai H, van Noordwijk M. Fire management on *Imperata* grassland as part of agroforestry development in Indonesia. Agroforestry Systems 1996;36(1–3):203–2017.
53. Holzmueller EJ, Jose S. Response of invasive plant *Imperata cylindrica* to disturbance in the southeastern forest, USA. Forests 2012;3:853–63.
54. Pathak K, Nath AJ, Sileshi GW, La LR, Das AK. Annual burning enhances biomass production and nutrient cycling in degraded *Imperata* grassland. Land Degradation and Development 2017;28(5):1763–71.
55. Peter G, Ken M. On-site effects of *Imperata* burning by Indonesian smallholders: a bioeconomic model. Bulletin of Indonesian Economic Studies 1997;33(3):79–96.
56. Soerjani M. Alang-alang (*Imperata cylindrica* (L.) Beuv), pattern of growth as related to its problem of control. BIOTROP Bulletin 1970;1:82–88.
57. Lee SA. Germination, rhizome survival and control of *Imperata cylindrica* (L.) Beuv. on peat. MARDI Research Bulletin 1978;5(2):1–9.
58. Terry PJ, Adjers G, Akobundu IO, Anoka AU, Drilling ME, Tjitrosemito S, et al. Herbicides and mechanical control of *Imperata cylindrica* as a first step in grassland rehabilitation. Agroforestry Systems 1997;36:151–79.
59. Fairhust T, McLaughin D. Sustainable farm development on degraded land in Kalimantan. 2020. Available from: URL: https://c402277.ssl.cf1.rackcdn.com/publications/355/files/original/Sustainable_Oil_Palm_Development_on_Degraded_Land_in_Kalimantan__Indonesia.pdf?1345735065 [accessed: 13 May 2020].
60. Chikoye D, Manyong VM, Carsky RJ, Ekeleme F, Gbehounou G, Akanchede A. Response of spear grass (*Imperata cylindrica*) to cover crops integrated with handweeding and chemical control in maize and cassava. Crop Protection 2002;21(2):145–56.
61. ICRAF. *Imperata* grassland rehabilitation using agroforestry and assisted natural regeneration. Bogor, Indonesia: International Centre for Research in Agroforestry; 1999. p. 167.
62. DENR. Agroforestry technology information kit. Silang, The Philippines: Department of Environmental and Natural Resources, International Institute of Rural Reconstruction and Ford Foundation; 1989. p. 237.
63. Dugan PC. Rehabilitation of logged-over forests in the Asia/Pacific region. Final (draft) report to Japan Overseas Forestry Consultants Association. 1992. p. 69.
64. Friday KS, Drilling ME, Gamty DP. *Imperata* grassland rehabilitation using agroforestry. Bogor, Indonesia: International Centre for Research in Agroforestry, Southeast Asian Regional Research Programme; 1999.
65. Miller JH. Refining rates and treatment sequences for cogongrass (*Imperata cylindrica*) control with imazapy and glyphosate. In: Proceedings, 53rd Annual Weed Science Society meeting, January 24–26, 2000, Tulsa, Oklahoma. Champaign (IL): Southern Weed Science Society; 2001. p. 131–2.
66. Myers JP, Antoniou MN, Blumberg B, Carrol L, Colborn T. Concern overuse of glyphosate-based herbicides and risk associated with exposures: a consensus statement. Environmental Health 2016;15(19):9.
67. Wibawa W, Mohammad RB, Puteh AB, Omar D, Juraimi AS, Abdullah ASA. Residual pytotoxicity effects of paraquat, glyphosate and glyfosinate-ammonium herbicides in soils from fields-treated plots. International Journal of Agriculture and Biology 2009;11(2):214–6.
68. Kogan M, Alister C. Glyphosate use in forest plantation. Chilean Journal of Agricultural Research 2010;70(4):652–66.
69. Sellers BA, Ferrell JA, MacDonald GE, Enloe SF, Flory SL. Cogongrass (Imperata cylindrica) biology, ecology, and

management in Florida grazing lands. USA: IFAS Extension, University of Florida; 2019. Available from: URL: http://edis.ifas.ufl.edu/pdffiles/WG/WG20200.pdf [accessed: 3 March 2019]

70. Udensi UE, Akobundu IO, Ayeni AO, Chikoye D. Management of cogongrass (*Imperata cylindrica*) with velvetbean (*Mucuna pruriens* var. utilis) and herbicides. Weed Technology 1999;13:201–8.

71. Aulakh JS, Enloe SF, Loewenstein NJ, Price AJ, Wehtje G, Miller JH. Pushing toward cogongrass (*Imperata cylindrica*) patch eradication: the influence of herbicide treatment and application timing on cogongrass rhizome elimination. Invasive Plant Science and Management 2014;7:398–407.

72. Richardson SG. Control and management of cogongrass and other exotic grasses on disturbed lands in Florida: research report. Bartow Florida, USA: Florida Industrial and Phosphate Research Institute; 2003.

73. Ramsey CL, Jose S, Miller DL, Cox J, Portier KM, Shilling DK, et al. Cogongrass (*Imperata cylindrica* (L.) Beauv.) response to herbicides and disking on a cutover site in a mid-rotation pine plantation in southern USA. Forest Ecology and Management 2003;179:195–207.

74. Minogue PJ, Miller JH, James H, Lauer DK. Use of glyphosate and imazapyr for cogongrass (*Imperata cylindrica*) management in southern pine forest. Southern Journal of Applied Forestry 2012;36(1):19–25.

75. Willard TR, Gaffney JF, Shilling DG. Influence of herbicide combinations and application technology on cogongrass (*Imperata cylindrica*) control. Weed Technology 1997;11:76–80.

76. Faiz MAA. Effects of herbicide mixtures, surfactants and spray volumes on the control of *Imperata cylindrica* (L.) Raeuschel. Journal of Rubber Research 1998;1(3):179–89.

77. Isah KM, Abdulmaliq SY, Lawal AF, Tswanya NM, Majin NS. Effect of rice husk, hoe weeding and glyphosate in the management of speargrass (*Imperata cylindrica*) on maize (*Zea mays*). Journal of Experimental Biology and Agricultural Sciences 2013;1(3):159–65.

78. Caunter IG. *Colletotrichum caudatum*, a potential bioherbicide for control of *Imperata cylindrica*. In: Moran VC, Hoffman JH, editors. Proceedings of the IX International Symposium on Biological Control of Weeds, Stellensbosch, South Africa. Cape Town, South Africa: University of Cape Town; 1996. p. 525–7.

79. Mangoendihardjo S. Some notes on the natural enemies of alang-alang (*Imperata cylindrica* (L.) Beauv.) in Java. In: Soewardi B, editor. Proceedings of BIOTROP Workshop on Alang-alang, Bogor, Indonesia, 27–29 July 1976. Bogor, Indonesia: BIOTROP SEAMEO Regional Center for Tropical Biology; 1980. p. 47–55.

80. Overholt WA, Hidayat P, Le Ru B, Takasu K, Goolsby A, Racelis A, et al. Potential biological control agents for management cogongrass (Cyperales: Poaceae) in the southeastern USA. Florida Entomologist 2016;99(4):734–9.

81. Yandoc CB, Charudattan R, Shilling DG. Evaluation of fungal pathogens as biological control agents for cogongrass (*Imperata cylindrica*). Weed Technology 2005;19(1):19–26.

82. Wong PW. Evaluation of the isopropylamine salt of glyphosate for *Imperata cylindrica* (L.) Beuv. control in oil palm. In: Proceedings of the Eighth Asian Pacific Weed Science Society Conference, Bangalore, India. 1981. p. 273–6.

83. Tanner GW, Wood JM, Jones SA. Cogongrass (*Imperata cylindrica*) control with glyphosate. Florida Scientist 1992;55(2):12–115.

84. Chikoye D, Udensi UE, Ogunyemi S. Integrated management of cogongrass (*Imperata cylindrica* (L.) Rauesch.) in corn using tillage, glyphosate, row spacing, cultivar and cover cropping. Agronomy Journal 2005;97(4):1164–71.

85. Yeoh LH, Puspharajah E. Chemical control of *Imperata cylindrica* (L.) Beuv. (lalang) in Malaysia. In: Proceedings of the Rubber Research Institute of Malaysian Planters Conference, Kuala Lumpur, Malaysia. 1976. p. 250–73.