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Mini-review

Pteridophytes as active components in gardening, agricultural and horticultural ecosystems in Japan

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Abstract: Many members of Pteridophytes have been traditionally used in the designs of Japanese gardens and a large variety of ferns attract gardeners as greening pieces in the garden designs. However, details or examples of practical uses of ferns in traditional gardening in Japan have only rarely been introduced in non-Japanese literatures to date, despite the importance of ferns in Japanese gardening traditions. In addition to the discussion of ferns in gardening, the use and association of these plants in Japanese agricultural and horticultural sceneries are addressed. The presence and importance of 40 familiar fern species in local gardening, agricultural and horticultural ecosystems are also discussed, as well as the roles of introduced ferns as key elements of ecosystems and their interaction with neighboring biota. Finally, some examples of uses of fern species in environmental science and engineering are also reviewed.

1. Introduction

It is widely known that traditional Japanese gardening requires moss species as key botanical components for covering natural rocks, wooden and stone walls, tree trunks and sidewalk surfaces. The use of mosses is frequently described in the world of Japanese literatures, chiefly in Haiku, as symbolized by a mythical conversation between legendary Haiku poet Basho and Zen master Buccho in which they discuss the Buddhist philosophy on growing green mosses (Suzuki, 1975). In typical Japanese gardens, natural rocks partially covered by a layer of thick moss and ponds surrounded by mossy stones represent miniature-sized rocky mountains with forestry slopes and lakes located deep in the forest. These approaches for miniaturizing natural landscapes are well in line with the Buddhist-affected and Shintoist-mixed nature-respecting philosophical preferences in Japan which encourage people to be surrounded by pieces of nature.

In Japan, second to mosses, many Pteridophytes (ferns and fern allies) have also been traditionally used in Japanese garden designing. Interestingly, some ground-covering ferns such as members of Selaginellaceae have been considered as mosses by gardening practitioners lacking taxonomical background, largely due to their moss-like appearance (Fig. 1). In place of mossy mats, two Selagi-

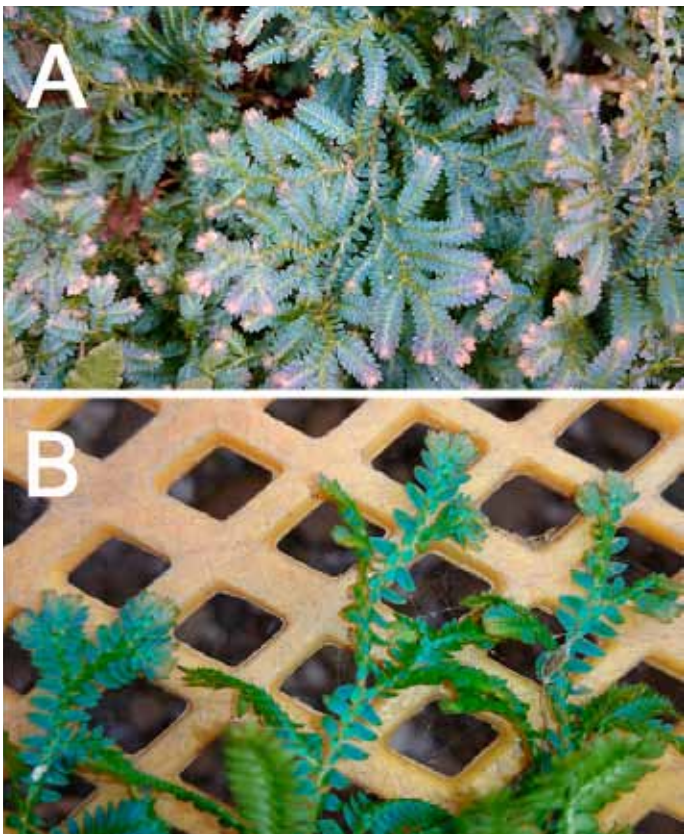

Fig. 1 - Living *Selaginella remotifolia* found in a private garden (Kiyotake-cho, Miyazaki, Japan). (A) Sheet of growing *Selaginella remotifolia* covering the ground. (B) Blue-green colored leaflets.

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nellaceae members, such as *Selaginella remotifolia* Spring (Japanese name: Kuramagoke) and *Selaginella unicinata* (Desv.) Spring (Japanese name: Konterikuramagoke), can be installed in Japanese gardens. Japanese names ending with -goke or -koke are conventionally given to moss species, despite the fact that these species are taxonomical members of ferns.

Furthermore, a large variety of ferns (including standing types) also attract the gardeners as greening pieces in gardening designs. Not only in Japan but also in other East Asian regions such as Taiwan and Korea, some fern species such as *Lycopodium fordii* Bak. (Lycopodiaceae) are grown as gardening plants and reflect the local flora (Huang *et al*., 2000).

In addition to the Lycopsida members mentioned above (eg. *Lycopodium* among subclass Aglossopsidae and *Selaginella* among subclass Glossopsidae, within the class Lycopsida), *Psilotum nudum* (L.) P. Beauv. (Psilotaceae; Japanese name: Matsubaran) belonging to the class Psilotopsida has long been utilized in Japanese gardening landscapes. Recently it was suggested that this plant communicates with neighboring plants through a arbuscular mycorrhizal network (Winther and Friedman, 2009). Accordingly, *Psilotum nudum*, with its non-photosynthetic life cycle, can thrive underground mostly by depending on the transport of photosynthetically fixed carbon from the green plants growing nearby. In the gardens where this plant has been introduced, the micro-ecosystem which allows such ecophysiological interspecies communication should be developed.

The above fern species have conventionally been considered as members of the phylum Microphyllophyta. As might be expected, other pteridophytes belonging to two other conventional phyla, namely Spherophyta and Pterophyta, are also commonly found in Japanese gardening and agricultural landscapes. Despite the importance of Pteridophytes in Japanese gardening traditions, details or examples of practical uses of ferns have only rarely been introduced in non-Japanese literatures to date. As most ferns favor a humid subtropical climate, this article aims to briefly describe and list the Pteridophytes found in the local gardening and agricultural landscapes in the southwestern half of Japan.

2. Gardening and Ferns

Historically, the inclusion of ferns in gardens has been popular among people of various classes such as farmers, warriors, monks and aristocrats, thus ferns were often found in the gardens and backyards of imperial and aristocratic palaces, Shintoist shrines, Buddhist temples, and ordinary houses. Today, it has become much harder to find fern culturing in ordinary houses in the large cities in Japan, yet in rural areas surrounded by semi-wild forests and far from urban areas, the use of ferns can still be found readily.

In traditional Japanese gardens, the following fern species can be found. *Matteuccia struthiopteris* (L.) Todaro (Athyriaceae; Japanese name: Kusasotetsu also known as Kogomi in the northern Japan) often welcomes the visitor to the gardens. *Cyrtomium falcatum* (L. fil.) Presl. (Dryopteridaceae; Japanese name: Oniyabusotetsu) and *Equisetum hyemale* L. (Equisetaceae; Japanese name: Tokusa) are likely planted surrounding ponds and/or waterfalls. Beneath the bushes, *Polystichum polyblepharum* (Roem. Ex Kunze) Presl. (Dryopteridaceae; Japanese name: Inode) can be frequently found. *Equisetum hyemale* and *Dryopteris erythrosora* (Eaton) O. Ktze (Dryopteridaceae; Japanese name: Benishida) can be found in the shade of structures such as a Chashitsu (a tea-ceremony house). Gaps among the rocks or stones can be naturally filled by *Cyrtomium falcatum* and *Pteris multifida* Poir (Pteridaceae; Japanese name: Inomotosō). *Pteris multifida* is a specific host plant that supports the life of caterpillars of a domestic moth of the Noctuidae family, *Callopistria japonibia* (Fig. 2). Inoue and Sugi (1958) suggested that geographical distribution (size of habitat) of *Callopistria japonibia* largely depends on the distribution of this fern. This could be a model for studying the contribution of garden environments to harbor specific ferns for insect biodiversity.

Moreover, some fern species have been passively but very frequently installed in Japanese gardens, thus their presence strongly reflects the nature of original wild flora. Such species include *Pteris cretica* L. (Pteridaceae; Japanese name: Ōbanoinomotosō), *Osumunda japonica* Thunb., *Botrychium japonicum* (Prantl) Underw. (Ophioglossaceae; Japanese name: Fuyunohanawarabi), *Cyrtomium falcatum*, *Athyrium niponicum* (Mett.) Hance (Athyriaceae; Japanese name: Inuwarabi), *Deparia japonica* (Thunberg) M. Kato (Woodsiaceae; Japanese name: Shikeshida) (Fig. 3A, D) and *Pteridium aqualinum* (L.) Kuhn var. *latiusculum* (Desv.) Underw. Ex Hell (Dennstaedtiaceae; Japanese name: Warabi) (Fig. 3E, F).

Fig. 2 - *Pteris multifida* growing on the stone wall in a private garden (Kiyotake-cho, Miyazaki, Japan). (A) Top view of growing plants. (B) Spore-bearing adaxial side of the leaves. (C, D) Plants being fed on by caterpillars of *Callopistria japonibia*. Arrows indicate the presence of caterpillars.

Among passively introduced ferns, members of Polypodiaceae such as *Lemmaphyllum microphyllum* Pres (Japanese name: Mamezuta), *Lepisorus thunbergianus* (Kaulf.) Ching (Japanese name: Nokishinobu), and *Pyrrosia lingua* (Thunb.) Farw (Japanese name: Hitotsuba) are epiphytic species which are often attached to trees and rocks (Fig. 4). On the surface of rocks and walls, *Lemmaphyllum microphyllum* is often exposed to competition with higher epiphytic plants such as *Ficus pumila* L. (Moraceae; Japanese name: Ōitabi).

In addition to epiphytic plants, a climbing species, *Lygodium japonicum* (Thunb.) Sw. (Lygodiaceae; Japanese name: Kanikusa) is of great interest. Historically, sun-tracking movements associated with a the climbing growth habit were described by Charles Darwin (1875) in two members of *Lygodium* (*L. articulatum* and *L. scandens*). Darwin concluded that "*As ferns differ so much in structure from phanerogamic plants, it may be worthwhile here to show that twining ferns do not differ in their habits from other twining plants.*"

The climbing fern native to Japan, *Lygodium japonicum*, is commonly known as "Japanese climbing fern". This fern grows very fast and thus often covers nearby living trees, rocks and walls (Fig. 5). *Lygodium japonicum* has been exported for ornamental purposes. For instance, this plant was introduced in Florida, USA, in 1932 (Gordon and Thomas, 1997).

Fig. 3 - *Deparia japonica* and *Pteridium aqualinum* sampled in a private garden (Kiyotake-cho, Miyazaki, Japan). (A) Adaxial side (top side) and (B) Abaxial side (bottom side) of mature and young bladed of *Deparia japonica*. (C) Mature and (D) immature sporangia on leaflets of *Deparia japonica*. (E) Living *Pteridium aqualinum*. (F) Roots and young emerging frond of *Pteridium aqualinum.*

Fig. 4 - Epiphytic ferns found in a countryside private garden (Kiyotake-cho, Miyazaki, Japan). (A) *Lepisorus thunbergianus* grown on the trunk of a loquat tree (*Eriobotrya japonica* (Thunb.) Lindl.). (B-D) *Lemmaphyllum microphyllum* growing on the tree and rocks.

3. Ferns and Japanese people

Even before ferns were introduced into man-made gardens, people in Japan traditionally enjoyed going out

Fig. 5 - A climbing fern, *Lygodium japonicum*, found in a countryside private garden (Kiyotake-cho, Miyazaki, Japan). (A) Climbing growth of *Lygodium japonicum* on the wooden wall by competing with other climbing plants such as *Ficus pumila*. (B, C) Aggressive growth of *Lygodium japonicum* winning the competition with other standing plants. (D) Vegetative leaflets. (E, F) Development of sporangia on dorsal side of the leaflets.

to the fields and forests to gather edible young fronds of wild ferns. The relationships between Japanese people and ferns, especially Bracken ferns, are historically, socially and culturally so tight that recreational fern gathering was hardly weakened even among Americans of Japanese origin, as is revealed by the various recipes for cooking ferns found among traditional Japanese communities in the United States (Anderson *et al*., 2000). Edible wild ferns in Japan include *Equisetum arvense* L. (Equisetaceae; Japanese name: Sugina), *Pteridium aqualinum* (popularly known as Warabi), *Osumunda japonica* Thunb. (Osmundaceae; Japanese name: Zenmai), and *Matteuccia struthiopteris*.

Historically, among the Japanese, *Equisetum arvense* has been used as an herbal medicine with diuretic, antitussive, antipyretic, hemostatic, and roundworm-eliminating actions. Therefore, this herbal medicine has been given to patients with gonorrhea, cystitis, edema, bronchitis, and bleeding hemorrhoids (Ikegami, 2013). Furthermore, search for lymphangiogenesis-inhibiting agents in the crude extracts from *Equisetum arvense* was recently attempted (Jeong *et al*., 2013).

Figure 6 shows classical illustrations of rhizome anatomy of *Equisetum arvense* L. These illustrations remind us that, like higher plants, ferns, including *Equisetum arvense*, finely develop rhizomes under the soil, suggesting that ferns are one of the key players in the soil ecosystem.

Apart from edible and medicinal species, Japanese people are also familiar with some fern species for ornamental purposes and crafts. The mature fronds of *Gleichenia japonica* Spr. (Gleicheniaceae; Japanese name: Urajiro) are important for traditional New Year's decorations. In summer, outside doors or windows of houses, one can find hanging fern-bearing, peat moss-based green balls called "*Shinobudama*", which are usually about 10 cm in diameter, as one of the favored customs in Japan. A *Shinobudama* literally means a ball of Shinobu which is the Japanese common name for *Davallia mariesii* Moore ex Baker (Davalliaceae). This ornamental arrangement of *Shinobu* fern is often combined with a wind chime hung outside.

Use of *Equisetum hyemale* L. in traditional craft works should be also noted. The silicate-rich stems of *Equisetum hyemale* L. have long been used for grinding and honing the surface of wooden table wares and furniture.

4. Agriculturally associated flora of ferns in Japan

Paddy fields for culturing rice plants (*Oryza sativa* L.) are man-made wetlands which cover about 50% of the agricultural land in Japan. Some fern allies bloom out in the paddy field after the harvest of rice. Typical examples of dominating aquatic and semi-aquatic ferns in the post-rice paddy include *Ceratopteris thalictroides* (L.) Brongn. (Adiantaceae; Japanese name: Mizuwarabi), *Salvinia natans* (L.) All (Salviniaceae; Japanese name: Sanshōmo), *Azolla japonica* Fr. et Sav. (Azollaceae; Japanese name: Ōakaukikusa), *Azolla imbricata* (Roxb.) Nakai (Azollaceae; Japanese name: Akaukikusa), and *Marsilea quadrifolia* L. (Marsileaceae; Japanese name: Denjisō). *Marsilea quadrifolia* is most likely to be very sensitive to rice field herbicides and thus this plant species is rarely found nowadays (Luo and Ikeda, 2007).

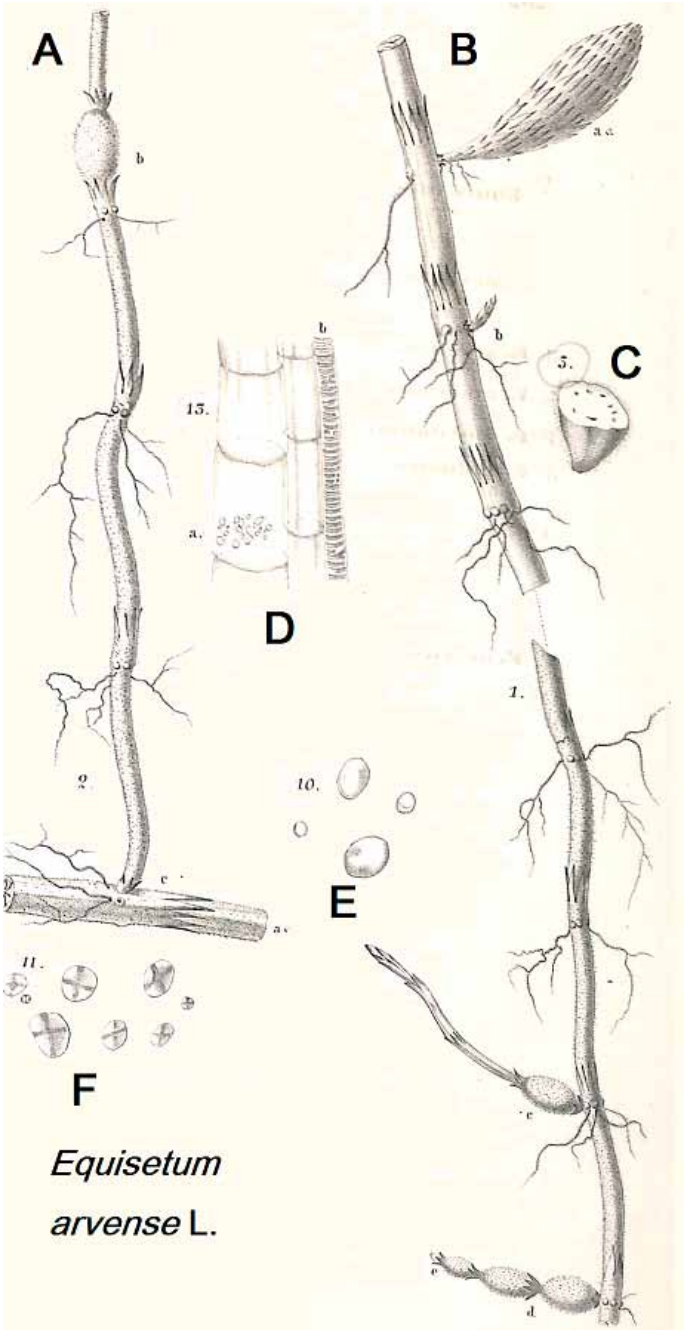

Fig. 6 - Anatomical illustrations of underground structures of *Equisetum arvense* L. found in a classical book by J. Duval-Jouve (1864). (A) Horizontal rhizomes. (B) Vertical rhizomes. (C) Section of large tuber attached to rhizome. (D) Cells of a tuber with starch granules (left) and vessel (right). (E, F) Starch granules. This book was originally collected and preserved through collaborative research between Université Paris Diderot and The University of Kitakyushu (Kawano and Bouteau, 2007; Kawano *et al*., 2008). Original images were digitally scanned and slightly modified (illustrations of other plant species were masked).

5. Breeding for horticultural purposes

Some Pteridophytes have been positively subjected to breeding efforts, especially during the era of Tokugawa Japan known as the Edo period (1603-1868). Among the ferns listed in this section, the breeding history for *Psilotum nudum* (known as Matsubaran) is estimated to have a long history and thus a number of varieties are available (Murata and Yashiro, 2006). Also some ornamental species with attractive leaf orientation, such as *Onychium japonicum* (L.) (Thunb.) Kunze (Parkeriaceae/Adiantaceae; Japanese name: Tachishinobu) and *Nephrolepis cordifolia* (L.) Presl (Lomariopsidaceae; Japanese name: Tamashida) are popularly bred and cultivated for both garden use and for ornamental pots. Note that, nowadays, *Nephrolepis cordifolia* often requires protection under a glass house especially during the winter season.

Some fern species are also favored by gardeners and plant growers and are nowadays bred and available on the market. Such ferns considered as gardening plants include *Selaginella unicinata* (Fig. 1), *Selaginella tamariscina* (Beauv.) Spring (Selaginellaceae; Japanese name: Iwahiba), *Selaginella involvens* (Sw.) Spring (Selaginellaceae; Japanese name: Katahiba), *Adiantum capillus-veneris* L. (Adiantaceae; Japanese name: Hōraishida), *Sphenomeris chinensis* (L.) Maxon. (Lindsaeaceae; Japanese name: Horashinobu), *Pteris nipponica* W. C. Shieh (Pteridaceae; Japanese name: Matsuzakashida) and *Asplenium antiquum* Makino (Aspleniaceae; Japanese name: Ōtaniwatari; this plant often requires green house or similar facilities). *Selaginella unicinata* is believed to have been brought from southern regions in China several centuries ago. *Adiantum capillus-veneris* is naturally found in the western half of Japan, but there are still some discussions on the origins of this fern (Murata and Yashiro, 2006). Among *Adiantum* species, *Adiantum monochlamys* Eaton (Adiantaceae; Japanese name: Hakoneshida) is hardly cultivated in gardens (Murata and Yashiro, 2006). Among the varieties of *Pteris nipponica,* lines or individuals with white spots on the leaves are likely favored on the market (Murata and Yashiro, 2006). It should be noted that even today, many efforts to develop and/or introduce new horticultural fern varieties of East Asian origin are being made (Xu *et al*., 2006).

6. Uses of ferns in environmental science and engineering

Unlike mosses, Pteridophytes possess a highly developed root system (rhisomes) by which minerals and metals are effectively taken up by growing plants. From an environmental point of view, some ferns are receiving more attention than ever, after pioneering works by Japanese fern specialists, since some ferns might be useful indicators and/or tools to assess and remediate contaminated soils.

Most metallic ions present at high concentrations are toxic to living plants by targeting and damaging the root cells exposed to the soil (Kawano *et al*., 2005). *Athyrium yokoscense* (Fr. Rt Sav.) Christ (Athyriaceae; Japanese name: Hebinonegoza), indigenous to East and North East Asia including Japan and Korea, is known to thrive in and around the sites of mining by rooting in soils contaminated with high concentrations of heavy metals (such as Zn, Cd, Pb, and Cu) and As (Morishita and Boratynski, 1992; Van *et al*., 2006). Therefore, the presence or distribution of this plant strongly indicates the history of the soil use or contaminations (Morishita and Boratynski, 1992). It has been well documented that *Athyrium yokoscense* not only tolerates but also effectively takes up the contaminating elements from the surrounding environments, as examined both at cellular level (Yoshihara *et al*., 2005) and field-grown plant level (Morishita and Boratynski, 1992; Kamachi *et al*., 2005).

Similar approaches are now being attempted with regard to other fern species. Use of a hyper-accumulator fern for arsenic and metals, *Pteris vittata* L. (Pteridaceae; Japanese name: Moejimashida) is one successful example of fern-based phytoremediation of metal-contaminated and arsenic-poisoned soils (An *et al*., 2006; Xie *et al*., 2009). Interestingly, a recent proteomic approach by Bona *et al*. (2011) suggested that the hyper-accumulating nature of *Pteris vittata* requires the presence of symbiotically formed arbuscular mycorrhizae. Furthermore, unpublished results presented by Chien *et al*. (2012) during an oral presentation at the 64th annual meeting of the Society for Bioscience and Bioengineering, Japan, suggested a possible relationship between the mechanism of arsenic accumulation by *Pteris vittata* L. and bacterial flora in the rhizosphere. These studies consistently support the view that composition of the micro-flora in the soil inevitably affects the environmental responses performed by rhizome-developed fern species.

7. Preservation of ferns and related flora and fauna in the gardens

Based on statistical techniques, namely two-way indicator species analysis (TWINSPAN) and Detrended Correspondence Analysis (DCA), Murakami *et al.* (2003) reported that there is a relationship between micro-landforms and the fern species composition in forest islands. This is the case of surveys on the ecological status of fragmented forests within the urbanized area of Kyoto city since fern members are largely considered to form a group of environmental indicators in the urban matrix. The authors concluded that the difference in species composition of ferns was shown to reflect differences in micro-landforms. For example, *Polystichum polyblepharum* and many other species are favored in valley bottoms in the small forest islands while some species such as *Dryopteris erythrosora* and *Gleichenia japonica* are favored on the slopes.

Japanese gardens can be considered as a local ecosystem that allows semi-wild propagation of fern species. This is largely due to the diversified micro-landforms in

Japanese garden designs which allocate rocks, mounds, valleys, falls and ponds within small areas. Indeed, Japanese gardens can be considered models for botanical display and/or preservation of semi-wild fern species and interacting flora, fauna and microbiota.

8. Conclusions

In this article, the use and associations of ferns in Japanese agricultural and horticultural sceneries are reviewed and discussed. Through listing 40 key Japanese fern species in gardening, horticulture and environmental studies in Japan, the author has shown that these ferns behave as key building blocks for the semi-wild and half man-made local ecosystems in gardens and agricultural fields. The author has also noted that these ferns are highly and actively communicating and competing with other organisms such as weeds, trees and insects, and also cope with environmental stress through rhizomes. Human-fern interaction may be one such interspecies communication.

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