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Growth and Morphological Characteristics of *Undaria pinnatifida* in the Cultivation Ground at Busan, Korea

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Monthly growth of a large brown alga, *Undaria pinnatifida*, was investigated during 5 months from November 2005 to March 2006 from a cultivation ground at Busan, Korea. A total of 10 character of *Undaria* were measured determine a reliable morphological character representing its growth of sporophytes. Plant weight of *Undaria* sporophytes increased steadily during the experimental period, the maximum weight was recorded as 9,344.6 g m^{-1} rope in March 2006. The optimal condition of their growing corresponded to that when the seawater temperature was decreasing and just before the coldest period of the year. Plant weight was positively correlated and fitted well with frond length, stipe length and midrib width. We suggest that plant weight with frond length, stipe length and midrib width is the most feasible morphological character with which to estimate the growth of *U. pinnatifida* sporophytes in the cultivation ground.

INTRODUCTION

The brown seaweed *Undaria pinnatifida* grows commonly in the temperate regions of Korea, Japan and China. It grows on rocks to a depth of 1–8 m below tidal level in open seas. Recently, *Undaria* has been found in the coasts of France, Britain, New Zealand, Australia and Argentina (Ohno and Largo, 1998). Moreover, *U. pinnatifida* is important as a nursery ground for marine animals and as food for marine animals and human in Asian countries (Koh and Shin, 1990; Choi *et al*., 2007).

It is an annual species with a life cycle typical of the Laminariales with alternating gametophytic and sporophytic generations. In Korea, sporophytes appear between October and November, and then grow rapidly from December to March when seawater temperatures are between 10 and 16 °C (Oh and Koh, 1996; Choi *et al*., 2007). Sporophytes of *U. pinnatifida* produce zoospores in spring from sporophylls positioned on the basal part of the stipe, and die off in summer with increasing temperature (Akiyama and Kurogi, 1982; Lee and Sohn, 1993).

In Korea, *U. pinnatifida* cultivation began with artificial seeding and experimental cultivation which started in 1964 (Sohn, 1993; Sohn, 1998). Experimental cultivation by artificial seeding began around 1950 and commercial cultivation was started from about 1960 in Japan (Saito, 1984; Ohno and Largo, 1998). Thereafter, the annual production of cultured *Undaria* rapidly increased from 110,000 tons (wet wt.) in 1973 to 410,000 tons (wet wt.) in 1994 (Sohn, 1998).

There are two forms of *Undaria*, i.e. the southern type and the northern type (Lee and Sohn, 1993). Compared to the southern form, the northern form has a longer stipe with sporophylls arising from the lower region with a deeply divided blade (Ohno and Matsuoka, 1993). This morphological character has very important implications for the efficiency of *Undaria* processing. However, variations in such characteristics are sometimes not significant and vary according to environmental conditions (Sohn, 1984). Recently, these morphological forms have been hybridized by cultivators to produce good shapes for harvesting and processing (Ohno and Largo, 1998).

Punched–hole and tagging methods have been applied to estimate the growth of *U. pinnatifida* sporophytes as has been done in kelp, but these methods are impractical because the frond is so thin and breakable in the field (Ishikawa, 1993; Castric–Fey *et al*., 1999a). Thus, it is necessary to find a suitable morphological character to estimate the growth of *U. pinnatifida* sporophytes and to know whether the vegetative growth stops as reproduction occurs. These data are invaluable in commercial seaweeds for estimating total production and deciding the harvesting period of *Undaria* sporophytes (Choi *et al*., 2007).

The aims of the present study were to examine the growth and morphology of *U. pinnatifida* in a cultivated population and to determine a reliable morphological character representing its growth.

MATERIALS AND METHODS

Sporophytes of *U. pinnatifida* were collected monthly in a cultivation grounds located in Busan, Korea from November 2005 to March 2006. During the study period, the average water temperature was 12.5±2.2 °C (mean ± standard deviation [SD]) and salinity was between 31.7 to 33.8 psu.

The cultivation ground was established 100–200 m

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from the shore. For cultivation in the sea, culture techniques (e.g., seeding, rearing, planting, and attaching to the main cultivation rope) of *U. pinnatifida* and a horizontal hanging from a single floating line method for cultivation were used as described by Ohno and Largo (1998). During September–October seeding strings are taken to intermediate culture grounds for the adaptation of the young sporophytes. After the young fronds have grown to 1–2 cm in length, the seed strings attached to the main culture rope in one of several ways. The main rope was suspended at 1m depth in the cultivation ground. All plants within 50 cm of cultivation ropes were collected using a knife on boat. *U. pinnatifida* sporophytes were collected from three different cultivation ropes in order to use replicates, and were transported to the laboratory using an icebox.

Weight (g m^{-1} rope) and density (plants m^{-1} rope) for each replicate were determined. The growth of *U. pinnatifida* sporophytes was measured for 10 characters (Fig. 1). Plants were weighed with a balance and the thickness of the midrib measured using a digital caliper. To determine a reliable morphological character representing the growth of *U. pinnatifida*, the relationships between weight and other growth characters were examined with all samples of 3 replicates (n=368).

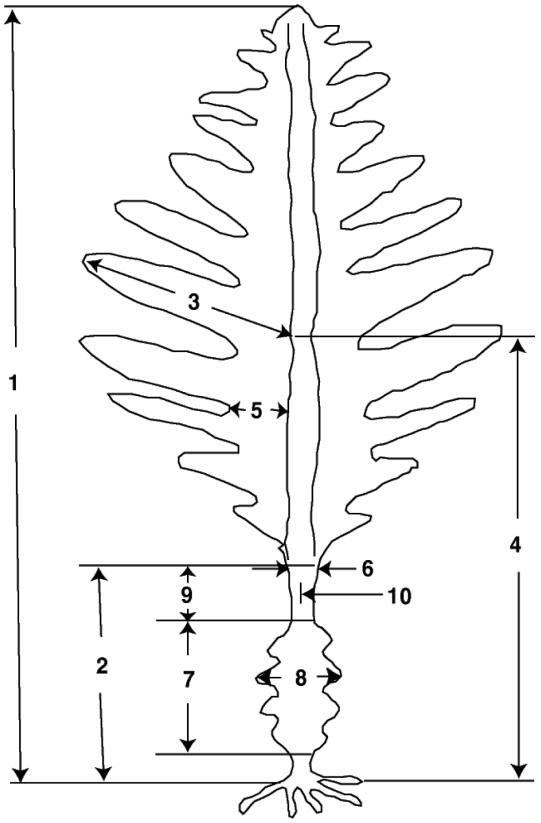

Fig. 1. Morphometric measurements of *Undaria pinnatifida*. 1: total length, 2: stipe length, 3: length of the longest pinnate blade, 4: length between the longest pinnate blade and holdfast, 5: undivided blade width, 6: midrib width, 7: sporophyll length, 8: sporophyll width, 9: length between blade and sporophyll, 10: thickness of the midrib.

RESULTS

Weight of *Undaria pinnatifida* rapidly increased, whereas density decreased over the study period (Fig. 2). The maximal weight was 9,344.6 g m^{-1} rope in March 2006, and the minimal weight was 183.8 g m^{-1} rope in November 2005. During the cultivation period, maximal weight was fifty times greater compared to initial plants (November 2005). Density decreased from 261.0 ±20.3 (mean ± SE, n=3 replicates) to 84.0±16.6 plants m^{-1} rope at the cultivation period from November 2005 to March 2006.

Sporophytes of *Undaria* grew fast both in plant length and width resulting in an increase of plant weight during the survey period (Fig. 3). Mean plant length was 9.1±6.8 cm (mean ± SE) in November 2005 and increased 135.7±27.8 cm in March 2006. Mean stipe length ranged between 0.74±0.74 g and 23.6±9.3 g (mean ± SE) with minimal and maximal values in November 2005 and February 2006, respectively. Midrib width of sporophytes steadily increased from 0.14±0.1 cm to 1.5±0.5 cm at the cultivation period.

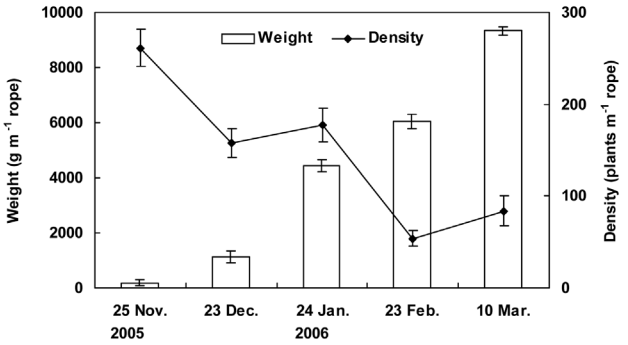

Fig. 2. Variation in weight and density of *Undaria pinnatifida* during the study period. Bars show standard errors (n=3 replicate ropes).

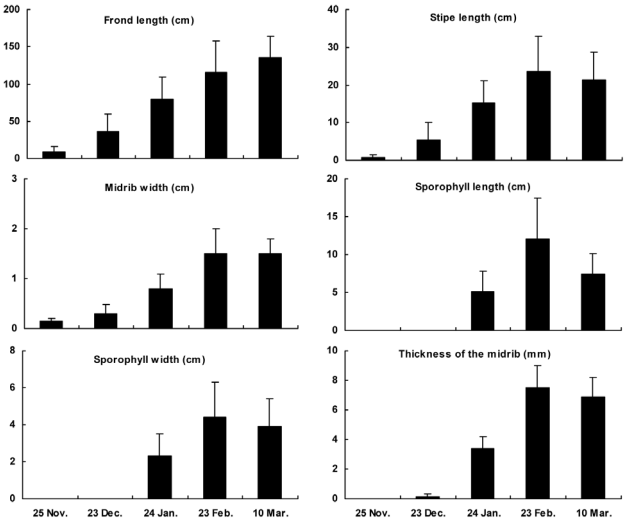

Fig. 3. Morphological variations of *Undaria pinnatifida* during the study period. Bars show standard errors (n=3 replicate ropes).

Also, sporophyll length, sporophyll width and thickness of the midrib increased over time, and they were also greater at the last period compared to the initial period. Formation of sporophyll was middle of December 2005 to early in January 2006 at the study period. In this study, *Undaria* sporophytes bearing sporophyll was measured on end of January 2006 during the survey period. At the initial survey, most of the plants had no sporophyll or formed without undulations. Over the cultivation period, sporophylls of *Undaria* formed undulation, and the sporophyll length increased from 5.1±2.7 cm to 12.1±5.3 cm (mean ± SE) and sporophyll width changed from 2.3±1.2 cm to 4.4±1.9 cm (mean ± SE), respectively.

Relationship between plant weight and morphological character of *U. pinnatifida* was positively correlated with frond length, stipe length, midrib width, and sporophyll width. But plant weight was negatively correlated with undivided blade width and sporophyll length (Table 1). Plant weight were adequate with midrib width (R^2=0.79, n=368), frond length (R^2=0.66, n=368) and stipe length (R^2=0.60, n=368), respectively. Plant weight were unsuitable with undivided blade width (R^2=0.06) and sporophyll length (R^2=0.24).

Table 2 shows the ratios of several important morphological characteristics of *U. pinnatifida*. Total weight (TW):total length (TL), length of the longest pinnate blade (LB):TL and sporophyll width (SW):length between blade and sporophyll (LW) ratios were continuously increased compared to initial plants ratios during survey period. Total weight:TL ratio was changed from 0.08 on November 2005 to 0.97 on February 2006. This increased value show that total weight was grow constantly rather than total length over the cultivation time. Total length has no affected with LW and undivided blade width (LM), because LW:TL and LM:TL ratios were decrease or similar at the study period.

Table 1. Relationship between plant weight and morphological character of *Undaria pinnatifida* (n=368)

Correlation	Equation
Weight vs frond length	Y=0.68x + 47.17, R^2=0.66
Weight vs stipe length	Y=0.16x + 4.73, R^2=0.60
Weight vs undivided blade width	Y=0.01x + 2.11, R^2=0.06
Weight vs midrib width	Y=0.01x + 0.28, R^2=0.79
Weight vs sporophyll length	Y=0.05x + 2.86, R^2=0.24
Weight vs sporophyll width	Y=0.02x + 1.13, R^2=0.48

Table 2. The ratio of several important morphological characteristics of *Undaria pinnatifid*a

Month	TW:TL	LW:TL	LB:TL	LM:TL	SW:SL	SW:LW
Nov. 2005	0.08	–	–	–	–	–
Dec. 2005	0.20	–	0.15	0.05	–	–
Jan. 2006	0.31	0.19	0.22	0.02	0.45	0.15
Feb. 2006	0.97	0.15	0.24	0.03	0.36	0.26
Mar. 2006	0.82	0.10	0.28	0.02	0.52	0.28

TW: total weight, TL: total length, LW: length between blade and sporophyll, LB: length of the longest pinnate blade, LM: undivided blade width, SW: sporophyll width, SL: sporophyll length.

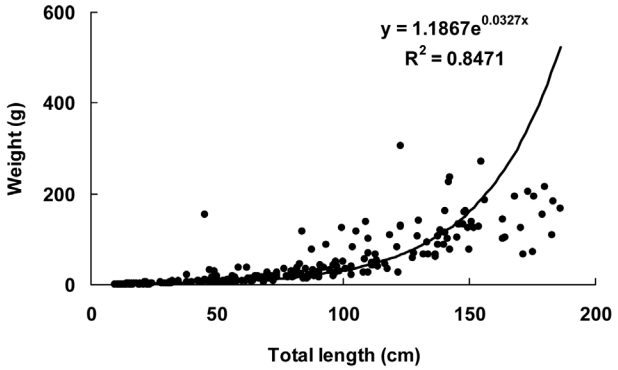

Fig. 4. The relative growth between total length and weight of *Undaria pinnatifida*.

The relative growth between total length and plant weight of *U. pinnatifida* was a high rate (R^2=0.85, Fig. 4). Total length was positively correlated with plant weight very higher until 100 cm plant length, but this growth patterns negatively change above 100 cm plant size at the cultivation period from November 2005 to March 2006.

DISCUSSION

It has been known through many floristic or ecological studies that *Undaria pinnatifida* (Harvey) Suringar was common in Korean waters (Lee and Yoon, 1998). Also the cultivation of this species has been very popular in the southern coast of Korea (Sohn, 1993). A great interest in the growth and morphology of *U. pinnatifida* has been made with the plants from cultivation farm (Saito, 1960; Sohn, 1984; Lee and Sohn, 1993; Ohno and Matsuoka, 1993; Kim and Nam, 1997). Due to its ecological and commercial importance, numerous studies on the various field of *U. pinnatifida* have been carried out (Yamanaka and Akiyama, 1993).

The growth of *U. pinnatifida* shows maxima in late winter to early spring. Numerous laboratory studies have documented seasonality in marine macroalgae (Oh and Koh, 1996). The season of fastest growth of *U. pinnatifida* in late winter is similar to that of *Ecklonia cava* (Laminariales) growing in far–east Asian coastal waters (Haroun *et al*., 1992). Choi *et al*. (2007) demonstrated that plant weight of *U. pinnatifida* sporophytes increased steadily over the experimental period in four different ways. It increased by both vertical and horizontal growth (Octerber–early December), and by horizontal growth with the thickening of blade and stipe when sporophytes began to be fertile. In the middle of January, vertical and horizontal growth had almost stopped with maturation. Finally, the weight increased again by horizontal growth at the end of February. In this results showed that the plant weight of *Undaria* sporophytes steadily increased over the cultivation period, and the growth of sporophytes very fast after December 2005. Weight of plants on January 2006 was

four times higher compared to initial plants (December 2005) with the thickening of blade and stipe.

Castric–Fey *et al*. (1999a) reported that midrib width is one of the parameters used to distinguish for growth from many morphological characteristics. Stipe length, which is more variable, does not seem significant (Taniguchi *et al*., 1981; Kito *et al*., 1981). Table 1 of our result showed that plant weights are positively correlated with midrib width and stipe length. According to the monthly result (Fig. 3), midrib width and stipe length steadily increased during the study period. Thus, midrib width and stipe length of *Undaria* sporophytes can be used as a suitable growth character.

The growth and reproduction of the kelp *U. pinnatifida* depend on the activity of the meristematic zone. When the meristematic zone is very active, the vertical elongation and horizontal expansion of *Undaria* sporophytes occur and plant weight increases rapidly (Choi *et al*., 2007). Weight and length of *Undaria* sporophytes continuously increased from initial stage, and vegetative growth was maintained during the cultivation period in the present study. Sporophytes start to form sporophylls, the meristematic region becomes inactive; the growth was retarded or stopped (Choi *et al*., 2007). But we cannot found retarded or stopped about the growth of *Undaria* sporophytes in this study.

Environmental factors are not necessarily responsible for the morphology of *Undaria* sporophytes also two forms of *Undaria*, i.e. *f. typica* and *f. distans* (Sohn, 1984; Castric–Fey *et al*., 1999a). According to the previous results (Sohn, 1984; Hara and Akiyama, 1985; Lee and Sohn, 1993), the descendants of the *Undaria* sporophytes contains the two forms grown experimentally in the same environment are still detectable by several characters: pinnule length, incision depth, midrib width, total length and weight of the thalli. Present results indicate that morphological character of *Undaria* sporophytes steadily increases over the experimental period, and several characters has to be a close similarities compare to previous results.

Studies on *Laminaria spp.* on European coasts suggest that the fastest growth and most active photosynthesis occur primarily in spring and summer (King and Schramm, 1976; Drew, 1983). In kelps, the activity of the growth is usually regulated by photoperiod or endogenous clocks (Lünning, 1993). When the plant growth is very active, the vertical elongation and horizontal expansion of *Undaria* sporophytes occur and plant weight increases rapidly. The results of the present study demonstrated a plant weight maximum in March 2006 when the thalli reached their maximum frond length. Although plant weight is a representative growth character, the growth estimation of *Undaria* sporopytes is not easy because of the growth pattern (Castric–Fey *et al*., 1999b). In the present study, it is difficult to determine clearly which factor was more responsible for growth and morphological character. Thus, we suggest that plant weight with frond length, stipe length and midrib width is the most feasible morphological character with which to estimate the growth of *U. pinnatifida*.

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