ランドサット TM データによる北印旛沼の ヒシのバイオマスの年変化の評価

Estimation of Yearly Changes of Waterchestnut Biomass in Lake North Inbanuma based on Landsat TM data

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論文要旨

近年、千葉県印旛沼において水性植物のヒシの繁殖が顕著である。このヒシの被覆面積の季節変動を調査するために、ヒシの群落に設けた10ヶ所のコドラートを2週間毎にボートから写真に記録し、群落の変化を観測した。試料のサンプリングを行い、実験室において葉面積指数(LAI)を計測すると共に、採集した試料をオープンで乾燥し、葉身、葉柄、茎等の構成部分の乾燥重量を測定した。

データを解析した結果、ヒシの葉の密度と葉面積は6月の末と9月の末に2つのピークがあることがわかった。また全乾燥重量を評価した結果、9月の末が年間の最大値で320g/m²を示した。これらの現地観測の結果と合わせてランドサット TM データによって湖全体のヒシの被覆面積とバイオマスを見積った。その結果、1984年から1987年にかけてその増加は著しいことがわかった。

Abstract : The waterchestnut (*Trapa natans* var. *japonica* Nakai) has been dominating the entire in Lake North Inbanuma, Chiba Prefecture, Japan. In order to investigate the seasonal variation of its surface coverage area, photographic recording of surface areas occupied by waterchestnuts in ten quadrats carried out from a boat every two weeks over a period of two years. In addition, the waterchestnuts were sampled to determine the dry weight of each part of them.

The seasonal variation of waterchestnut coverage area in all quadrats appears to be bimodal; there are two peaks which occurred at the end of June and at the beginning of September. During this period, the total biomass estimated from the laboratory measurements of the dry weight of each part of the waterchestnuts is 320g/m².

The geographical distribution of waterchestnuts over the whole lake can be mapped on the basis of the Landsat TM data. The combination of remotely sensed infestation areas with the directly determined coverage areas and dry weight of waterchestnuts allows us to estimate the total biomass in each component of the waterchestnuts in the whole lake.

1. Introduction

The Chiba Prefectural Laboratory of Water Pollution¹⁾ summarized the results of comprehen-

sive studies on the change of ecology in Lake Inbanuma. Some results useful as a background for the present studies are briefly described below. Eutrophication of the water in the Lake North Inbanuma has progressed rapidly in the last 25 to 30 years. This is ascribed to the recent intensive industrial and other human activities around the Lake including the area reduction of the Lake through reclamation. Eutrophication of the Lake has been accelerated by the fact that the water depth is

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shallow (<3m). As a result of eutrophication, the ecology of the Lake has greatly changed. For example, the change in the dominant species of aquatic plant in summer has been outstanding; aquatic plants such as reed (*Phragmites australis* W. Clayton), cat-tail (*Typha latifolia* L.) and vegetable wildrice (*Zizania latifolia* Turcz) were the dominant species in the coastal region of the Lake, but they have been replaced, year by year, by the waterchestnut (*Trapa natans* var. *japonica*, Nakai) which is active in eutrophic water. The growth form of the waterchestnuts is depicted in Fig. 1.

Fig.1 Schematic growth form of waterchestnut (*Trapa natans* var. *japonica* Nakai).

At the initial stage of infestation (around 1965), the waterchestnut distribution was restricted to the coastal zones. Recently, however, they have occupied larger areas toward the center of the lake. In fact, the waterchestnut leaves have occupied the lake surface even in the center of the Lake during the summer season for the past ten years, such that they have even caused serious damage to the navigation of fishing boats. This recent situation is demonstrated in Fig. 2 which is the infrared aerial

photograph taken from on airship on August 26, 1987. In the photograph, the infestation area appears as pale pink. Thus, the waterchestnut infestation in Lake North Inbanuma has become a serious problem in recent years. For improving this situation, a suitable counter-plan should be investigated thoroughly. In this case, the temporal and spatial distribution of the waterchestnut must be known in a quantitative base. This because the temporal and spatial variation of waterchestnut infestation areas extending over vast areas is large. However a direct ground survey of their infestation area over the whole lake is impractical and uneconomical. Accordingly, up to date, little information on the waterchestnut distribution is available on the whole Lake although the seasonal variation of biomass in fixed quadrats are reported by Ishiyama et. al.²⁾.

The remote sensing technique for estimating the distribution is very attractive and useful because it can collect simultaneous data from a large area. Application of remote sensing to mapping aquatic plants has previously been attempted by other investigators. For example, Link and Long³⁾ mapped aquatic plant infestation in lakes from infrared aerial photographs. Using the Landsat MSS data, the area coverage of water hyacinth was mapped by Bina et al⁴⁾. A multi spectral approach to monitoring giant kelp resources is reported by Jensen et al⁵⁾. Judging from their results, the waterchestnut in Lake North Inbanuma may be also mapped by the remote sensing data. For reliable measurements, however, remote sensing data with excellent spatial resolution is desirable. The waterchestnut infestation areas evaluated from the Landsat MSS may not give reliable spatial distribution because of the low spatial resolution. On the other hand, the Landsat TM with the improved spatial resolution provides a detailed distribution of the waterchestnuts. Therefore, the TM data acquired on July 31, 1984, Aug. 6, 1986 and July 24, 1987 are used to evaluate the waterchestnut infestation areas in Lake North Inbanuma.

Fig. 2 Infrared aerial photograph of eastern part of Lake North Inbanuma taken by airship on August 25, 1984.

Fig. 3 Quadrat location in the Lake North Inbanuma are shown by the numerals on Landsat TM imagery (Aug. 31, 1984).

2. Methods

The seasonal variation of the waterchestnut in the Lake North Inbanuma was observed from 1984 to 1986 by Kurihara et al. They observed directly the coverage areas of the waterchestnut leaves and also determined the biomass in each component of them in terms of the dry weight of the waterchestnuts sampled in ten quadrats in the lake. The waterchestnut coverage areas within quadrats of $1 \times 1 \text{ m}^2$ was determined by photographs taken from a boat about every two weeks in the growth season from 1984 to 1986. The surface coverage areas determined by the photographs in ten quadrats were averaged. The quadrat location selected in Lake North Inbanuma is shown on the Landsat TM imagery in Fig. 3. At the same time, the waterchestnuts growing within the quadrats were plucked by the roots. The number of both leaves and rosettes from the sampled waterchestnuts were recorded in each quadrat. Further, the length and width for more than three leaves of an individual waterchestnut were measured and averaged to assess the mean areas of leaves. From the mean leaf areas together with the number of leaves, the leaf area index (LAI) is calculated.

The sampled waterchestnuts were then separated into six components: leaf, stalk, petiole, roots above and below the bottom and seed. After each component was placed on 80°C oven for 48 hours and dried, the dry weight of each component was determined gravimetrically.

3. Results and discussion

3.1 Seasonal variation of waterchestnut biomass.

As shown in Fig. 4, a bimodal seasonal variation of the leaf coverage areas was observed. The waterchestnut begins to grow at the beginning of May. At the end of May, when the main stalk first reaches the lake surface, the coverage area in a quadrats is

Fig. 4 Seasonal variation of density and coverage area of waterchestnut leaves.

about 25%. The coverage areas increases quickly towards the first peak with 80% at the end of June. After attaining a peak, an increase in the number of withered leaves results in a decrease of the coverage area; at the end of July, the coverage areas decreases to a minimum of 60%. Then, the coverage area again increases gradually and attains a second peak at the beginning of September. In this case, the coverage is about 90% indicating a slightly larger value than that for the first peak that occurred at the end of June. The coverage level of about 80% is kept for a month, followed by an abrupt decrease at the beginning of October.

The seasonal variation of rosette density is also shown in Fig. 4. A similar pattern of variation to that for the coverage of infestation areas is kept until the end of July. However, the second peak in rosette density appears earlier, in the middle of August, than that in the coverage areas. From this peak stage to the decay stage appearing of the beginning of November, an inverse relationship between density and coverage is found. This inverse relationship is ascribed to an insufficient light intensity level. The low light intensity below the surface results from the shadowing causes by the surface leaves of a dense population. After and before the first peak stage, however, the parallelism between the coverage areas and rosette density was kept although shadowing by the surface leaves may occur in a similar way. This is due to the fact that the underwater light intensity from spring to sum-

mer is stronger than in the autumn because direct sun light itself arriving at the water surface is stronger than in autumn and also, that the average attenuation of under water light coming from near the zenith is smaller than that for more oblique beams in autumn.

On the other hand, the seasonal variation of LAI which is defined by the total leaf area in a water column with in a $1 \times 1\text{m}^2$ quadrat is shown in Fig. 5. The shape of seasonal variation is very similar to that for the rosette density. This is reasonable because the LAI, like the rosette density, may obey the inverse relationship to the coverage area after the second peak stage. A peak in the LAI of nearly 2.0 was found of the end of both June and August. Accordingly, the total area of leaves placed continuously in horizontal direction without piling up against one another can make a double layer in a water column. Experimental facts obtained by Whittker⁶⁾ suggest that LAI for terrestrial plants such as a tree range, from 4 to 6, in general, but LAI obtained here for the waterchestnut indicated at most 2.0. This discrepancy is ascribed to the lower light intensity in the water than on land because of the mainly strong light absorption of the water.

Fig. 5 Seasonal variation of LAI and divided by coverage area of waterchestnut.

On the other hand, Ikushima⁷⁾ reported that LAI for aquatic plants usually ranges from 1 to 2. Accordingly, LAI for the waterchestnut is larger than that for other aquatic plants suggesting that the waterchestnut is adaptable not only to a strong

light field, but also to a weak light one. LAI divided by coverage areas at the surface is calculated and plotted also in Fig. 5. LAI/(coverage area) is an indicator for the piling of leaves which refers to the number of a hypothetic layers having equal coverage area to that at the surface. Since the LAI/(coverage area) is 2.7 during the peak period, it follows that a nearly triple layer, which has an equal coverage area density at the surface, is formed in the water column during this peak period.

Fig. 6 shows the seasonal variation of biomass in each component of the waterchestnut. All the components, except the seed, grow very fast after the seed sprouts. Faster growing is observed just after the leaves reach the surface at the end of May, and then in each component to the first peak at the end of June. In this case, the leaves share a large part (40%) of total biomass of 190g/m^2 in terms of dry weight suggesting a large amount of the photosynthetic products are distributed to the leaves. After attaining the peak, the leaf share decreases rapidly as the result of an increase in the number of withered leaves. During this period, not only the leaves, but also other components (except the roots) decrease, reaching a minimum of the end of July. Then, they gradually recover, followed by the second peak of the end of September. Flowering begins of the end of August and the seeds are formed from September. In the middle of October, the seed share exceeds 40% of the total biomass. At the same time,

Fig. 6 Seasonal variation of waterchestnut biomass in each component.

the total biomass is 320g/m² , the maximum attains during the year.

Accordingly, a large amount of photosynthetic products are stored in the seeds just after the other components attain the second peak at the end of September. Thus the annual variation of the waterchestnut coverage area, as well as in the biomass of each component in ten selected quadrats has been obtained experimentally. However, the total infestation areas and biomass over the whole Lake is still unknown. The seasonal trend of the waterchestnut cycle obtained in the ten quadrats in the present study is probably similar to that in other parts of the Lake. However, even if a similar variation is accepted all over the Lake, the total biomass for the whole Lake is still unknown since little quantitative information above the spatial distribution of the waterchestnut infestation area is available.

3.2 Analysis of the satellite image

A direct survey of the infestation area of a large area is impractical and uneconomical. With the capability of observing a wide area nearly simultaneously and being able to repeat it with the same sensor, a satellite observation offers a powerful tool for this purpose. The estimation of the total waterchestnut infestation area has been attempted from the radiance collected by Landsat TM over North Lake Inbanuma. The false color images of Landsat TM (path=105 and row=37) collected on July 31, 1984, Aug. 6, 1986 and July 24, 1987 are shown in

Figs. 7a, 7b and 7c, respectively. For comparison, the false color image obtained in the winter season (Jan. 7, 1985) is also shown in Fig. 7d. As seen from the figures, most of the lake surface in summer is covered by waterchestnut leaves, but no waterchestnut signature is found in winter. Comparison of these images obtained in the summer season in different years, indicates a remarkable extension of the waterchestnut coverage area during this three years period.

The total area covered by the waterchestnut leaves can be estimated in a quantitative base in each year ; the infestation areas were obtained by summing up the pixel which shows a strong intensity on the false color imagery. Strictly speaking, this estimation method is rough. Mathematical treatment of the infestation area is presented and discussed by Ishiyama and Sugihara⁸⁾. They show that the result from the present estimation method, in general, agrees with those obtained mathematically. Accordingly, the present results of infestation areas are believed to be reliable. The area coverage of waterchestnut infestation, and their ratio (percentages) to total Lake area when the Landsat overpassed each year is given in Table 1. The increase in the coverage area with each year is remarkable ; the percentage of the leaf coverage area in 1984 and 1987 were 28.5% and 54.1%, respectively, indicating a doubling in just three years. It should be noted here that the infestation of waterchestnuts was still progressing during the period for

Table 1 Estimated coverage area of waterchestnut in North Lake Inbanuma based on Landsat data.

Satellite Overpass	Estimated Coverage Area(ha)	Coverage Ratio(%)
1984.7.31	144.5	28.5
1986.8. 6	194.3	38.4
1987.7.24	273.9	54.1

(Total area of North Lake Inbanuma: 504 ha)

(a)

(b)

(c)

(d)

Fig. 7 False color TM images of Lake North Inbanuma. (a : Jul. 31, 1984, b : Aug. 6 1986, c : July 24, 1987, d : Jan. 7, 1985).

Table 2 Estimated dry biomass of waterchestnut in North Lake Inbanuma.

Year/	1984	1986	1987
Satellite Overpass	190.8	256.5	361.6
Maximum Values in the Year	462.6	621.8	876.6

(unit: 10^3 kg)

three years beginning in 1984, although eutrophication of Lake North Inbanuma had already begun around 1965.

As described before, we estimated the area coverage and the biomass of the waterchestnut in terms of dry weight within a quadrat measuring 1m^2 . On the basis of these results and the total coverage area of the waterchestnuts obtained here, the total biomass of the waterchestnut in terms of dry weight in the whole Lake is estimated on each day of a Landsat overpass assuming that the relative annual variation of biomass is constant. Specifically, biomass is obtained by multiplying the total biomass in a quadrat by satellite determined coverage area. The results in each year are given Table 2 along with the maximum dry weight. At least $876 \times 10^3\text{kg}$ of dry weight of waterchestnut biomass was produced in 1987 in Lake North Inbanuma.

In autumn, all parts of the waterchestnut except the seeds are resolved into particulate or dissolved matter. Some fraction is stored in the lake and some flows out of the lake through rivers. As far as only these processes are taken into consideration, the amount of materials in the lake might decrease. However, larger amount of materials actually flow into the lake from rivers so that the lake water becomes richer in nutrients every year. This can explain the rapid increase in waterchestnut infestation. In fact, a large amount of material flow into the lake via rivers is reported (The Chiba Prefectural Laboratory of Water Pollution¹⁾).

The waterchestnut infestation in Lake North Inbanuma progressed rapidly during the period between 1984 and 1987. Since the situation is serious, a suitable counter plan should be presented and practiced as soon as possible. In discussing the counter plan, the spatial and temporal variation in the waterchestnut infestation becomes necessary. However, it is not easy to obtain this data by direct surveys since the spatial and temporal variation is large. With a capability of observing a wide area nearly simultaneously and in a repetitive manner, optical remote sensing offers a powerful tool for this purpose. In this case, the remote sensing data collected by a sensor giving excellent spatial resolution such as Landsat TM should be used for obtaining a detailed distribution.

It should be noted that the remote sensing technique can study the surface area covered by the waterchestnut leaves present only at the water surface. On the other hand, LAI, which is also an important biological parameter, estimates the total leaf area in a water column. Accordingly, the difference between them becomes large when the waterchestnut leaves pile up on one another and when they are present below the surface. On the contrary, if the waterchestnut density is small, the difference appears to become smaller. In this case, however, the remote sensing technique will treat them as water area (not infestation area). Thus, an accurate LAI is not obtained directly from the remote sensing data alone. Only if the true lake data is available (as

that in the present study), or a relationship between them is present and determined, LAI can be derived from the remote sensing data. Even in this case, however, it is desirable that the total infestation area is determined from the waterchestnut leaf density in each pixel of the remote sensing data, if possible. An approach to retrieving the density in each pixel may be obtainable by introducing of the linear mixing model. This algorithm and its application to the waterchestnuts in the Lake is presented and discussed by Ishiyama and Sugihara⁸⁾.

4. Conclusion

- 1) The seasonal variation of the surface waterchestnut leaf coverage area in lake North Inbanuma was photographed every two weeks in ten quadrats selected on the lake.
- 2) At the same time, the number and surface area of blades of waterchestnuts plucked by the roots were measured to evaluate the total blade area.
- 3) The dry weight of six components of the waterchestnut; blade, petiole, roots above and below the bottom, and seed (all of which were separated from the samples) was determined gravimetrically.
- 4) The seasonal variation of waterchestnut coverage area appears to be bimodal with peaks both at the end of June and at the beginning of September.
- 5) The horizontal distribution of waterchestnuts over the whole Lake was mapped on the basis of Landsat TM data.
- 6) Total biomass in the whole Lake is estimated from remotely sensed infestation areas along with directly determined coverage areas and the dry weight of waterchestnuts.
- 7) Comparison of satellite images collected in different years shows that waterchestnut infestation has progressed rapidly during the period between 1984 and 1987.

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