



Original Paper

Yearly Fluctuations in Honey Production in Hokkaido, Northern Japan, with Special Reference to Weather Conditions and Masting Behavior

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Abstract— The factors controlling yearly fluctuations in honey production are poorly understood. To evaluate yearly fluctuations in honey production, the coefficient of variation (CV) and the autocorrelation analysis were used to determine the magnitude and periodicity of the fluctuations for seven major nectar-source plants (basswood, black locust, Amur cork tree, white clover, buckwheat, Kamchatka thistle, and horse chestnut) using 15-years of data obtained in Hokkaido, Japan. Regression analysis was conducted to evaluate the relationship between annual honey production and the corresponding weather conditions during the flowering month. The periodic synchronous flowering and fruiting observed in tree species is called masting or masting behavior. A masting model, based on the resource budget, was applied to tree species if periodicity was detected by an autocorrelation analysis. The CV differed markedly among species. Black locust and the Amur cork tree had the smallest and largest CVs, respectively, whereas basswood was periodic. A negative correlation was observed between monthly precipitation and honey production in black locust, white clover, thistle and the Amur cork tree. This result implies that rain inhibits honey bee foraging. Production of buckwheat honey, however, tended to increase with increasing mean temperature. It might be difficult to detect the effect of rain on the honey production using buckwheat presumably because of the long flowering period. Annual honey production in basswood could be described by the resource budget model, but not in horse chestnut. Some horse chestnut trees produce flowers even in non-mast year implying that it was difficult to detect the periodicity in this species. According to beekeepers, honey production in this last decade in Hokkaido has been disrupted by climate change and the transitioning of the industrial structure.

Keywords—Coefficient of variation, Periodicity, Rain, Resource budget model, Wholesale price

I. INTRODUCTION

Though there was growing concern about the pollination service of honey bees for crop monocultures after Colony Collapse Disorder [2], honey production is the regular business of beekeepers since honey is their most valuable commodity. Beekeepers must secure nectar-source plants to manage their honey bees, select apiary sites carefully, and move beehives to a new apiary during the flowering season for honey bees to forage.

Annual honey production shows yearly-fluctuation if beekeepers depend on wildflowers as their nectar source, since honey production is influenced by the weather conditions during flowering [5, 11, 24]; *i.e.*, honey bees cannot work outside of their beehive on a rainy day [28]. But few reports are available on the quantitative relationship between weather condition and the honey production [14]. On the other hand, tree species often show periodic synchronous flowering and fruit production called masting or masting behavior [13, 17, 22]. Honey bees can collect little nectar from trees in a non-mast year [19]. However, no researchers have taken the masting into consideration to evaluate the fluctuation in annual honey production, and it has been explained empirically by beekeepers. For example, Hill and Webster [7] regretted that “*unfortunately, only incomplete and anecdotal reports of flowering intensity exist in most cases*”.

Because recent climate change may have a substantial impact on the honey bee activity and the production of honey [14], we must understand the mechanism underlying the yearly-fluctuation in the honey production to predict the effect of climatic change. This study focuses on a record that has been collected over a period of 15 years with different major nectar-source plants in Hokkaido, northern Japan. In the present study, the following two questions were addressed: 1) What trends can be discerned in annual honey production according to the nectar-source plants? and 2) To what extent do the weather conditions, *i.e.*, monthly precipitation and mean temperature, affect honey production?

II. MATERIAL AND METHODS

A. Focal nectar-source plants

Seven major nectar-source plants are found in Hokkaido: black locust (*Robinia pseudoacacia* L., Fabaceae), basswood (*Tilia japonica* [Miquel] Simonkai and *T. maximowicziana* Shirasawa, Malvaceae), white clover (*Trifolium repens* L., Fabaceae), Kamchatka thistle (*Cirsium kamtschaticum* Ledeb. subsp. boreale [Kitam.] Kitam., Asteraceae), the Amur cork tree (*Phellodendron amurense* Rupr., Rutaceae), buckwheat (*Fagopyrum esculentum* Moench, Polygonaceae), and horse chestnut (*Aesculus turbinata* Blume, Sapindaceae) in

decreasing order of the annual honey production [18]. These nectar-source plants are distributed heterogeneity in Hokkaido depending on either regionality of natural vegetation or land-use [18, 19]. Basswood, Kamchatka thistle (hereafter, thistle), the Amur cork tree, and horse chestnut are major components of the natural vegetation in Hokkaido [8, 9], whereas black locust is a non-native species in Japan. Large black locust forests have been established in former coal mine areas in central Hokkaido [33]. Black locust stands are also observed in riparian forests due to river modifications [23]. White clover is often sown on the ranches, and large ranches have developed in the Pacific coastal and Okhotsk coastal regions due to the cool summers [34]. Buckwheat fields are increasing due to the rice paddy acreage reduction program [19]; i.e., rice fields are often replaced by buckwheat fields. These observations show that the production of some honeys in Hokkaido strongly depends on the history of land use.

B. Data analyses

i. Yearly fluctuations in honey production

Statistical apiculture data in Hokkaido have been collected in the ‘Annual report of nectar source plants’ since 2007 by the Livestock Production and Feed Division in Hokkaido Prefecture via the Hokkaido Apicultural Association. The number of members of beekeepers in the association is 180 – 200. This report includes the location and duration of the establishment of each apiary, the number of beehives and target plants at each apiary, the total amount of apicultural products (honey and beeswax), pollination, and the frequencies of diseases and bear attacks. The amounts of honey produced from the seven major nectar-source plants and ‘other honeys’ are also recorded. The other honeys include multifloral flower honey and minor single-flower honeys. In this study, the annual amount of honey produced using the seven major nectar-source plants during 2007–2021 (14 years; 2008–2021 for horse chestnut and thistle) was the focus.

ii. Effect of weather conditions on annual honey production

Climate differs markedly among regions, because Hokkaido is surrounded by three seas: i.e., the Japan Sea, the Pacific Ocean, and the Okhotsk Sea, and a mountain range stretches north to south that prevents the north-eastern monsoon. Although the amount of honey produced is aggregated for all of Hokkaido, the main target nectar plants differ among regions [18]. Therefore, the most representative weather station sites of the Japan Meteorological Agency (JMA) were selected for each region (Fig. 1). Weather stations were selected to refer interview survey with the beekeepers [cf. 18]. Basswood is a major target in northern Hokkaido and the back-country of Tokachi in eastern Hokkaido and, therefore, the weather station sites at ‘Nayoro’ and ‘Kamishihoro’ were selected. The weather station site at ‘Sapporo’ was selected for black locust because black locust is a major nectar-source plant in central Hokkaido. White clover is dominant on the Pacific

and Okhotsk coasts due to the large number of ranches, and weather station sites at ‘Urakawa’, ‘Obihiro’, ‘Kushiro’, ‘Nemuro’, and ‘Monbetsu’ were selected. Buckwheat honey is mainly collected in the northern and central Hokkaido. Horokanai and Fukagawa are the major production areas for buckwheat; therefore, the weather station sites at ‘Horokanai’ and ‘Fukagawa’ were selected. Thistle honey is also collected in the northern part of Hokkaido, and the weather station site at ‘Kitami-Esashi’ was selected. The Amur cork tree honey is also collected in northern Hokkaido; thus, the weather station site at ‘Toyotomi’ was selected for the Amur cork tree. As horse-chestnut is naturally distributed and restricted to southwestern Hokkaido, the weather station sites at ‘Otaru’ and ‘Esahi’ were selected. Otaru is at the northern limits of the horse-chestnut distribution in Hokkaido. Weather data during the flowering month was obtained at the JMA website as follows: May for horse chestnut; June for black locust, white clover and the Amur cork tree; July for basswood; July–August for thistle; July–September for buckwheat. Sum of monthly precipitation and mean monthly temperature during the period were used for thistle and buckwheat.

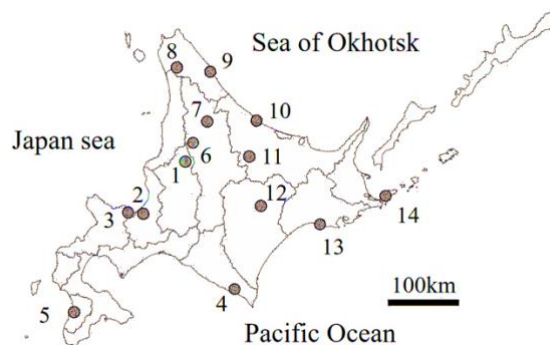


Fig. 1. Location of weather station sites in Hokkaido. 1, Fukagawa; 2, Sapporo; 3, Otaru; 4, Urakawa; 5, Esashi; 6, Horokanai; 7, Nayoro; 8, Toyotomi; 9, Kitami-Esashi; 10, Monbetsu; 11, Obihiro; 12, Kamishihoro; 13, Kushiro; 14, Nemuro.

iii. The model with reference to masting behavior

If periodicity is detected in the focal tree species by the autocorrelation analysis, the masting model will be applied to the species. The model is based on the negative correlation between the current year t_2 and the latest odd lag year t_1 . It is because that trees often produce few flowers in the following mast year [17]. Thus, honey production during the current year t_2 (Pt_2) is the objective variable, whereas honey production during the latest odd lag year t_1 (Pt_1), and the weather conditions during the flowering period of the current year t_2 (Wt_2) are explanatory variables.

iv. Statistical analyses

Regression analysis was carried out between the annual honey production and the corresponding weather conditions during the flowering period. We conducted the

autocorrelation analysis using R ver. 4.1.2 [25], employing the “acf” function. Box-Ljung test was used to verify whether a group of autocorrelations are different from zero. The model with reference to masting behavior was evaluated using a generalized linear mixed model (GLMM). Monthly precipitation and monthly mean temperature (Wt2) were set as explanatory variables. Response variables (Pt2) were assumed to follow a normal distribution. The “glmer” function was used for GLMM. The effects of weather conditions were evaluated by the combination of four conditions; i.e., 1) precipitation and temperature, 2) precipitation only, and 3) temperature only. 4) No weather condition is the null model, where weather condition has no effect on the response variable. Akaike’s information criterion (AIC) was used to identify the best GLMM [1, 4]. The model with the smallest AIC was considered the best model for explaining each variable. ΔAIC is the difference between the best model and each other model in the set. If the model with the second smallest AIC value was simpler with fewer parameters than the best model, the second model should be employed to follow principle of parsimony under $\Delta AIC < 2$ [4, 19]. The best model for masting was also selected in a similar way as mentioned above.

III. RESULT

A. General aspects of annual honey production

The mean frequency of annual honey production is shown in Fig. 2 in decreasing order. Average annual production of basswood honey during the study period (91.1 ton/yr.) was a little more than that of black locust honey (91.0 ton/yr.) in this study, although [16] documented that average annual production of black locust honey was the greatest among the major nectar-source plants.

The yearly fluctuation in honey production is shown in Fig. 3. Annual honey production in basswood increased and then decreased every other year. The maximum honey production using white clover, buckwheat, and thistle was observed in 2011. The maximum peak was observed in 2021 for black locust, and the Amur cork tree and thistle also showed good crop in this year. The smallest and largest CVs were observed in black locust and the Amur cork tree, respectively (Fig. 4).

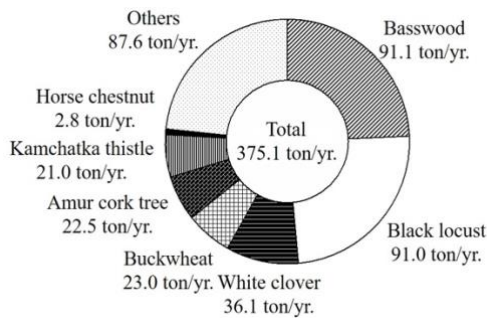


Fig. 2. Mean annual honey productions in Hokkaido with different major nectar-source plants and others. Others includes the mixed honeys and minor nectar-source plants.

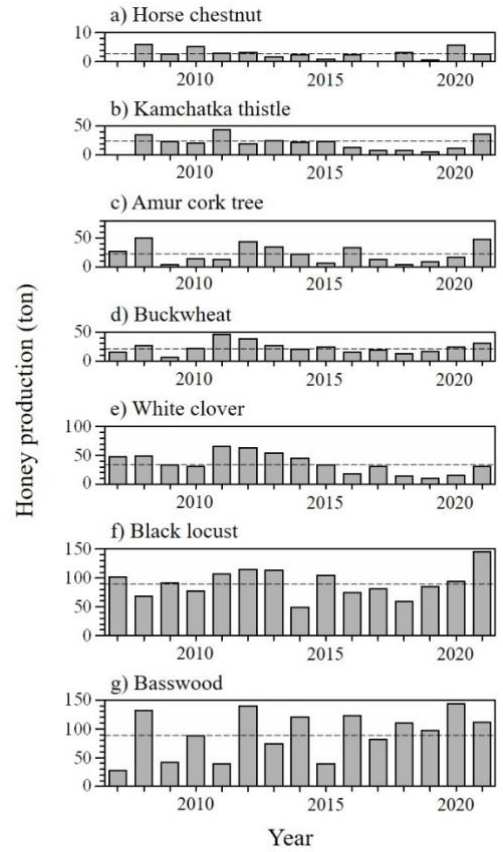


Fig. 3. Yearly fluctuation in honey production with different major nectar-source plants. Dashed line indicates the average value. No data in 2007 for Kamchatka thistle and horse chestnut.

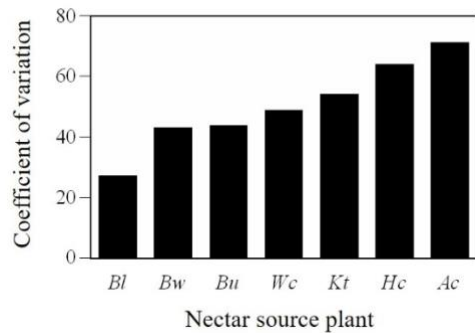


Fig. 4. Coefficient of variation (CV) in annual honey production with different major nectar-source plants. Bl, black locust; Bw, basswood; Bu, buckwheat; Wc, white clover; Kt, Kamchatka thistle; Hc, horse chestnut; Ac, Amur cork tree.

B. Relationship between honey production and weather conditions

Results of regression analyses between honey production and the corresponding monthly weather conditions during the flowering period were shown in Table 1. Significant negative correlation was found in the relationship between the precipitation and annual honey production using black locust, white clover, and the Amur cork tree, respectively. A negative sign indicates that annual honey production of these four

species decreased with increasing precipitation in the flowering month (Table 1). The monthly temperature did not contribute to annual honey production for the nectar-source plants except for buckwheat. A positive sign indicates that annual honey production using buckwheat increased with increasing mean temperature during the flowering period (Table 1). A non-significant correlation was detected in basswood and horse chestnut (Table 1).

TABLE I. REGRESSION COEFFICIENT OF THE RELATIONSHIP BETWEEN ANNUAL HONEY PRODUCTION AND WEATHER CONDITION AT THE CORRESPONDING FLOWERING MONTH(S) FOR CONSECUTIVE 15 YEARS (14 YEARS FOR THISTLE AND HORSE CHESTNUT). SIGNIFICANT COEFFICIENTS WERE WRITTEN IN BOLD.

Nectar source plants	Weather station site	Period	Correlation coefficient	
			Precipitation (mm)	Mean temperature (°C)
Horse-chestnut	Otaru	May	-0.204 ^{ns}	-0.402 ^{ns}
	Esashi	May	0.281 ^{ns}	-0.485 ^{ns}
Kamchatka thistle	Kitami-Esashi	Jul. – Aug.	-0.654*	0.212 ^{ns}
Amur cork tree	Toyotomi	July	-0.582*	0.525*
Buckwheat	Horokanai	Jul. – Sep.	0.148 ^{ns}	0.645*
	Fukagawa	Jul. – Sep.	0.022 ^{ns}	0.645*
White clover	Urakawa	June	-0.646*	-0.239 ^{ns}
	Obihiro	June	-0.425 ^{ns}	0.028 ^{ns}
	Kushiro	June	-0.525*	-0.211 ^{ns}
	Nemuro	June	-0.551*	-0.190 ^{ns}
Black locust	Monbestu	June	-0.427 ^{ns}	-0.164 ^{ns}
	Sapporo	June	-0.532*	-0.213 ^{ns}
Basswood	Nayoro	July	0.137 ^{ns}	0.286 ^{ns}
	Shirataki	July	-0.138 ^{ns}	0.130 ^{ns}

Notes: *, $p < 0.05$; ns, non-significant.

C. Periodicity in the yearly fluctuations in honey production using tree species

Autocorrelation analysis revealed that only basswood was periodic (Box-Ljung test, $p < 0.001$), whereas no significant periodicity was detected for the other tree species (Fig. 5). In basswood, positive correlations were found at the even lags, while negative correlations were found at the odd year lags.

TABLE II. BEST MODEL FOR THE ANNUAL HONEY PRODUCTION USING BASSWOOD BASED ON THE MASTING MODEL. COEFF., ESTIMATED COEFFICIENT; SE, STANDARD ERROR; PT1, HONEY PRODUCTION IN THE PREVIOUS YEAR.

Variables	Coeff.	SE	t
Intercept	176.838	16.956	10.429
P_{t-1}	-0.556	0.129	-4.313
Precipitation	-0.243	0.075	-3.223

Notes: Variance and standard deviation (\pm SD) of the random effect of the intercept and the residual was $0 (\pm 0)$, $684.8 (\pm 26.17)$, respectively.

D. The model with reference to masting behavior

As periodicity specific to masting was detected only in basswood, then the resource budget model was applied only to basswood. GLMM analysis revealed that precipitation was included in the best model (Table 2), implying that the rain decelerated the annual honey production using basswood. Temperature was not included from the analysis because of the multicollinearity.

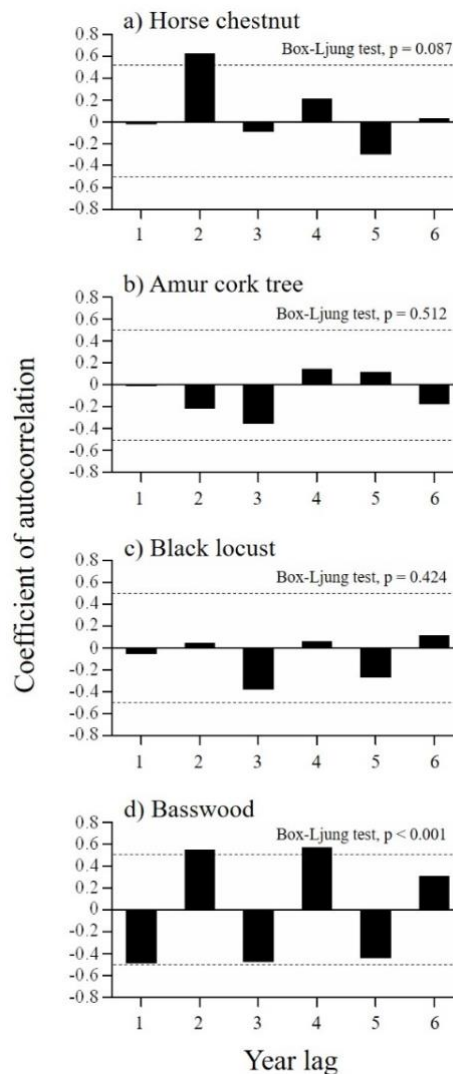


Fig. 5. Coefficients of autocorrelation in annual honey production with different nectar-source trees. Dashed line indicates 95% confidence interval.

IV. DISCUSSION

Annual honey production showed species-specific yearly fluctuations in magnitude and periodicity (Fig. 2 and 3). Weather conditions play a vital role in honey production. For example, we experienced brutal heat with average annual precipitation in 2011 summer in Hokkaido [27], in which the beekeepers enjoyed the best crop for white clover, buckwheat and thistle (Fig. 3). In this study, precipitation rather than temperature explained the annual honey production using white clover, black locust, thistle, and the Amur cork tree, whereas

temperature explained buckwheat (Table 1). As rain inhibits foraging by honey bees [32], honey production in this study was regulated by the rain during the flowering period. Whereas temperature can also contribute to the honey crop [cf. 14]. After the long decreasing trend in white clover since 2011, beekeepers enjoyed record honey production for black locust, thistle and the Amur cork tree (Fig. 3). We experienced record long drought summer in 2021 at the Japan Sea coast and Okhotsk Sea coast of Hokkaido [28]. Besides, mean temperature during flowering period was correlated with the annual honey production using buckwheat (Table 1). It does not necessarily mean that the honey production using buckwheat was not influenced by rain. Compared with the other nectar-source plants, buckwheat has longer flowering periods (Jul. – Sep.). For example, the nectar-producing period of black locust is 10–12 days [3]. The flowering periods of the Amur cork tree and horse chestnut are ca. 10 days [22] and ca. 15 days [35], respectively. It is considered that the long flowering period makes it difficult to detect the effect of rain on honey production in buckwheat.

In black locust, no periodicity in the yearly fluctuation of honey production was confirmed by the autocorrelation analysis (Fig. 5). The magnitude of the yearly fluctuation in black locust was the smallest among the seven major nectar-source plants (Fig. 4). Black locust is a legume that forms a symbiotic relationship with nitrogen-fixing soil bacteria [15]. Black locusts produce many flowers every year, presumably because the species is not nitrogen deficient. Consequently, rain during the flowering period, rather than the resource budget, was a major factor influencing yearly fluctuations in the production of black locust honey (Table 1). In addition to the recent good harvests of basswood honey (see Fig. 3), the long rain may also contribute to the change of the order between basswood and black locust. This does not necessarily mean that there are no internal factors in the yearly fluctuation of flowering. Hill and Webster [7] reported the phenomenon of dramatic flowering black locust in the Midwest and of southwestern USA in 1993, which beekeepers have never seen.

Similar to black locust, the periodicity was not also detected in the Amur cork tree (Fig. 5). In contrast to black locust, however, magnitude of the yearly fluctuation in this species was the greatest among the seven major nectar-source plants (Fig. 4). Mizui [21] investigated flowering and the seed crop of two Amur cork trees for 9–10 years in central Hokkaido, and concluded that the length of the periodicity was intermittent and the magnitude of the yearly fluctuation was low among 35 deciduous broad-leaved tree species. Terasawa [31] documented the magnitude of the yearly fluctuation in acorn production by Mizunara oak (*Quercus crispula* Blume var. *crispula*, Fagaceae), and found that the magnitude differed among regions in Hokkaido. Terasawa [31] reported a negative correlation between the magnitude of acorn production and warmth during the growing season. The main production area for the Amur cork tree honey is northern Hokkaido [18] where the climate is cooler than that of central Hokkaido. It can be

hypothesized that the cool climate caused the greatest CV in the honey production of the Amur cork tree.

Significant periodicity in the yearly fluctuation of honey production was found only in basswood (Fig. 5). It is well-known that basswood shows masting behavior every other year in Hokkaido [21]. In addition to the periodicity, precipitation during flowering period influence is likely to influence the annual honey production using basswood (Table 2). If the periodicity was not taken into consideration, the influence of precipitation could not be detected in this study.

In horse chestnut, neither the significant correlation with the weather condition nor the periodicity in the yearly fluctuation of honey production were detected in this study (Figs. 2 and 5). Yoshino and Taniguchi [35] and Taniguchi [30] investigated the fruit-bearing in horse chestnut growing in Hyogo Prefecture, western Japan, and documented masting behavior every other year. Horse chestnut trees produce seeds even during non-mast years [30, 35]. This characteristics of horse chestnut may have led to the non-significant result in the autocorrelation analysis. According to the beekeeper Y. Hasada, furthermore, flowering period of horse chestnut in Hokkaido has often overlapped with that of the black locust in the Tohoku District of Honshu Island over the past last decade, due to global warming. Traveling beekeepers give priority to black locust in the Tohoku District rather than to horse chestnut in Hokkaido because the wholesale price of black locust honey is much higher than that of horse chestnut honey (344.8–379.3 USD [50,000–55,000 JPY]/18-liter-square-can for black locust honey vs. 241.4–275.9 USD [35,000–40,000 JPY]/18-liter-square-can for horse chestnut honey [145 JPY/1 USD on 15 Aug. 2023]; beekeeper Y. Hasada, personal communication). The decrease in the production of horse chestnut honey in the last decade may have been caused by a change in the target nectar source based on the difference in the wholesale price of honey.

This study evaluated honey production at a specific period in time. The target nectar-source plants have changed over time, with changes in social conditions. For example, the main nectar-source plants in Hokkaido before World War II were basswood, white clover, and canola flower (*Brassica rapa* L. var. *nippo-oleifera*, Brassicaceae) [29]. The biomass of basswood in natural forests in Hokkaido has decreased because it is an important commercial tree species, and many natural forests have been replaced by monocultural conifer stands [16]. Replacing paddy fields with buckwheat fields can also affect the production of basswood honey. The flowering period of the early variety of buckwheat overlaps with that of basswood and causes a reduction in the production of ‘pure’ basswood honey (beekeeper H. Hashimoto at Bibai, personal communication). Notes that the demand for buckwheat honey is likely to increase due to health conscious in Japan (beekeeper H. Hasegawa at Horokanai, personal communication); i.e., buckwheat honey has high antioxidant activity and is rich in iron and potassium [10]. An increase of health intension will accelerate the production of buckwheat honey. As for canola, strained lee of canola seeds, i.e., oil cake, was used as an important fertilizer

in Japan until chemical fertilizer was available after WWII [12]. But canola honey is only one of the minor nectar-source plants in the present days. Large black locust forests in Hokkaido have been established in former coal mine areas [33] and riversides [23]. Annual production of black locust honey had a long lead in honey production over the other nectar-source plants in Hokkaido [16], though the amount of basswood honey production caught up with that of black locust honey production recently (see Fig. 2). Most coal mines in Hokkaido closed during the 1950s–1970s, indicating that the present stand age of black locust in central Hokkaido is 50–70 years. Since black locust is a pioneer species that lives for 90 years [5], the natural black locust forests will be replaced by shade-tolerant tree species in the future. These facts suggest that beekeepers will experience a loss of the black locust nectar source soon. Furthermore, an increase in the number of rainy days in June will inhibit black locust honey production as well as that of white clover, thistle and the Amur cork tree (Table 1). Sapporo Regional Headquarter, JMA [26] suggested an increase in the number of heavy rainy days in Hokkaido, associated with climate change, would occur. Trends in honey production should be watched carefully in relation to climate change [14] and regarding the transition of the industrial structure to the cultivation of nectar-source plants for apiculture in the future.

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