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Tadauchi, Osamu
Entomological Laboratory, Faculty of Agriculture, Kyushu University

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A Numerical Taxonomic Study of the Genus *Andrena* (Hymenoptera, Andrenidae) of Japan*

Osamu Tadauchi

Entomological Laboratory, Faculty of Agriculture,
Kyushu University 46-01, Fukuoka 812

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Numerical taxonomic relationships of eighty-five OTU's (operational taxonomic units) or taxa of the genus *Andrena* (Hymenoptera, Andrenidae) of Japan were studied based on 130 adult female morphological characters using five clustering methods. The phenogram derived from distance coefficient was much more congruent with the original matrix and the conventional classification than that derived from correlation coefficient. The position of each OTU was examined at the subgeneric level. The results were in considerable agreement with current classification. Twenty-three groups were developed in the 85 OTU's of the genus *Andrena* of Japan. Differences between numerical taxonomy and conventional classification were as follows: 1) the *ishikawai-taniguchiae* species group of the subgenus *Holandrena* was recognized better to be raised to the subgeneric level; 2) *amamiensis* was away from the subgenus *Notandrena*; 3) the *knuthi-knuthi okinawana* group was transferred to the subgenus *Chlorandrena*.

INTRODUCTION

In Japan the Andrenidae are represented by only two genera, *Andrena* and *Panurginus*, which belong to the independent subfamily, Andreninae and Panurginae, respectively (Hirashima, 1962). The genus *Andrena* which is one of the principal genera in the Japanese Apoidea is abundant both in species and individuals. Sixty-one species, one of which was divided into two subspecies, of the genus *Andrena* in Japan were classified into 20 subgenera by Hirashima (1962-1966). Tadauchi (1975) already studied numerical phenetic relationships of the genus *Andrena* of Japan based on 70 female characters derived from 60 species using three clustering methods and principal component analysis. Since the correspondence between conventional classification and numerical taxonomic grouping was found, Hirashima and Tadauchi (1975) erected a new subgenus *Oreomelissa*.

Recently Tadauchi (in preparation), Hirashima and Tadauchi (in preparation), and Hirashima, Tadauchi and Matsumura (in preparation) made a revisional study of the genus *Andrena* of Japan and found 13 new species. In the present study 85 OTU's (operational taxonomic units) or taxa including

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color forms and geographical forms as well as the above new species were investigated based on 130 female morphological characters. The purpose of the present study is to examine the position of each OTU at the subgeneric level. Further intent of this study is to make comparisons between the phenograms derived from correlation and distance matrices and comparisons among the phenograms based on the five clustering methods.

MATERIAL AND METHODS

Material

The material used in the present study was based on female specimens of 85 OTU's of the genus *Andrena* of Japan. The material is listed in Table 1 with subgeneric codes and OTU's code numbers. Among 85 OTU's there are 76 species, two subspecies of *A. knuthi*, two subspecies of *A.* (*Hoplandrena*) sp. 1 (Hirashima and Tadauchi, in preparation), two color forms of *A. mikado* (A is a blackish form and B is a fulvous one), four geographical forms of *A. takachihoi* (A is from Kyushu Mainland, B is from the Tsushima Island, both C and D are from Central Honshu), two geographical forms of *A. edashigei* (A is from the Amami Island and B is from the Okinawa-Honto Island), two geographical forms of *A. komachi* (A is from Kyushu and B is from Hokkaido), and two geographical forms of *A. kaguya* (A is from Kyushu and B is from Hokkaido). Since this study was restricted to the adult females, *A. macroceps*

Table 1. Eighty-five OTU's (taxa) of the genus *Andrena* of Japan used in the present study.

Subg. code	Subgenus	OTU code	OTU
AND	*Andrena*	1	*brevihirtiscopa* Hirashima 1962
〃	*A.*	2	*mikado* Strand et Yasumatsu 1938, form A
〃	*A.*	3	*bombiformis* Yasumatsu et Hirashima 1962
〃	*A.*	4	*ishiharai* Hirashima 1953
〃	*A.*	5	*nawai* Cockerell 1913
〃	*A.*	6	*esakii* Hirashima 1957
〃	*A.*	7	*longitibialis* Hirashima 1962
〃	*A.*	8	*maukensis* Matsumura 1911
〃	*A.*	9	*shirozui* Hirashima 1962
〃	*A.*	10	*hondoica* Hirashima 1962
〃	*A.*	11	*aburana* Hirashima 1962
〃	*A.*	12	*saragamineensis* Hirashima 1962
〃	*A.*	13	*benefica* Hirashima 1962
CAL	*Calomelissa*	14	*prostomias* Pérez 1905
〃	*Cal.*	15	*tsukubana* Hirashima 1957
ORE	*Oreomelissa*	16	*mitakensis* Hirashima 1963
〃	*O.*	17	*kamikochiana* Hirashima 1963
CHL	*Chlorandrena*	18	*taraxaci chikuzenensis* Hirashima 1957
〃	? *Chl.*	19	*knuthi* Alfken 1900
〃	? *Chl.*	20	*knuthi okinawana* Matsumura et Uchida 1926
CNE	*Cnemidandrena*	21	*seneciorum* Hirashima 1964
〃	*Cnem.*	22	*maetai* Hirashima 1964
〃	*Cnem.*	23	*albicaudata* Hirashima 1966
EU	*Euandrena*	24	*hebes* Pérez 1905
〃	*E.*	25	*stellaria* Hirashima 1964
〃	*E.*	26	*ruficrus rabicrus* Hirashima 1957
〃	*E.*	27	*takachihoi* Hirashima 1964, form A

Table 1. Continued.

Subg. code	Subgenus	OTU code	OTU
GYM	*Gymnandrena*	28	*watasei* Cockerell 1913
〃	*G.*	29	*wulungshanensis* Yasumatsu 1935
〃	*G.*	30	*parathoracica* Hirashima 1957
〃	*G.*	31	*okabei sapporensis* Hirashima 1957
〃	*G.*	32	*edashigei* Hirashima 1960, form A
〃	*G.*	33	*sasakii* Cockerell 1913
HAB	*Habromelissa*	34	*omogensis* Hirashima 1957
HOL	*Holandrena*	35	*valeriana* Hirashima 1957
〃	*Hol.*	36	*ishikawai* Hirashima 1958
〃	*Hol.*	37	*taniguchiae* Hirashima 1958
HOP	*Hoplandrena*	38	*dentata* Smith 1879
〃	*Hopl.*	39	*miyamotoi* Hirashima 1964
〃	*Hopl.*	40	*sachalinensis* Yasumatsu 1930
〃	*Hopl.*	41	*pruniphora* Hirashima 1964
MIC	*Micrandrena*	42	*hikosana* Hirashima 1957
〃	*Micr.*	43	*brassicae* Hirashima 1957
〃	*Micr.*	44	*kaguya* Hirashima 1965, form A
〃	*Micr.*	45	*komachi* Hirashima 1965, form A
〃	*Micr.*	46	*sublevigata* Hirashima 1966
〃	*Micr.*	47	*falsificissima* Hirashima 1966
MIT	*Mitsukuriella*	48	*japonica* (Smith) 1873
〃	*Mits.*	49	*fukaii* Cockerell 1914
NOT	*Notandrena*	50	*nitidiuscula* Schenck 1853
〃	? *N.*	51	*richardsi* Hirashima 1957
〃	? *N.*	52	*amamiensis* Hirashima 1960
PAR	*Parandrena*	53	*yasumatsui* Hirashima 1952
PLA	*Plastandrena*	54	*astragalina* Hirashima 1957
POE	*Poecilandrena*	55	*fukuokensis* Hirashima 1952
SIM	*Simandrena*	56	*opacifovea* Hirashima 1952
〃	*Sim.*	57	*kerriae* Hirashima 1965
STE	*Stenomelissa*	58	*halictoides* Smith 1869
TAE	*Taeniandrena*	59	*ezoensis* Hirashima 1965
TRA	*Trachandrena*	60	*foveopunctata* Alfken 1932
〃	*Tra.*	61	*haemorrhoa japonibia* Hirashima 1957
ORE	*Oreomelissa*	62	*coitana pilosodorsata* Alfken 1929
LAR	*Larandrena*	63	*echizenia* Hirashima et Haneda 1973
〃	*L.*	64	*fukuiana* Hirashima et Haneda 1973
AND	*Andrena*	65	*mikado* Strand et Yasumatsu 1938, form B
〃	*A.*	66	sp. 1*
〃	*A.*	67	sp. 2*
〃	*A.*	68	sp. 3*
〃	*A.*	69	sp. 4**
EU	*Euandrena*	70	sp. 1**
〃	*E.*	71	*takachihoi*, form B
〃	*E.*	72	*takachihoi*, form C
〃	*E.*	73	*takachihoi*, form D
GYM	*Gymnandrena*	74	*edashigei*, form B
HOP	*Hoplandrena*	75	sp. 1 ssp. 1**
〃	*Hopl.*	76	sp. 1 ssp. 2**
MIC	*Micrandrena*	77	sp. 1***
〃	*Micr.*	78	sp. 2***
〃	*Micr.*	79	sp. 3***
〃	*Micr.*	80	sp. 4***
〃	*Micr.*	81	*komachi*, form B
〃	*Micr.*	82	*kaguya*, form B
SIM	*Simandrena*	83	sp. 1**
〃	*Sim.*	84	sp. 2**
〃	*Sim.*	85	sp. 3**

* Hirashima, Tadauchi and Matsumura, in preparation
** Hirashima and Tadauchi, in preparation
*** Tadauchi, in preparation

(Matsumura) 1912, which was classified into the subgenus *Hoplandrena* by Hirashima (1964), was excluded because of the discovery of only a single male specimen. *A. praecociformis* Cockerell 1911, which seemed to belong to the subgenus *Euandrena,* was also excluded because of the discovery of only a few male specimens.

Characters

A total of 130 morphological characters were used in this study. A character was defined according to the concept of the phenetic school, i.e., as a feature that varies among the OTU's used and can not be further subdivided logically. The characters and the numbers of the states for the characters are listed in Table 2. The qualitative and quantitative characters were distributed over various regions of the body as follows: body size character 1; structural character 81 (head 33, thorax 23, wings 6, legs 6, metasoma 13); pubescence character 40; and body color character 8. The number of alternative states shown clearly in OTU's determined the number of state codes for that character. Quantitative or multistate characters were coded taking the sizes and ranges of the characters over all the OTU's into consideration. The code numbers of multistate characters ranged from 1 to 5. The average state was used from the characters varying among individual representatives of the OTU's. After the characters were coded for each OTU, these data were keypunched and processed on FACOM M-200 computer at the Computer Center of Kyushu University.

Table 2. One hundred and thirty characters used in the present study with the numbers of the states for the characters.

1.	Body length	5
2.	Basal width of process of labrum	3
3.	Shape of process of labrum	4
4.	Convexity of apex of process of labrum	3
5.	Existence of median longitudinal impunctate line on clypeus	3
6.	Protuberance of clypeus from line running bases of eyes	5
7.	Convexity of medial portion on clypeus	4
8.	Size of punctures on clypeal median area	3
9.	Strength of punctures on clypeal median area	4
10.	Density of punctures on clypeal median area	3
11.	Tessellation on clypeus	4
12.	Length of inner subantennal sutures	4
13.	Degree of separation of facial fovea from eye margin	3
14.	Extension of lower ends of facial foveae	3
15.	Extent of upper end of facial fovea	4
16.	Depth of facial foveae	2
17.	Strength of frontal line	3
18.	Strength of lugulae on upper paraocular areas	3
19.	Shininess on area under median ocellus	3
20.	Angle of posterior end of vertex seen from above	3
21.	Shape of vertex in frontal view	4
22.	Density of punctures on vertex	3
23.	Concavity or convexity of genal area seen from above	3
24.	Comparison of width between genal area and eye	3
25.	Strength of punctures on genal area	3
26.	Tessellation on genal area	5
27.	Length of malar space	3
28.	Curvature of hypostomal carina	4

Table 2. Continued.

29.	Strength of hypostomal carina	4
30.	Comparison of length between 1st flagellar segment and 2nd–3rd segments together	3
31.	Divergence or convergence of eyes with inner margines above	3
32.	Curvature of posterior line of eye	4
33.	Front-postocellar distance	3
34.	Postocellar width	3
35.	Strength of humeral angle on pronotum	3
36.	Length of pronotal suture	3
37.	Strength of pronotal suture	3
38.	Existence of emargination on antero-medial portion on pronotum	3
39.	Existence of lateral lugulae on pronotum	2
40.	Size of punctures on medial mesoscutum	3
41.	Strength of punctures on medial mesoscutum	3
42.	Density of punctures on medial mesoscutum	3
43.	Tessellation on medial mesoscutum	3
44.	Density of punctures on scutellum	3
45.	Tessellation on scutellum	4
46.	Strength of punctures on mesepisternum	3
47.	Tessellation on medial-posterior mesepisternum	5
48.	Size of propodeal enclosure	3
49.	Shape of propodeal enclosure	3
50.	Distinctness of propodeal enclosure	3
51.	Rugosity on propodeal enclosure	5
52.	Existence of a carina on posterior area of propodeal enclosure	2
53.	Angle of posterior propodeum seen from laterally	3
54.	Tessellation on dorsal face of propodeum	5
55.	Existence of lateral keels on dorso-lateral face of propodeum	2
56.	Rugosity on corbicula area	4
57.	Tessellation on posterior tegulae	4
58.	Number of submarginal cells	2
59.	Position of 3rd submarginal cell receiving 2nd recurrent vein	3
60.	Position of 1st intercubital vein from pterostigma	3
61.	Position of 2nd submarginal cell receiving 1st recurrent vein	2
62.	Position of basal vein from nervulus	3
63.	Wing length	5
64.	Existence of spines near apex of hind femur	2
65.	Form of hind tibiae	3
66.	Curvature of posterior spurs on hind tibiae	3
67.	Form of medial portion of mid basitarsi	2
68.	Form of hind basitarsi	3
69.	Length of hind basitarsi	3
70.	Strength of punctures on 1st metasomal tergum	5
71.	Density of punctures on 1st metasomal tergum	4
72.	Tessellation on 1st metasomal tergum	4
73.	Strength of punctures on 3rd metasomal tergum	4
74.	Density of punctures on basal portion of 3rd metasomal tergum	4
75.	Tessellation on 3rd metasomal tergum	4
76.	Strength of posterior depression on 3rd metasomal tergum	3
77.	Width of posterior depression of 3rd metasomal tergum	4
78.	Existence of reflection on apex of 3rd metasomal tergum	2
79.	Distinctness of triangular area of pygidial plate	4
80.	Strength of punctures on 3rd metasomal sternum	3
81.	Tessellation on 3rd metasomal sternum	3
82.	Number of graduli on metasomal sterna	5
83.	Amount of hairs on basal portion of clypeus	4
84.	Color of hairs on clypeus	3
85.	Color of facial foveae	4
86.	Existence of fuscous hairs on vertex	2
87.	Amount of hairs on genal area	3
88.	Length of hairs on genal area	2
89.	Amount of hairs on antennal region	3
90.	Amount of hairs on mesoscutum	4
91.	Length of hairs on mesoscutum	2

Table 2. Continued.

92.	Color of chief hairs on mesoscutum	3
93.	Existence of mixed hairs on mesoscutum	2
94.	Amount of hairs on metanotum	3
95.	Color of hairs on mesepisternum	3
96.	Arrangement of trochanteral floccus	2
97.	Amount of trochanteral floccus	3
98.	Length of trochanteral floccus	3
99.	Existence of branched hairs on femoral floccus	2
100.	Color of femoral floccus	3
101.	Existence of branched hairs on tibial scopa	2
102.	Arrangement of tibial scopa	2
103.	Length of tibial scopa	3
104.	Color of tibial scopa	4
105.	Amount of hairs on propodeum	3
106.	Amount of dorsal fringe of propodeal corbicula	3
107.	Length of dorsal fringe of propodeal corbicula	3
108.	Arrangement of dorsal fringe of propodeal corbicula	3
109.	Existence of branched hairs on dorsal fringe of propodeal corbicula	2
110.	Existence of branched hairs on anterior portion of propodeal corbicula	2
111.	Existence of simple hairs on interior corbicula	3
112.	Coarseness of internal hairs on propodeal corbicula	4
113.	Amount of hairs on 1st metasomal tergum	4
114.	Amount of hairs on medial portion of 2nd metasomal tergum	4
115.	Color of hairs on posterior portion of 2nd metasomal tergum	3
116.	Length of hairs on posterior portion of 3rd metasomal tergum	3
117.	Development of posterior fringe on 3rd metasomal tergum	5
118.	Density of posterior fringe on 3rd metasomal tergum	3
119.	Arrangement of apical hairs on 3rd metasomal tergum	2
120.	Color of caudal fimbria	3
121.	Length of hairs on 2nd metasomal sternum	3
122.	Amount of apical hairs on 3rd metasomal sternum	2
123.	Color of 3rd-10th flagellar segments beneath	3
124.	Color of tegulae	4
125.	Color of wings	3
126.	Color of veins and stigma	3
127.	Color of hind basitarsi	3
128.	Color of tibial spurs	3
129.	Color of metasomal terga	2
130.	Color of posterior portion of metasomal terga	5

Methods

The following operations were performed. Pearson's product-moment correlation coefficient and average Euclidian distance coefficient (taxonomic distance of Sokal, 1961) were used to compute each pair of OTU's in order to obtain correlation and distance matrices. Various cluster analyses were used to summarize the phenetic relationships in terms of clusters from these original matrices. In the present study the following five clustering methods were employed:

1. Furthest neighbor method (Lance and Williams, 1967)
2. Group average method (Lance and Williams, 1967)
3. Flexible method (Lance and Williams, 1967)
4. Flexible group-average method (Lance and Williams, 1967)
5. Ward method (Ward, 1963)

The following Lance and Williams' combinational formula (Lance and Williams, 1967) was applied to the above five methods.

$$d_{hk}=\alpha_i d_{hi}+\alpha_j d_{hj}+\beta d_{ij}+\gamma|d_{hi}-d_{hj}|\ ,$$

where d_{ij} stands for the distance between a cluster i and a cluster j, d_{hk} is the distance between a cluster k (cluster i+cluster j) and a cluster h which does not admit a cluster k, and α_i, α_j, β and γ are parameters.

Furthest neighbor method is known as the complete linkage method by Sneath and Sokal (1973) or the maximum method by Johnson (1967). In this method similarity or dissimilarity is computed as a value between an OTU that is a candidate for an extant cluster and the furthest member within the extant cluster.

Lance and Williams (1967) proposed a flexible clustering method which overcomes the disadvantages of nearest neighbor and furthest neighbor methods. They imposed four constraints upon their linear formula for combinational strategy, as follows:

$$\alpha_j+\alpha_k+\beta=1,\quad \alpha_j=\alpha_k,\quad \beta<1,\quad \gamma=0\ .$$

By adjusting the value of β from 1 to -1, Lance and Williams were able to simulate the results of chaining by nearest neighbor method and of extremely compact clustering by furthest neighbor method. In the present study -0.25 was adopted as the value of β.

Sokal and Michener (1958) developed average linkage method. This method requires computation of some kind of average similarity or dissimilarity between a candidate OTU or a cluster and an extant cluster. In the average linkage techniques the group average method (UPGMA, unweighted pair-group method using arithmetic averages) has been frequently used. The group average algorithm computes the average similarity or dissimilarity of a candidate OTU to an extant cluster, weighing each OTU in that cluster equally.

Ward (1963) developed the hierarchical grouping method, which is called the Ward method in the present study. This method starts out with t separate OTU's (t is the number of OTU's) grouping them successively into t–1, t–2, t–3……, 1 OTU and computing a so-called objective function at each stage. This is some measure of the desirability of the particular arrangement of the t OTU's into $k<t$ OTU's at any stage. Such objective function is used as the "loss of information".

RESULTS AND DISCUSSION

Phenograms obtained by the various clustering methods are discussed below under separate headings. The cophenetic correlation coefficient (Sokal and Rohlf, 1962) was used to judge the degree of the fitness of the resulting phenograms to the original matrices. The taxonomic significances of the groupings at the subgeneric level were considered by drawing some arbitrary phenon line. Plotting ranked similarity diagrams (Moss, 1968), which indicated the original similarity or dissimilarity matrix, were also used to observe the displacement of OTU's in the phenograms.

1. A comparison of phenograms based on distance and correlation coefficients

In this part two phenograms are compared. One is based on a distance (standardized distance) matrix, and the other is based on a correlation one. The group average method of Lance and Williams (1967) was used to summarized the phenetic relationships.

A distance phenogram in Fig. 1 summarized the relationships given by the distance matrix. The code numbers of the OTU's and subgeneric codes are given in Table 1. The cophenetic correlation coefficient for the distance phenogram was relatively high (0.912). A line drawn through the phenogram corresponding to a distance value of 1.25 divided the OTU's into groupings identical with most of the recognized subgenera. The line produced the following 23 groups (Fig. 1): 1) *Andrena* (2-66 cluster), 2) *Larandrena* (63-69 cluster), 3) *Euandrena* (24-70 cluster), 4) *Hoplandrena* (38-40 cluster), 5) *Cnemidandrena* (21-23 cluster), 6) *Gymnandrena* (32-30 cluster), 7) *Simandrena* (56-85 cluster), 8) *Micrandrena* (43-42 cluster), 9) *Notandrena* I (50-51 cluster), 10) *Poecilandrena* (55 cluster), 11) *Notandrena* II (52 cluster), 12) *Calomelissa* (14-15 cluster), 13) *Oreomelissa* (17-16 cluster), 14) *Taeniandrena* (59 cluster), 15) *Habromelissa* (34 cluster), 16) *Chlorandrena* (19-18 cluster), 17) *Stenomelissa* (58 cluster), 18) *Mitsukuriella* (48-49 cluster), 19) *Plastandrena* (54 cluster), 20) *Trachandrena* (60-61 cluster), 21) *Holandrena* I (36-37 cluster), 22) *Holandrena* II (35 clsuter), and 23) *Parandrena* (53 cluster). OTU's of the same subgenus were clustered tightly together, for instance, in *Euandrena, Hoplandrena, Cnemidandrena, Simandrena,* and *Micrandrena.* However, the line also divided the OTU's in the same subgenus into two groups in *Holandrena,* i.e., the *ishikawai-taniguchiae* cluster (36-37) and the *valeriana* cluster (35), which connected at the distance value of 1.33 with each other. The following was a list of the interesting results indicated by the distance phenogram: 1) *mikado* A-*ishiharai* cluster (2-4) including five OTU's was extremely separated from the other OTU's of the same subgenus *Andrena,* showing the connecting distance value of 1.23, 2) although the OTU's of the *Gymnandrena* were clustered together with one another, they connected at relatively higher distance values, especially in the juncture of *parathoracica* (30) with the other OTU's at a distance value of 1.23, 3) *amamiensis* (52) was relatively separated from the other OTU's of the *Notandrena* and it did not connect with the *nitidiuscula-richardsi* cluster (50-51) but with the *nitidiuscula-fukuokensis* cluster (50-55) at the value of 1.29, 4) the *Calomelissa* cluster (14-15) was relatively close to the *Oreomellissa* cluster (17-16), showing the connecting value of 1.25, 5) *taraxaci chikuzenensis* (18) was relatively close to the *knuthi-knuthi okinawana* cluster (19-20), showing the value of 1.08. Above the subgeneric level five major groups were developed as follows: 1) *Andrena, Larandrena, Euandrena, Hoplandrena, Cnemidandrena, Gymnandrena, Simandrena,* 2) *Micrandrena, Notandrena* I, *Poecilandrena, Notandrena* II, *Calomelissa, Oreomelissa, Taeniandrena, Habromelissa,* 3) *Chlorandrena, Stenomelissa,* 4) *Mitsukuriella, Plastandrena, Trachandrena, Holandrena* I, *Holandrena* II, 5) *Parandrena.*

The other phenogram (Fig. 2) produced by the group average method was

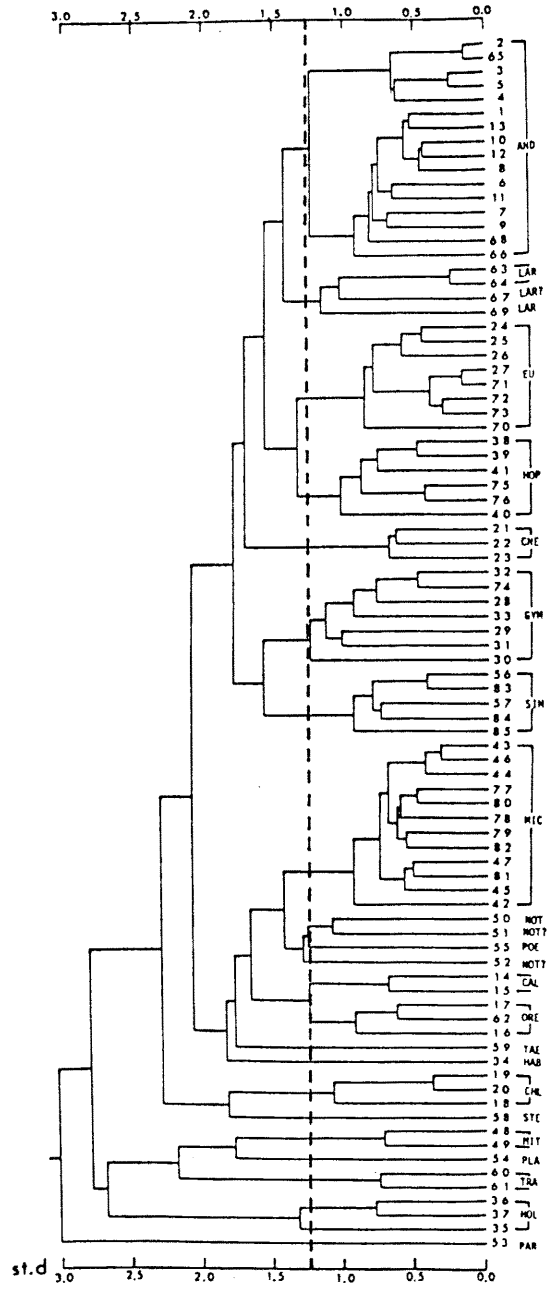

Fig. 1. Distance phenogram obtained by the group average method based on 130 characters derived from 85 OTU's.

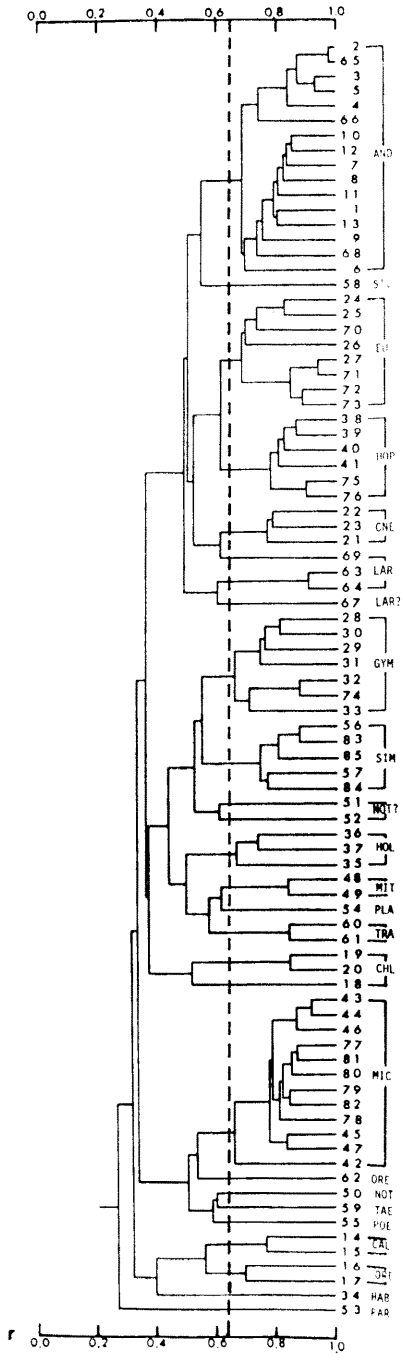

Fig. 2. Correlation phenogram obtained by the group average method based on 130 characters derived from 85 OTU's.

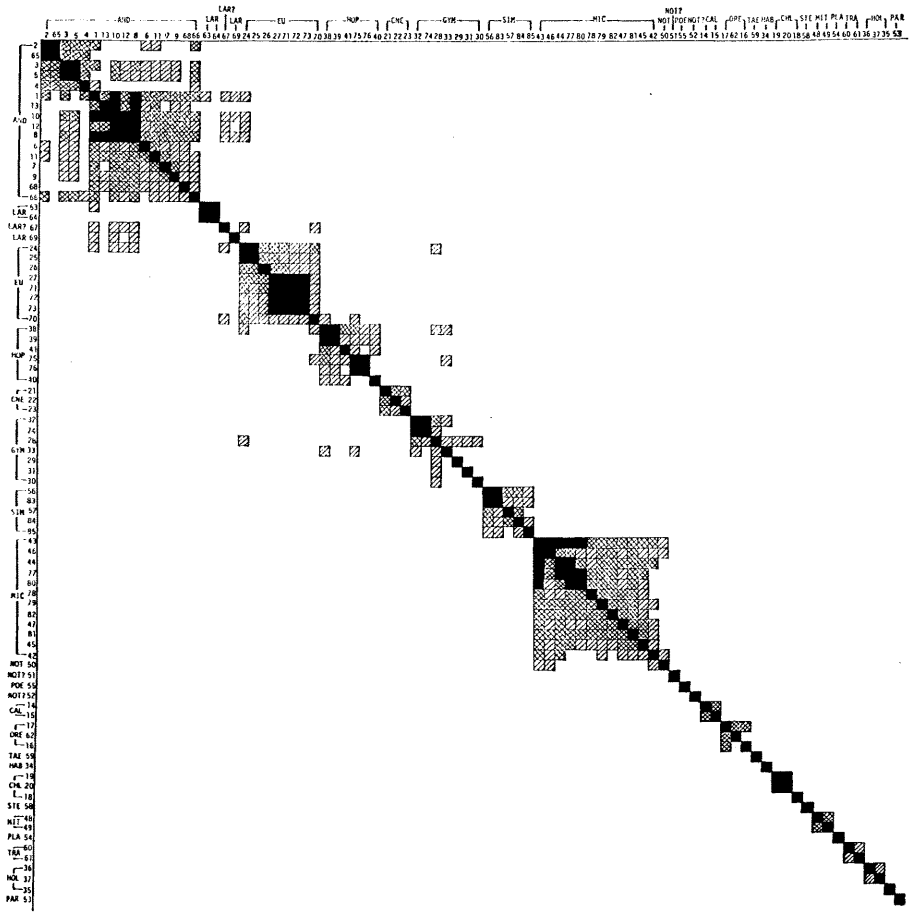

Fig. 3. Plotting ranked similarity diagram based on the distance matrix.

based on the correlation matrix. The cophenetic correlation coefficient was 0.846. The results obtained from this procedure were basically similar to the preceding distance phenogram. The phenon line at the correlation value of 0.62 separated the OTU's into groupings identical with most of the recognized subgenera. The principal differences evident in this phenogram were as follows: 1) *A.* (*Andrena*) sp. 4 (69) was extremely isolated from the other OTU's of *Andrena* (2-6 cluster) and connected with *Cnemidandrena* cluster (22-21), 2) the *richardsi-amamiensis* cluster (51-52) was extremely separated from *nitidiuscula* (50), 3) *coitana pilosodorsata* (62) was isolated from the other OTU's (16-17) of *Oreomelissa* and clustered with *Micrandrena* cluster (43-42), 4) the *ishikawai-taniguchiae* cluster (36-37) was relatively close to *valeriana* (35), showing the correlation value of 0.67, 5) *taraxaci chikuzenensis* (18) was comparatively separated from the *knuthi-knuthi okinawana* cluster (19-20), showing the value of 0.52.

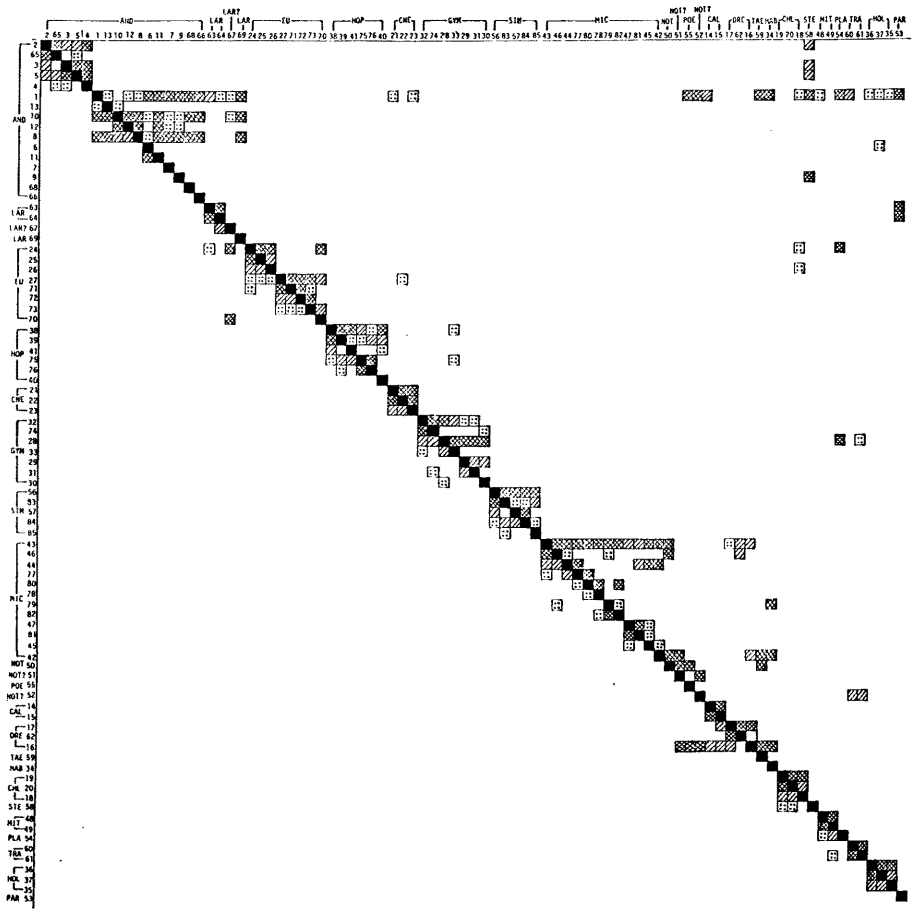

Fig. 4. Plotting ranked similarity diagram based on the correlation matrix.

One method of comparing clustering techniques is to compute their correlations with each other, using the cophenetic values obtained from their respective phenograms. Thus the distance phenogram derived from the distance matrix showed higher cophenetic correlation value as mentioned above. Although this operation indicates that clustering methods are closest to each other in the placement of OTU's, it does not provide information on the content of the actual clusters themselves. Figs. 3-4 show plotting ranked similarity diagrams. In these figures the vertical and horizontal sequence of OTU's is determined by the order in the distance phenogram. Similarity or dissimilarity values derived from the original matrices are plotted columnwise for each OTU. It can be seen from the distance diagram (Fig. 3) that the black squares indicating first-order similarity (distance value; 0.00-0.50) are all placed along the diagonal or at most a few squares away from it. Thus it shows that adjacent OTU's in the distance phenogram are most closely re-

lated to each other. Where among the adjacent OTU's mutually highest similarities are involved, a square is formed, e.g., for three OTU's (21–23) of *Cnemidandrena*. In case of second-order (cross oblique squares, distance value; 0.51–0.85) and third-order (oblique squares, distance value; 0.86–1.00) distances, the majority of these are also situated along the diagonal, with some exceptions of the third-order relationship. It can be said that the phenogram can be checked by the displacements of the OTU's in this diagram. From the arrangement of squares in the distance diagram, it is obvious that the distance phenogram shows comparatively exact content of the original matrix. However, the diagram indicates that *A.* (*Andrena*) sp. 2 (67) and *A.* (*Andrena*) sp. 4 (69) are more closely related to the subgenus *Andrena* than can be shown in the phenogram. The subgenus *Andrena*, which was divided into two groups in the phenogram, clustered loosely together as a whole. The diagram agrees with the phenogram on the separation of *valeriana* from the *ishikawai-taniguchiae* cluster. It also shows that three OTU's of *Notandrena* are isolated from one another. It indicates that *Gymnandrena* is one loosely connected group. The OTU *taraxaci chikuzenensis* is further separated from the *knuthi-knuthi okinawana* cluster than can be shown in the phenogram. The similar relationship is found between the *Oreomelissa* and the *Calomelissa*. The subgenera *Cnemidandrena, Simandrena, Poecilandrena, Calomelissa, Oreomelissa, Mitsukuriella, Trachandrena, Habromelissa, Stenomelissa, Plastandrena,* and *Parandrena* are considered to be distinct groups because they do not connect with any OTU's of the other subgenera in the plotting ranked similarities.

Fig. 4 shows the plotting ranked similarity diagram based on the correlation matrix. Although the vertical and horizontal sequence of OTU's are determined by the order in the distance phenogram, it is obvious that the distance diagram is much more congruent with the conventional classification than the correlation one. The correlation diagram shows that the correlation phenogram has many displacements of OTU's. For instance, *A.* (*Andrena*) sp. 4 (69) connected with the *Cnemidandrena* cluster in the phenogram, however it is more closely related to a few OTU's (1, 10, and 8) of the subgenus *Andrena* in the diagram.

Sokal and Michener (1967) found that correlation phenograms were much more congruent than distance ones with the conventional classification. However, the above result shows that the distance phenogram is much more congruent with the original matrix and the conventional classification.

2. A comparison of phenograms based on five clustering methods

In this part five clustering methods are compared based on the distance matrix of the 130 original characters derived from 85 OTU's. Fig. 1 and Figs. 5–8 show the five distance phenograms produced by the five different clustering methods. The results obtained from the group average method were formally used as standard in order to compare with those from the other methods.

(*1*) *Group average method* (Fig. 1)

This method showed the highest value of cophenetic correlation coeffi-

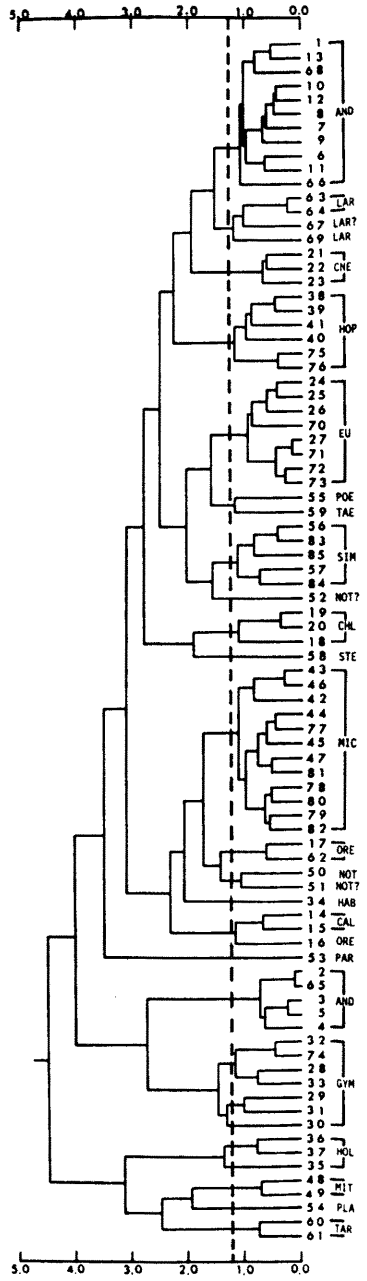

Fig. 5. Distance phenogram obtained by the furthest neighbor method based on 130 characters derived from 85 OTU's.

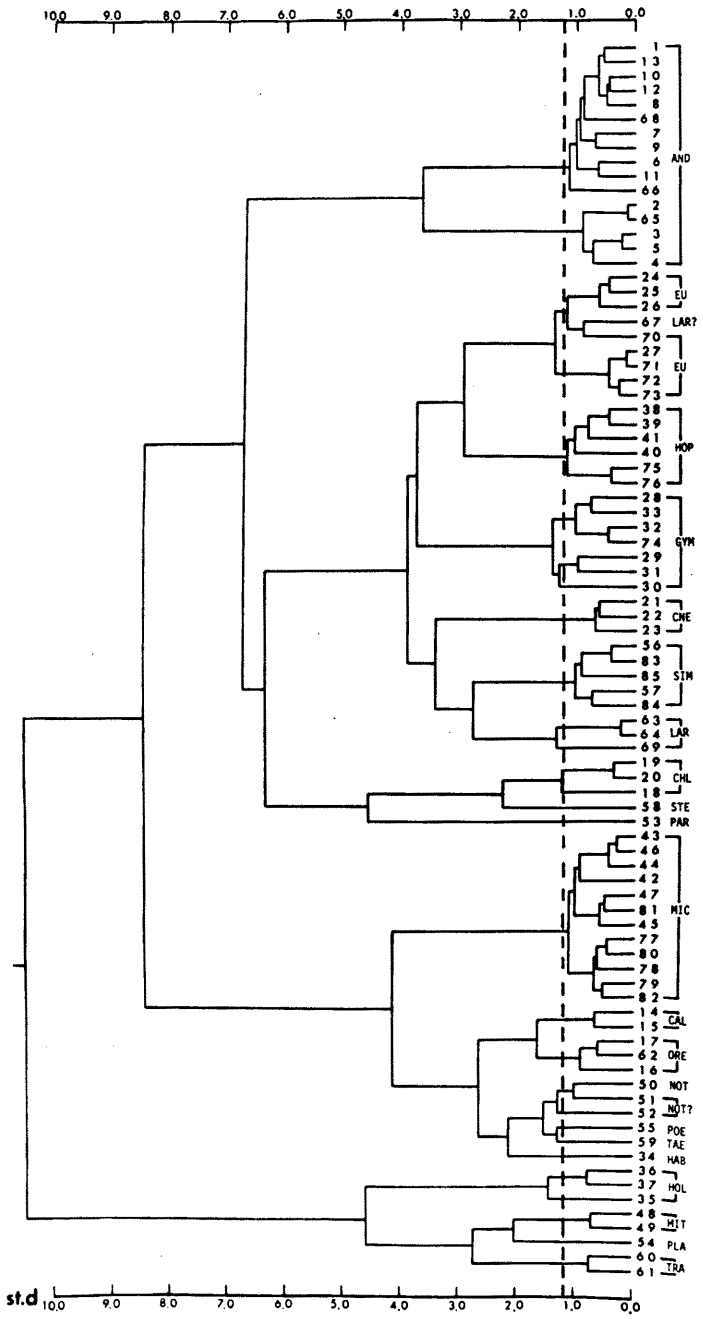

Fig. 6. Distance phenogram obtained by the flexible group-average method based on the 130 characters derived from 85 OTU's.

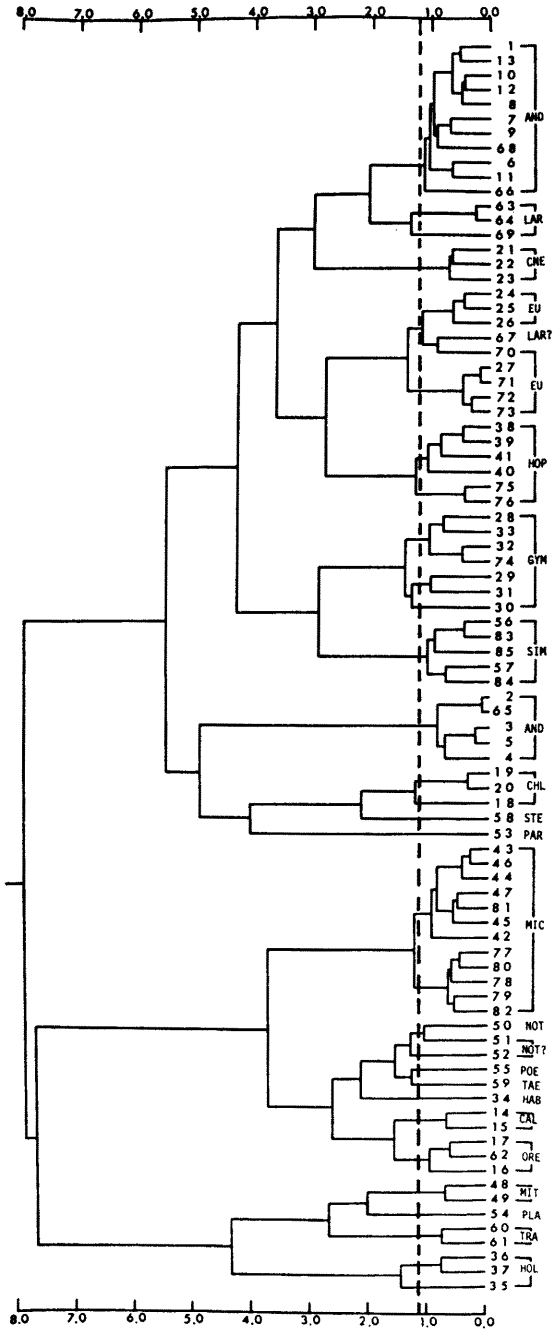

Fig. 7. Distance phenogram obtained by the flexible method based on 130 characters derived from 85 OTU's.

cient as mentioned above.

(*2*) *Furthest neighbor method* (Fig. 5)

The results obtained from this method were basically similar to the above method. The *brevihirtiscopa-A.*(*Andrena*) sp. 1 cluster (1–66) of the subgenus *Andrena* connected with the *Larandrena* cluster (63–69) and extremely separated from the *mikado* A-*ishiharai* cluster (1–4). The other differences evident in this phenogram were as follows: 1) *mitakensis* (16) clustered with *Calomelissa* cluster (14–15) and separated from *Oreomelissa* cluster, 2) *amamiensis* (52) strongly isolated from *nitidiuscula* (50) and *richardsi* (51).

(*3*) *Flexible group-average method* (Fig. 6)

The results derived from this procedure were similar to the above phenograms. However, the higher distance level is prolonged in this method Two groups of the subgenus *Andrena* clustered with each other at the higher distance value of 3.67. The OTU *A.* (*Andrena*) sp. 2 (67) strongly isolated from the *Larandrena* cluster (63, 67) and joined the *Euandrena* cluster (24–73). This phenogram indicated that the subgenus *Gymnandrena* is composed of OTU's widely separated from one another. *Oreomelissa* (17–16) was well separated from *Calomelissa* (14–15), showing the connecting value of 1.65. The three OTU's of *Notandrena* clustered with one another at the relatively lower distance value of 1.33. The *ishikawai-taniguchiae* cluster (36–37) considerably separated from *valeriana* (35), showing the connecting value of 1.46.

(*4*) *Flexible method* (Fig. 7)

The results of this method considerably resembled to the preceding one. The important difference observed in this phenogram was the strong isolation of *mikado* A-*ishiharai* cluster (2–4) from the other OTU's of the subgenus *Andrena*. The OTU *A.* (*Andrena*) sp. 2 (67) also joined the *Euandrena* cluster (24–73).

(*5*) *The Ward method* (Fig. 8)

In case of this method the stem at the higher distance level was quite elongated. This is a distinctive feature of this method. At the lower distance level this method also produced basically similar groupings as the previous ones. One group (10–11) of the subgenus *Andrena* connected with the OTU's (63–69) of the *Larandrena* and then clustered with the *mikado* group (3–65). In this phenogram *A.* (*Andrena*) sp. 2 (69) joined the OTU's of *Euandrena* (24–75). This relationship was also observed in the flexible and the flexible group-average methods.

From an inspection of the five phenograms it seems that they share a number of similarities in their groupings. The taxonomic significances of the groupings within the major groups are considered by drawing some arbitrary phenon line. Such a line cuts the stem and results in defining a number of groups. Tadauchi (1978) already compared six clustering methods by similar fashion at the major clustering level, which was above the subgeneric level. In the present study the comparing level is lowered to the subgeneric level.

Because it has been found that cluster analysis has more distortions at the higher distance level than at the lower distance level. Emphasis also has been given on the examination of the position of each OTU in the genus *Andrena* of Japan. Therefore the distance scale of 1.25, which was adopted

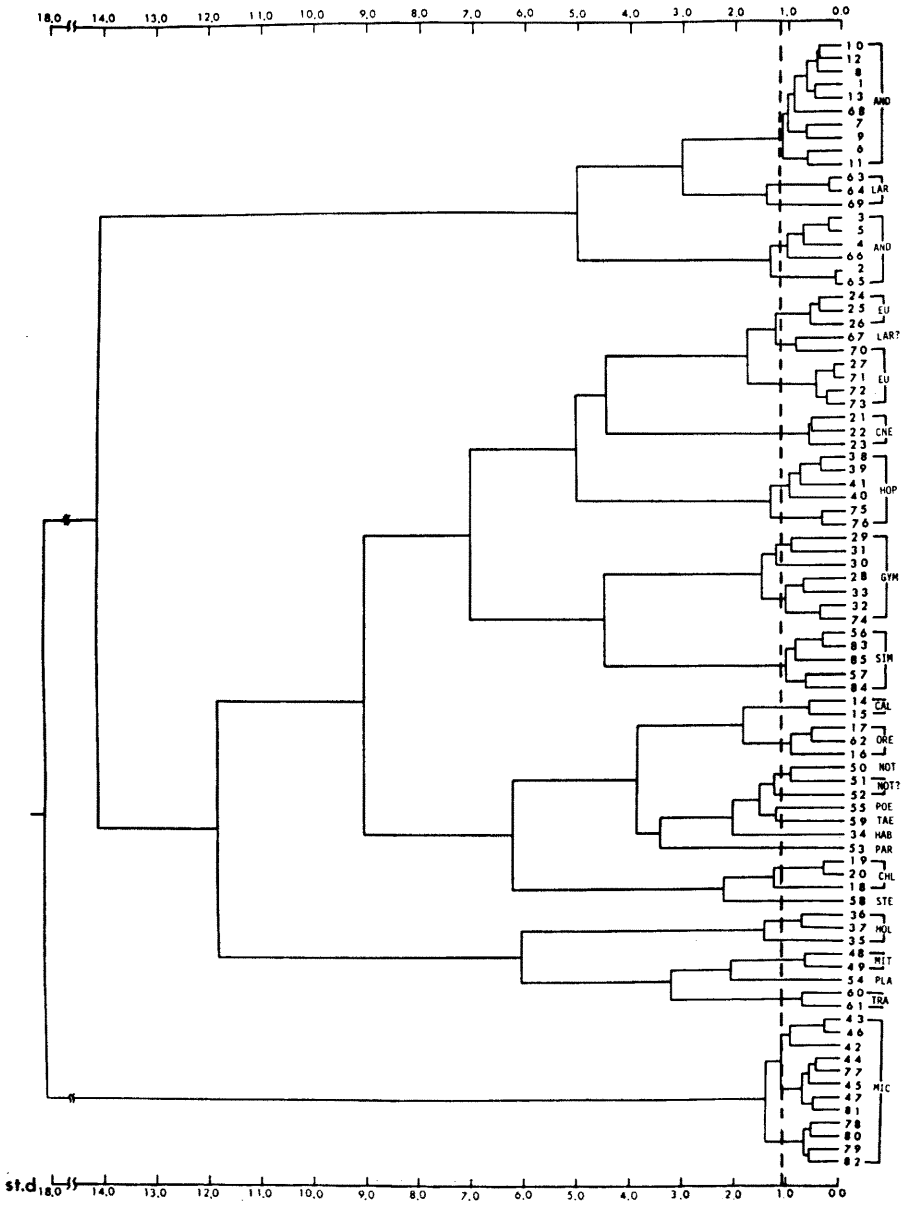

Fig. 8. Distance phenogram obtained by the Ward method based on 130 characters derived from 85 OTU's.

Table 3. Groupings obtained by five clustering methods based on the values of distance coefficient. Criterion of group recognition is a line drawn across the phenogram at the 1.25 level of the distance scale. The presence or absence of a group is denoted by a "+" or a "−".

Subg. code		Group Av.	Furth. N.	Flexible Group-Av.	Flexible	Ward
AND	(1-3, 66, 68)	+	−	−	−	−
AND	(1, 6-13, 66, 68)	−	+	+	+	−
AND	(2, 3, 4, 5, 65)	−	+	+	+	−
LAR	(63, 64, 67, 69)	+	+	−	−	−
LAR	(63, 64)	−	−	+	+	+
LAR	(69)	−	−	+	+	+
EU	(24-27, 70-73)	+	+	−	−	−
EU	(24, 25, 26, 67, 70)	−	−	+	+	−
EU	(27, 70, 72, 73)	−	−	+	+	+
EU	(67, 70)	−	−	−	−	+
EU	(24, 25, 26)	−	−	−	−	+
HOP	(38-41, 75-76)	+	+	+	−	−
HOP	(38-41)	−	−	−	+	+
HOP	(75, 76)	−	−	−	+	+
CNE	(21-23)	+	+	+	+	+
GYM	(28-33, 74)	+	−	−	−	−
GYM	(28, 32, 33, 74)	−	+	+	+	+
GYM	(29, 31)	−	+	+	+	+
GYM	(30)	−	+	+	+	+
SIM	(56-57, 83-85)	+	+	+	+	+
MIC	(42-47, 77-82)	+	+	+	+	−
MIC	(42-47, 77, 81)	−	−	−	−	+
MIC	(78, 79, 80, 82)	−	−	−	−	+
NOT	(50, 51)	+	+	+	+	+
?NOT	(52)	+	+	+	+	+
POE	(55)	+	+	+	+	+
CAL	(14-15)	+	−	+	+	+
CAL	(14, 15, 16)	−	+	−	−	−
ORE	(16-17, 62)	+	−	+	+	+
ORE	(17, 62)	−	+	−	−	−
TAE	(59)	+	+	+	+	+
HAB	(34)	+	+	+	+	+
CHL	(18-20)	+	+	−	−	−
CHL	(19-20)	−	−	+	+	+
CHL	(18)	−	−	+	+	+
STE	(58)	+	+	+	+	+
MIT	(48-49)	+	+	+	+	+
PLA	(54)	+	+	+	+	+
TRA	(60-61)	+	+	+	+	+
PAR	(53)	+	+	+	+	+
HOL	(35)	+	+	+	+	+
HOL	(36-37)	+	+	+	+	+

in the first comparison is preferred. Table 3 shows the groupings produced by this line concerning the five phenograms. In the table the presence of the groups obtained at the recognition line of 1.25 is denoted by a "+", and its absence by a "−". As shown in Table 3 it is recognized that the results obtained by the furthest neighbor method are similar to those by the group average method. The flexible method has a great resemblance to that by the flexible group-average method except for the grouping of the subgenus *Hoplandrena*. The Ward method is basically similar to the two flexible methods. Throughout the clustering methods many subgenera or OTU's are fairly consistent in their formation of groupings at the recognition level

chosen. They are the following 14 groups: *Cnemidandrena* (21–23), *Simandrena* (56–57, 83–85), *Poecilandrena* (55), *nitidiuscula*+*richardsi* (50, 51), *amamiensis* (52), *Taeniandrena* (59), *Habromelissa* (34), *Stenomelissa* (58), *Mitsukuriella* (48–49), *Plastandrena* (54), *Trachandrena* (60–61), *Parandrena* (53), *valeriana* (35), and *ishikawai*+*taniguchiae* (36, 37). However, clustering within these groupings is somewhat variable. As expected on theoretical grounds, the four methods except for the group average method produce groupings that were slightly more diverse or elongated than those formed by the group average one. For instance, OTU's of the subgenus *Gymnandrena* clustered with one another before the phenon line in the group average method. On the other hand, it was divided into three separate groups in the other four methods. The number of the groups produced by the line are 23 groups for the group average, 26 for the furthest neighbor, 29 for the flexible group-average, 30 for the flexible and 33 for the Ward method. Taking the plotting ranked diagram (Fig. 3) and the original matrix into consideration, some displacements of the OTU's in the phenograms are found at the subgeneric level. For example, *mitakensis* (16) was transferred from the *Oreomelissa* cluster in the furthest neighbor method. It is obvious that the subgenus *Andrena* is composed of two distinct groups. In the furthest neighbor and flexible methods the two groups of the subgenus *Andrena* were strongly isolated from each other and clustered with the other subgenus, respectively. These are considered to be the examples of the distortions judged from the original matrix. Among the five phenograms the group average method has the fewest distortions in the groupings at the phenon line level. Lance and Williams (1967) pointed out that contraction or dilation in space influences results of cluster analysis. The nearest neighbor method contracts the space, while the furthest neighbor method dilates it. The flexible method controls the space by the value of parameter β in Lance and Williams' combinational formula. In the present study -0.25 was applied as the value of the parameter. The results by the Ward method are nearly similar to the flexible methods at 1.25 level of the distance scale. At least concerning the cophenetic correlation coefficient, the Ward method shows a relatively low value because of a quite elongate results at the higher distance level

GROUPING OF OTU'S OF THE GENUS *ANDRENA* OF JAPAN

The following 23 groups are developed taking the above discussion into consideration.

1. 1st group (subgenus *Andrena*)
   (1) *mikado* group
   mikado A (2), *mikado* B (65), *nawai* (5), *bombiformis* (3), *ishiharai* (4)
   (2) *benefica* group
   benefica (13), *brevihirtiscopa* (1), *hondoica* (10), *saragamineensis* (12), *maukensis* (8), *esakii* (6), *aburana* (11), *longitibialis* (7), *shirozui* (9), (*Andrena*) sp. 3 (68), (*Andrena*) sp. 1 (66)
   (3) (*Andrena*) sp. 2 group

(*Andrena*) sp. 2 (67), (*Andrena*) sp. 4 (69)

2. 2nd group (subgenus *Larandrena*)
   echizenia (63), *fukuiana* (64)
3. 3rd group (subgenus *Euandrena*)
   hebes (24), *stellaria* (25), *ruficrus rabicrus* (26), *takachihoi* A (27), *takachihoi* B (71), *takachihoi* C (72), *takachihoi* D (73), (*Euandrena*) sp. 1 (70)
4. 4th group (subgenus *Hoplandrena*)
   dentata (38), *miyamotoi* (39), *pruniphora* (41), (*Hoplandrena*) sp. 1 ssp. 1 (75), (*Hoplandrena*) sp. 1 ssp. 2 (76), *sachalinensis* (40)
5. 5th group (subgenus *Cnemidandrena*)
   seneciorum (21), *maetai* (22), *albicaudata* (23)
6. 6th group (subgenus *Gymnandrena*)
   edashigei A (32), *edashigei* B (74), *watasei* (28), *sasakii* (33), *wulungshanensis* (29), *okabei sapporensis* (31), *parathoracica* (30)
7. 7th group (subgenus *Simandrena*)
   opacifovea (56), (*Simandrena*) sp. 1 (83), *kerriae* (57), (*Simandrena*) sp. 2 (84), (*Simandrena*) sp. 3 (85)
8. 8th group (subgenus *Micrandrena*)
   brassicae (43), *sublevigata* (46), *kaguya* A (44), (*Micrandrena*) sp. 1 (77), (*Micrandrena*) sp. 4 (80), (*Micrandrena*) sp. 2 (78), (*Micrandrena*) sp. 3 (79), *kaguya* B (82), *falsificissima* (47), *komachi* B (81), *komachi* A (45), *hikosana* (42)
9. 9th group (subgenus *Notandrena*)
   (1) *nitidiuscula* group
   nitidiuscula (50)
   (2) *richardsi* group
   richardsi (51)
10. 10th group (Subgenus ? *Notandrena* sensu Hirashima, 1965)
    amamiensis (52)
11. 11th group (subgenus *Poecilandrena*)
    fukuokensis (55)
12. 12th group (subgenus *Calomelissa*)
    prostomias (14), *tsukubana* (15)
13. 13th group (subgenus *Oreomelissa*)
    kamikochiana (17), *coitana pilosodorsata* (62), *mitakensis* (16)
14. 14th group (subgenus *Taeniandrena*)
    ezoensis (59)
15. 15th group (subgenus *Habromelissa*)
    omogensis (34)
16. 16th group (subgenus *Chlorandrena*)
    (1) *knuthi* group (subgenus *Chlorandrena* sensu Hirashima, 1963)
    knuthi (19), *knuthi okinawana* (20)
    (2) *taraxaci* group
    taraxaci chikuzenensis (18)
17. 17th group (subgenus *Stenomelissa*)

halictoides (58)

18. 18th group (subgenus *Mitsukuriella*)
japonica (48), *fukaii* (49)
19. 19th group (subgenus *Plastandrena*)
astragalina (54)
20. 20th group (subgenus *Trachandrena*)
foveopunctata (60), *haemorrhoa japonibia* (61)
21. 21st group (subgenus *Holandrena*)
valeriana (35)
22. 22nd group (subgenus *Holandrena* sensu Hirashima, 1964)
ishikawai (36), *taniguchiae* (37)
23. 23rd group (subgenus *Parandrena*)
yasumatsui (53)

As mentioned above, there are three main differences in comparison with the conventional classification as follows:

1) The *ishikawai-taniguchiae* group, which was classified into the subgenus *Holandrena* by Hirashima (1964), is recognized better to be raised to the subgeneric level.

2) The OTU *amamiensis*, whose position at the subgeneric level was left in doubt by Hirashima (1965), is recognized better to be separated from the subgenus *Notandrena*.

3) The *knuthi-knuthi okinawana* group placed in the subgenus *Chrysandrena* by Hirashima (1963) is transferred to the subgenus *Chlorandrena*.

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