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3   **Brown Bear Digging for Cicada Nymphs: a novel interaction in a forest ecosystem**

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19   The brown bear (*Ursus arctos*) is one of the most widespread large carnivores in

20   the northern hemisphere. Their diets are highly diverse and depend on resource availabilities

21   across regions and seasons (Bojarska and Selva 2012). Brown bears often consume starchy

22   plant roots and insects by digging into the soil (Mattson et al. 1991; Tardiff and Stanford

23   1998). In the Shiretoko World Heritage, Hokkaido, northern Japan (44° N, 145° E), where the

24   density of brown bears is high (Kohira et al. 2009), these animals have recently been

25   observed digging for cicada nymphs (*Lyristes bihamatus*) during summer (Fig.1a, b). This

26   behavior has not been previously reported, even though some other mammalian species

27   forage for cicada nymphs (Hahus and Smith 1990). In this article, we show some preliminary

28   results of our field survey on this novel interaction between brown bear and cicada. We then

29   discuss the reasons why brown bears forage on cicada nymphs and the possible ecological

30   consequences of their digging in the forest ecosystem.

31   Wildlife managers first observed brown bears digging for cicada nymphs in 2000 in

32   the study area. In fact, cicada nymphs have not been reported in scats of brown bears

33   collected in the summer of mid-1980s in the study area (Fig.2; Yamanaka and Aoi 1988).

34   This earlier study along with ours allows us to determine whether the proportion of cicadas

35   and other foods in the diet has changed during the past 30 years. In 2018, we evaluated the

36   composition of brown bear scats collected in the same season and region as the earlier study.

37   By comparing scat compositions between the mid-1980s and the 2018, we determined the

38   changes in brown bears diets in the study area during the past 30 years. The proportion of

39   cicada nymphs was estimated 14.3%, suggesting that brown bears consume cicada nymphs at

40   a certain rate in summer. Final instar nymphs are highly nutritious and finish their

41   development until emergence in shallow soil during summer, and so bears can easily dig for

42   them (Hayashi and Saisho 2011). Although herbaceous plants comprised the highest

43   proportion in scats in both periods, we found that the proportion of herbaceous plants in scats

44   in 2018 is half that recorded in mid-1980s (Fig.2).

45   Evidence of brown bear digging was frequently observed in the larch (*Larix*

46   *kaempferi*) plantations, whereas we could not find evidence of digging in the Sakhalin spruce

47   (*Picea glehnii*) plantations and the natural mixed forests. In August 2017, when final instar

48   cicada nymphs completed emergence, we created 10 survey plots of 100 m^2 area in each

49   forest type and counted the number of exuviae of *L. bihamatus* nymphs as a proxy of their

50   abundance in each plot. The largest number of the *L. bihamatus* exuviae occurred in the larch

51   plantations (mean $\pm$ SE / 100m^2 = 153.9 $\pm$ 15.6). The number of *L. bihamatus* exuviae in the

52   Sakhalin spruce plantations and the natural mixed forests was 8.7 $\pm$ 3.0 and 4.5 $\pm$ 2.3,

53   respectively. These data indicate that brown bears can most efficiently forage on cicada

54   nymphs by searching intensively in the larch plantation where the nymphs aggregate at high

55   density.

56   We set up 8 camera traps in the larch plantations where brown bears dug the

57   previous year to evaluate how many brown bears dug for cicada nymphs, by counting the

58   minimum number of brown bears based on useful features for individual identification (e.g.,

59   color, body size, and family structure). As a result, we captured 112 videos wherein bears

60   were recorded to be digging and detected a minimum number of 11 individuals; 3 adult bears

61   were females with cub(s), 2 were solitary adult female bears, and 2 were subadult bears. (See

62   Videos S1 and S2 for two examples.)

63   Why have brown bears begun foraging on cicada nymphs since 2000? One possible

64   reason may be that overgrazing by sika deer (*Cervus nippon yesoensis*) has altered the diet of

65   brown bears by reducing the available herbaceous plants for bears. An index of population

66   density of sika deer by spotlight surveys has revealed a remarkable increase from 1 deer/km

67   in the late 1980s to 20 deer/km in the early 2000s in the study area (Kaji et al. 2006). Because

68   herbaceous plant species preferred by sika deer were partially in common with the species

69   upon which brown bears foraged in summer during the 1980s (Kaji 1988), the availability of

70   herbaceous plants for bears during summer may have decreased in the study area. This is also

71   supported by the results of our scat analysis (Fig. 2). Therefore, brown bears may have

72   foraged on cicada nymphs as an alternative food resource to herbaceous plants.

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73   Our camera-traps revealed that 3 female brown bears with cub(s) dug for cicada

74   nymphs in the study area. Possibly, the digging behavior of brown bears will propagate

75   through the bear population via social learning from mother bear to cub, because bears likely

76   acquire foraging behavior through learning from their mothers during at least the first year of

77   their life (Gilbert 1999; Hopkins III 2013). Moreover, because home ranges of female brown

78   bears tend to be fixed in proximity to that of their mother's (Zedrossor et al. 2007), female

79   bears acquiring the digging behavior will remain in the same population. Thus, in the future,

80   the number of brown bears that dig for cicada nymphs will probably increase via social

81   learning in the study area.

82   Bioturbation by digging mammals is a well-studied example of ecosystem

83   engineering that alters habitat structure for other species and soil nutrient dynamics (Tardiff

84   and Stanford 1998; Meysman et al. 2006; Mallen-Cooper et al. 2019). We observed the area

85   of a dug patch was often over 100 m^2, and there were at least several dozens of the patches.

86   Furthermore, individual bear apparently dug up a large amount of soil according to

87   observation by our camera traps. Thus, bioturbation by brown bear digging may have

88   significant engineering effects in the forest ecosystem. Additionally, in the study area brown

89   bears may have exerted these effects since 2000 when they started digging for cicada

90   nymphs. In other words, the novel interaction between native species may have generated

91   novel bioturbation in the forest ecosystem.

92   As the number of brown bears that dig for cicada nymphs increases, the ecological

93   importance of the brown bear as an ecosystem engineer will increase in the forest ecosystem.

94   Finally, we propose a hypothesis that propagation of the digging behavior via social learning

95   might strengthen their ecological effects of bioturbation. This hypothesis may shed light on

96   linkage between social learning and ecosystem engineering (i.e. bioturbation). Testing this

97   hypothesis requires data on (1) population trends of digging bears; (2) their kinship based on

98   fecal DNA which can evaluate the relationship between kinship and diet; (3) temporal

99   dynamics in spatial patterns of brown bear digging; and (4) engineering effects of the digging

100   on other organisms and soil nutrient dynamics.

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Figure legends

144   **Figure legends**

145   Figure 1: (a) Female brown bear with two cubs dig for cicada nymphs in a larch plantation.

146   (b) Brown bear scat containing final instar *Lyristes bihamatus* nymphs. Scale bar: 50 mm

147   (photo credit: Shiretoko Nature Foundation)

148   Figure 2: Scat composition of brown bears in visually estimated percent volumes for major

149   categories, in 1985-1986 (left) and 2018 (right). Data of the scat composition in 1985-1986

150   from Yamanaka and Aoi (1988).

**Fruits
3.0 %**

**Ants
4.0 %**

**Herbaceous
plants
93.0%**

**1985-1986
（N=56）**

**Litter and
Pebbles 7.9 %**

**Deer
3.2 %**

**Cicada
nymphs
14.3 %**

**Herbaceous
plants
48.6 %**

**Ants
25.3 %**

**2018
（N=60）**