Landscape opening and herding strategies: Carbon isotope analyses of herbivore bone collagen from the Neolithic and Bronze Age lakeshore site of Zurich-Mozartstrasse, Switzerland

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Abstract

Carbon isotope analysis ($\delta^{13}\text{C}$) was performed on collagen extracted from 54 domestic cattle (*Bos taurus*) and 20 red deer (*Cervus elaphus*) bones from the Neolithic (3913-2586 BC) and Bronze Age (1950-950 cal. BC) layers of the lakeshore site Zurich-Mozartstrasse located in the lower Lake Zurich basin, Switzerland. We observed shifts in the $\delta^{13}\text{C}$ of both domestic cattle and red deer over two millennia. Mean $\delta^{13}\text{C}$ values of red deer changed from $-24.1 \pm 0.7\text{‰}$ to $-22.5 \pm 0.3\text{‰}$, while mean $\delta^{13}\text{C}$ values of domestic cattle showed minor changes from $-22.7 \pm 1.3\text{‰}$ to $-22.1 \pm 0.3\text{‰}$. Our data suggest that in the early 4th millennium BC the landscape was densely forested with red deer feeding in closed habitats and cattle grazing in more open landscapes. Forest was also a food resource for some young cattle as indicated by the lower $\delta^{13}\text{C}$ values of non-adult relative to adult animals. This points to a greater diversity of herding strategies and feeding techniques compared to the later periods. The landscape was still rather forested towards the mid-3rd millennium BC, with no obvious changes in the habitat use of the large herbivores. However, the carbon isotopes suggest a clearly reduced forest cover in the 2nd millennium BC with red deer using similar open feeding grounds as domestic cattle. Our study demonstrates that the stable carbon isotope composition of

archeological bone material from large herbivores can provide integrative constraints on paleoenvironmental and vegetation changes, prehistoric animal management and land-use.

Keywords: Prehistory, land-use, environmental change, canopy effect, domestic cattle, red deer

1. Introduction

Lakeshore settlements are amongst the best investigated archeological sites worldwide. Due to burial in waterlogged, and essentially anoxic, lake sediments, the preservation of (organic) finds and features is exceptional and a broad range of scientific approaches have been applied to study this legacy of our past (Menotti, 2004; 2012; Menotti and O’Sullivan, 2013). Dendrochronological investigation on almost pristine timber allows precise tree-ring dating of residential structures and the reconstruction of settlement histories (e.g. Hafner, 1993; Leuzinger, 2000; Schlichtherle et al., 2011). Within this framework, rich faunal remains provide detailed insights into subsistence strategies, and represent valuable proxies to be used for paleoenvironmental reconstructions (e.g. Hüster-Plogmann and Schibler, 1997; Deschler-Erb and Marti-Grädel, 2004; Chiquet, 2012).

While there is extensive knowledge about the actual settlement sites, little is known about the immediate surroundings of the lake dwellings in terms of subsistence activities beyond settlement frontiers. Some important conclusions have however been drawn using bio-archeological data. For example, it was shown that hunted animals, gathered plants and wood resources were of great importance in these settlements, and evidence from off-site pollen analyses suggests that the settlements’ surroundings were used for agricultural activities (e.g. Schibler et al., 1997; Schibler and Jacomet, 1999; Jacomet et al., 2004; Billamboz, 2012; Clarke, 2013). Nevertheless, these insights are rather sporadic, and the hinterland of lake dwellings remains a blind spot in many respects, despite its undoubted relevance to subsistence behavior and as potential source of information in the context of regional mobility patterns (e.g. Bleicher, 2009; Ebersbach, 2013).

The analysis of stable isotope ratios in archeological mammal bones is a promising tool for complementing archeological research of the settlements’ hinterland. Carbon isotope analyses have widely been used to distinguish between a diet predominated by plants exhibiting either C₃ or C₄ photosynthetic pathways, and to evaluate the contribution of terrestrial versus marine resources in human diet (e.g. Richards et al., 2006; Fischer et al., 2007; Oelze et al., 2011;

Cerling et al., 2013). As $\delta^{13}\text{C}$ values for bone collagen extracted from large herbivores are assumed to directly reflect the herbivores' diet, they can also be used as a proxy for vegetation conditions, e.g. the water availability and associated stomatal control, the dominance of specific plant types, or the degree of habitat closure, i.e. canopy (Drucker et al., 2003; Noe-Nygaard et al., 2005; Drucker et al., 2008; Drucker et al., 2011; Bonafini et al., 2013; Gąsiorowski et al., 2014; Stevens et al., 2014). The canopy effect produces a gradient of leaf $\delta^{13}\text{C}$ from ground to canopy of forested areas, with most ^{13}C -depleted plants near the ground, which can be explained by an enhanced recycling of ^{13}C -depleted CO_2 in the forest, elevated C isotope fractionation due to photosynthesis under low light conditions, and other physiological mechanisms (e.g. Vogel, 1978; van der Merwe and Medina, 1991). The depleted $\delta^{13}\text{C}$ is passed along the food chain from vegetation into animal tissues, such as bone collagen. More negative $\delta^{13}\text{C}$ values indicate feeding grounds with closed canopy. Hence, differences in carbon isotope values can help to distinguish between animals grazing in dense forests and those obtaining their food in open environments (e.g. Drucker et al., 2003; Drucker et al., 2008; Drucker et al., 2011). However, the isotopic threshold for distinguishing between grazing in densely forested versus open environment is ecosystem-dependent (Stevens et al., 2006), and may fluctuate with local climate conditions, atmospheric CO_2 concentration and atmospheric $\delta^{13}\text{C}$ value during a specific archeological period. In previous studies $\delta^{13}\text{C}$ cut-off values of -22.5‰ (Drucker et al., 2003) and -22.0‰ (Drucker et al., 2011) were suggested by analyzing red deer bone collagen from temperate and periarctic environments of the northern hemisphere.

We applied stable carbon isotope analyses to Neolithic and Bronze Age domestic cattle (*Bos taurus*) and red deer (*Cervus elaphus*) collagen samples in order to explore environmental conditions, changes in habitat use and livestock management in the temperate deciduous ecosystem of the lower Lake Zurich region. Our study complements archeobiological research showing human impact and exploitation of the lake's hinterland throughout the Neolithic (Jacomet et al., 1989; Schibler et al., 1997).

2. Archeological context

We focus on the well-described site of Zurich-Mozartstrasse, which is located at the northern end of Lake Zurich in Switzerland (Figure 1). An area of 2700 m² of the settlement was excavated in 1981 and 1982. The stratigraphy of this site is more than 2 m deep, and indicates repeated occupation and abandonment episodes of the same place. The settlement layers cover a time span from the early 4th to the 2nd millennium BC, and thus provide an archeological

record of more than 2000 years of human activity (Figure 2; Gross et al., 1987; Gross et al., 1992; Bleuer and Hardmeyer, 1993; Schmidheiny, 2011; Ebersbach et al., 2015). Six mainly dendrochronologically dated layers were attributed to the Cortaillod, Pfyn, Horgen, and Corded Ware periods (3913-2586 BC) and the Bronze Age (1950-950 cal. BC) (Figure 3).

The archeozoological remains of these layers have been extensively studied in previous work (Hüster-Plogmann and Schibler, 1997), and allowed detailed insights into the longer-term variation of the relative proportions of domestic versus wild animals, particularly with regard to large herbivores. Between the late 5th and the early 3rd millennium BC, the relative quantity of domestic animals (cattle, pig, sheep, and goat) with respect to wild animals varied substantially between 10% and 95% (Figure 4). Most notably, in the 37th century BC red deer were most intensively hunted so that the share of domestic animal remains declined to 10%. With regard to domestic animals, cattle were most important between ca. 4000 and 3300 BC, even though herd sizes were small especially in the early 4th millennium BC. This was succeeded by a period of intensified pig husbandry, followed by a period of enhanced domestic cattle, sheep and goat husbandry from the 28th century BC onwards (Hüster-Plogmann and Schibler, 1997). Wild animals preferring open forests and forest edges such as fox (*Vulpes vulpes*) and hare (*Lepus europaeus*), are frequent from 3300 BC onwards. The shift from a natural landscape (primeval forest) to a man-made cultural landscape is also supported by archeobotanic records that evidence the presence of specific wild plants. There is clear indication for the presence of widespread deforested areas (agricultural fields and fallow grounds) in the surrounding of the settlements during the late Corded Ware phase. In connection with growing herd sizes of domestic animals in the 3rd millennium BC these deforested areas, but also forests, were intensively used for pasturing (Hüster-Plogmann et al., 1999).

3. Material and methods

A total of 74 animal bones from 54 domestic cattle and 20 red deer and from four different layers were analyzed. The oldest Layers 6 and 5 (Cortaillod) date back to between 3913 and 3861 BC, whereas Layer 2 (Corded Ware) dates between 2625 and 2568 BC (Ebersbach et al., 2015). Layer 1 represents the Bronze Age, but is less precisely dated. It comprises settlement phases from the Early Bronze Age (between ca. 1950 and 1550 cal. BC), the Middle Bronze Age (between ca. 1504 and 1490 BC) and the Late Bronze Age (between ca. 1050 and 950 cal. BC) (Bleicher, 2011). The prime objective of this study was to compare the oldest with the youngest layers. The data from Layers 4 (Pfyn) and 3 (Horgen) are not

discussed here. Although subdivided originally into separate units, Layers 6 and 5 are treated as a single stratigraphic entity in the discussion and interpretive conclusions below, as it is now confirmed that they both belong to the same chronological phase (Ebersbach et al., 2015). Even though Layer 1 contains multiple Bronze Age settlement phases, it is considered here as one single stratigraphic entity.

Sample specimens were identified and assigned morphologically to specific macro-vertebrate faunal species. They were differentiated by skeletal element and body part in order to avoid double measurements of the same individuals. Collagen was analyzed from nine cattle and five red deer specimens from Layer 6, ten cattle specimens from Layer 5, 19 cattle and ten red deer specimens from Layer 2, and 15 cattle and five red deer specimens from Layer 1 (Table 1). Sampled skeletal elements have been investigated for age at death determination at the Institute of Prehistory and Archaeological Science (IPAS), University of Basel, applying a multi-proxy approach following the methods of Ducos (1968), Habermehl (1975), Grant (1982), Blaise (2009), Gillis (2012) and IPAS (Altersbestimmung) for domestic cattle, and Riglet (1977), Habermehl (1985) and von Raesfeld and Reulecke (1988) for red deer. We selected 23 non-adult and 31 adult domestic cattle samples as well as four non-adult and 16 adult red deer samples for bone collagen stable carbon isotope analysis. For each layer, both non-adult and adult animal specimens were considered, yet somewhat more non-adults were analyzed for the oldest layers, due to the fact that more bones of non-adult cattle were preserved in these layers. All but three samples were taken from jawbones as the age estimation using toothed jawbones is more accurate than for long bones. Based on intergrowth characteristics and general appearance, the three radius fragments sampled were assigned to adult red deer.

Collagen extraction followed the methodology outlined in Longin (1971), Ambrose (1990) and Oelze et al. (2011) with omission of the ultrafiltration step of which the benefit is rather uncertain (cf. Jørkov et al., 2007; Sealy et al., 2014). Chunks of bone were cut and the surfaces removed using dental cutting and milling equipment. Between 200 and 1000 mg of sample material was demineralized in 10 ml of 0.5 M HCl at 4°C for two weeks with daily shaking, occasional exposition to room temperature, and an acid bath change after one week. Samples were then rinsed with ultrapure water to restore neutral pH before treatment with 10 ml of 0.1 M NaOH at 4°C for about 24 hours in order to remove any humic substances. After rinsing to reach neutral conditions again, 4 ml of ultrapure water, and 200 µl of 0.5 M HCl

were added and the samples gelatinized at 70°C for 48 hours. Finally, the solution containing the dissolved collagen was filtered using Eze Filter separators (Elkay, UK) with pore size 60-90 μm to remove any remaining particulate organic remnants, frozen at -20°C, and lyophilized for 48 hours. Between 0.5 and 1 mg of freeze-dried sample were weighed into tin capsules, and the elemental and isotope composition was determined by Elemental Analysis – Isotope Ratio Mass Spectrometry (EA-IRMS) using an INTEGRA2 instrument (Sercon Ltd., Crewe, UK) at the Department of Environmental Sciences, University of Basel. All samples were analyzed in duplicate. Ultra high purity helium of grade 5.0 at a flow rate of 55 ml/min was used as carrier gas. The combustion and reduction reactors were operated at 1010°C and 600°C, respectively. Gas chromatographic separation of the combustion and reduction products N_2 and CO_2 was achieved on a column packed with Carbosieve G (stainless steel, 50 cm, 1/4" OD, 60/80 mesh; Analytical Columns, Croydon, UK). An EDTA laboratory standard ($\delta^{13}\text{C} = -30.25\text{‰}$), which has been isotopically calibrated against international reference materials, was measured after intervals of 10 samples throughout each of the eight analytical sequences to check and correct for instrumental drift. This EDTA laboratory standard was also used to check and correct for instrument induced amount linearity by measuring groups of four standards weighed in at different amounts (0.25, 0.5, 1.0, 1.5 mg) at the beginning, in the middle, and at the end of each analytical sequence. In addition, the international reference material IAEA-CH-6 ($\delta^{13}\text{C} = -10.449\text{‰}$) was measured at the beginning, in the middle, and at the end of each analytical sequence. The reproducibility (1σ) for the IAEA-CH-6 and EDTA standards over all eight analyzed sequences was 0.26‰ ($n = 23$) and 0.24‰ ($n = 110$), respectively. The raw carbon isotope data are normalized to the VPDB (Vienna Pee Dee Belemnite) scale by means of a two-point calibration based on the IAEA-CH-6 and EDTA standards in each analytical sequence. The final calibrated results are reported as $\delta^{13}\text{C}$ in ‰ relative to VPDB. We also analyzed replicates ($n = 8$) of a selected bone collagen sample, for which a larger quantity of material was available, in two analytical sequences separated by a time period of six months to test the analytical precision for a representative example of our sample material. The mean $\delta^{13}\text{C}$ for all eight analyses was -22.9‰ with a reproducibility (1σ) of 0.1‰.

The bone collagen yields, as well as the carbon and nitrogen contents of the bone collagen and the atomic C/N ratios of the samples were used to verify the preservation of the archeological specimens and the purity of the extracted collagen which may bias stable isotope analysis. Collagen yields $\geq 1.0\%$, carbon contents between 30 and 46%, nitrogen contents between 10 and 17%, as well as atomic C/N ratios between 2.9 and 3.6 were considered as thresholds for

good collagen preservation (DeNiro, 1985; Ambrose, 1990; van Klinken, 1999). All but one sample (MOZ 81) fulfilled the criteria of good collagen preservation, and are included in the subsequent discussion.

4. Results

The interpretation of our data is based on 53 domestic cattle and 20 red deer specimens. Statistical significance with respect to elemental and isotopic differences between groups of samples was tested using the approaches of Kruskal-Wallis (KW) and Mann-Whitney (MW). Relevant statistics are outlined in Table 2.

Collagen yields range between 1.0% and 18.6% for domestic cattle, and between 7.0% and 15.2% for red deer respectively, with no significant differences between the archeological layers, animal species or age groups. Independent of the faunal species, C/N ratios were quite invariant with values between 3.2 and 3.4 for domestic cattle and between 3.2 and 3.3 for red deer. Collagen carbon content for domestic cattle varied between 37.5% and 45.7%, collagen nitrogen content ranged between 13.5% and 16.1%. For red deer, the C ranged between 39.5% and 45.5% and N contents ranged between 14.0% and 16.0%. No significant differences in %C and %N could be discerned between faunal species, whereas significant differences were observed when comparing adult and non-adult domestic cattle (MW, $p=0.005$ for %C, $p=0.007$ for %N), with markedly reduced carbon and nitrogen contents in the collagen of non-adult domestic cattle. Analogous discrepancies were not observed for adult versus non-adult red deer, but this observation is based on a rather small number of individuals, especially for non-adult specimens ($n=4$). The differences in C and N content between layers, highly significant when considering all species and age groups (KW, $p<0.0001$ for %C and %N), remain significant when adult animals (KW, $p=0.001$ for %C, $p=0.005$ for %N) or non-adult animals (KW, $p=0.011$ for %C, $p=0.015$ for %N) are taken into account separately.

The $\delta^{13}\text{C}$ values for domestic cattle ranged from -25.6‰ to -21.1‰ ($-22.3\text{‰} \pm 0.85$, $n=53$), with a narrow range for adult animals (-22.8‰ to -21.6‰; $-22.1\text{‰} \pm 0.35$, $n=31$). Red deer samples displayed carbon isotope values between -25.0‰ and -22.1‰ ($-23.4\text{‰} \pm 0.78$, $n=20$). Differences in $\delta^{13}\text{C}$ values between all domestic cattle and red deer were highly significant (MW, $p<0.0001$), while there were no significant differences observed between adult and non-adult animals on an intra-species level. C isotope data of all domestic cattle are similar within Layers 1 and 2, but rather variable when Layers 1 and 6/5 or Layers 2 and 6/5 are compared, although differences are not significant. In contrast, $\delta^{13}\text{C}$ values of all red deer are

quite similar for Layers 2 and 6/5, but are significantly different between Layers 1 and 6/5 (MW, $p=0.008$) and between Layers 1 and 2 (MW, $p=0.004$).

The results of the $\delta^{13}\text{C}$ analyses are displayed in Figure 5. There is a considerable overlap between the carbon isotope values of red deer and domestic cattle in Layer 1, whereas Layer 2 shows a very different picture, with a distinct separation and a marginal overlap of red deer and domestic cattle C isotopic values. The variance of the carbon isotope composition for domestic cattle in Layers 6/5 is considerably larger and covers a range of almost 5‰. Interestingly, two non-adult domestic cattle show $\delta^{13}\text{C}$ values that are lower than those of red deer. The distinction between red deer and domestic cattle is obvious but not as clear as in Layer 2. Four young domestic cattle, between one and 18 months of age, exhibit $\delta^{13}\text{C}$ values that correspond to the red deer's C isotope range. One adult red deer yielded a very low $\delta^{13}\text{C}$ value, similar to the outlier values of domestic cattle. Apart from that, the values of red deer of the Layers 6/5 and 2 are rather similar. The carbon isotope values of adult versus non-adult herbivores clearly overlap within all layers, indicating that in general, no obvious differences exist between age groups, i.e. no obvious patterns in $\delta^{13}\text{C}$ values related to the age of the non-adult domestic cattle could be discerned (Figure 6).

5. Discussion

5.1 The application of stable carbon isotope analysis to wetland archeological sites

A regularly abandoned and reoccupied settlement site allows insights into changes of environmental conditions and domestic animal husbandry strategies over time in a specific region. In this respect, wetland archeological sites are a valuable source of information because the accurately dated stratigraphic evidence, together with well-preserved archeological material, permits diachronic observations. Animal bones are often preserved in large quantities, providing insight into subsistence and livestock management strategies. We know that domestic and wild animals played essential roles throughout the periods discussed here (Schibler, 2006). The application of stable carbon isotope analysis on faunal remains helps to understand prehistoric economic strategies in greater detail. There are only few carbon isotope data for prehistoric wetland sites, however. C isotope measurements from red deer dentin samples from the Horgen period lakeshore settlement Zug-Riedmatt (around 3250 and 3150 BC) in Central Switzerland (Schumpf, 2013) revealed $\delta^{13}\text{C}$ values between -25.5‰ and -22.5‰, indicative of a rather dense woodland environment around Lake Zug. Moreover, differential $\delta^{13}\text{C}$ values for collagen samples from red deer (-22.4‰) versus domestic cattle (-21.5‰ to -20.5‰) from the wetland site Reute-Schorrenried (38th century BC) in southern

Germany, has been taken as putative evidence for grazing in different habitats; that is, dense forest (red deer) on the one hand and open landscape (domestic cattle) on the other (Drucker and Bocherens, 2010). Similar observations enabling the differentiation between open grassland cattle grazing on the one hand and red deer forest browsing on the other were made by Noe-Nygaard and colleagues (2005), who compared $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of Holocene aurochs, cattle and red deer from settlement sites near lakes and bog deposits in southern Scandinavia. In analogy to these studies, we argue below that the marked differences in $\delta^{13}\text{C}$ values in domestic cattle and red deer bone collagen from Zurich-Mozartstrasse indicate an opening of the landscape over time and reflect the different habitat proclivities of the two species, with domestic cattle occupying areas of more open vegetation. Our results for Layer 1, which show a clear overlapping between the $\delta^{13}\text{C}$ values of red deer and domestic cattle, suggest that the differences in the bone collagen carbon isotopic compositions between red deer and domestic cattle in Layers 6/5 and 2 are not related to metabolically differing fractionation processes. The absence of any trophic level shift related to suckling is indicated by the absence of significant differences in $\delta^{13}\text{C}$ between non-adult and adult domestic cattle and red deer from all archeological layers. The lack of significant differences in collagen yield between layers, animal species and age groups confirms the good comparability of all our samples over time, and suggests that potential bias in $\delta^{13}\text{C}$ due to effects of differential preservation can be excluded. The significant differences in C% and N% in collagen in Layers 6/5 compared to Layers 2 and 1 may be explained by a more advanced degradation of bone collagen in the older layers, although the criteria of good collagen preservation are met in all cases. The difference in C% and N% in bone collagen of domestic cattle might be related to a different ratio of non-adult to adult specimens, which is 15:4 in the older Layers 6/5, but only 7:27 in the younger Layers 2 and 1.

5.2 Indications for a landscape opening based on red deer stable carbon isotope ratios

Habitat changes over time are suggested by the carbon isotope shifts observed for red deer bone collagen between stratigraphic layers: mean $\delta^{13}\text{C}$ values change from $-24.1 \pm 0.7\text{‰}$ (Layers 6/5) to $-22.5 \pm 0.3\text{‰}$ (Layer 1). These values are comparatively low, indicating pasture grounds in a rather closed environment. Based on our dataset, values between -22.1‰ (Layer 1) and -22.7‰ (Layer 2) can be regarded as threshold for differentiating between large herbivores feeding from open versus closed environments in a temperate deciduous ecosystem (Figure 5 and Table 1). These values are comparable to those reported in the studies of Drucker et al. (2003; 2011) on herbivores in similar pre-industrial ecosystems. The generally

low $\delta^{13}\text{C}$ values observed for red deer, with maxima of -23.5‰ for Layers 6/5, -22.7‰ for Layer 2 and -22.1‰ for Layer 1, as well as the low inter-individual variability with 1.5‰, 1.7‰ and 0.7‰, respectively, underscore the interrelation between forested areas and these animals. The very low $^{13}\text{C}/^{12}\text{C}$ values of red deer in the Layers 6/5 may reflect feeding grounds in a densely forested environment, which is in good agreement with red deer data from a modern primeval forest ecosystem in Poland/Belarus (National Park Bialowieza), as summarized in Bocherens and Drucker (2003). Links between increasing/decreasing $\delta^{13}\text{C}$ trends and an opening/closure of the landscape were also observed in Western Europe during more ancient periods (Noe-Nygaard et al., 2005; Drucker and Bocherens, 2009).

Apart from the canopy effect, an increase in precipitation and humidity might cause more depleted $\delta^{13}\text{C}$ values in the herbivore's feeding plants (Hedges et al., 2004; Kohn, 2010). Stevens et al. (2006) studied modern European red deer populations in various geographic environments. Excluding any detectable $\delta^{13}\text{C}$ canopy effect, they suggested that the differences in the mean-population $\delta^{13}\text{C}$ were related mainly to climatic factors. However, climatic variations cannot explain the differences seen between red deer and domestic cattle in our data set, given that the isotope ratios should be equally affected by changes in precipitation and humidity. Thus, we argue that our results indicate environmental changes, i.e. the existence of a dense forest in the early 4th millennium BC and an opening of the landscape during the 3rd millennium BC. Based on our data, it seems plausible that the red deer habitat underwent significant changes between the 27th and the 20th century BC. This proposed habitat shift is clearly supported by observations of archeobotanical and archeozoological studies in the Lake Zurich region that suggest floral and faunal community structure changes. For example, evidence exists for the intensified use of arable land with weeds such as creeping tormentil (*Potentilla reptans*) or white clover (*Trifolium repens*), and higher relative proportions of animals and birds preferring structured, rather open environments, e.g. red fox (*Vulpes vulpes*), brown hare (*Lepus europaeus*) or carrion crow (*Corvus corone*). Additional indirect indication for environmental change (i.e. deforestation and opening of the landscape) at that time is provided by the increased abundance of pike (*Esox lucius*) and carp fish (*Cyprinidae*), which can be related to the emergence of reed beds along lakeshores in response to the eutrophication through erosion of deforested soils (Jacomet et al., 1989; Schibler et al., 1997).

5.3 Implications for herding strategies based on domestic cattle stable carbon isotope ratios

In contrast to the observed red deer's C isotope shift, the shift in mean $\delta^{13}\text{C}$ values for domestic cattle bone collagen from $-22.7 \pm 1.3\text{‰}$ (Layers 6/5) to $-22.1 \pm 0.3\text{‰}$ (Layer 1) was not significant. This is not surprising, given that open environments are supposed to be the prime habitat of domestic cattle. The lowest $\delta^{13}\text{C}$ values clustered around -22.7‰ for Layers 2 and 1, respectively, with narrow inter-individual variations (1.3‰ for Layer 2 and 1.1‰ for Layer 1), suggesting the use of unforested areas. Given that in essentially all layers, single values are relatively low, it seems probable that some domestic cattle fed from a mixture of resources from both forest habitat and open environments. The very low $\delta^{13}\text{C}$ values of some non-adult domestic cattle in Layers 6/5 are of special interest. The inter-individual variation in these layers is quite extensive (4.6‰), at least when both non-adult and adult animals are considered (while it is 1.1‰ for the four adults only). This variance is clearly larger than the inter-individual range observed in modern large herbivores from a boreal forest environment (Central Saskatchewan, Canada), which did not exceed 3.1‰ within a given population (Drucker et al., 2008). Even though this observation is based on bison (which are also bovines), we suggest that the large intra-species variance of domestic cattle in the oldest layers from Zurich-Mozartstrasse is related to human intervention in livestock management, i.e. variation in grazing environments in a temperate deciduous forest or in foddering techniques.

Schnyder et al. (2006) looked at the influence of humidity on the variability of $\delta^{13}\text{C}$ in modern cattle grazing on temperate humid grassland. They concluded that variable site conditions (soil moisture) but also interannual variation of weather can affect the carbon isotope values of vegetation and consequently animal tissues, with more negative $\delta^{13}\text{C}$ values for grazing in humid areas. We will not be able to assess interannual weather variation, but it is reasonable to assume that grazing in open but wet environments such as riverside woodlands and river deltas (e.g. the *Sihldelta* in close vicinity to Zurich-Mozartstrasse) would result in low $\delta^{13}\text{C}$ values of domestic cattle bone collagen samples. Several authors outlined that domestic cattle management and feeding practices were highly elaborated, and seasonally differing strategies are likely (Schibler et al., 1997; Ebersbach, 2002; Kühn et al., 2013). One of these strategies to consider is leaf foddering in winter. That is, mainly young animals were kept in, or at least near, the settlement during winter times and fed by humans, who gathered low- $\delta^{13}\text{C}$ plants or harvested leaves and twigs from dense woodland and possibly from riverside woodlands and river deltas. Winter leaf foddering may thus result in very low $\delta^{13}\text{C}$ values in cattle bone collagen, as already suggested for Bercy, a Neolithic dryland settlement in the Paris Basin, France (Balasse et al., 2012). However, the isotope effect of winter leaf foddering may not

always be that pronounced and it simply depends on the $\delta^{13}\text{C}$ of the fodder and thus the harvest time. For example, winter leaf foddering as a potential feeding strategy of domestic cattle in southern Scandinavia was discussed in line of the elm decline at the Atlantic-Subboreal transition (Noe-Nygaard et al., 2005), where the authors did not see any indications of leaf foddering on the basis of their isotopic data set. Irrespective of the potential of C isotopic measurements to gain constraints on winter leaf foddering, dung analyses can provide independent evidence for such feeding strategies, as has been shown for small and large ruminants at several wetland sites in Switzerland (Kühn et al., 2013). One example is the settlement Wetzikon-Robenhausen, canton Zurich, another one is Thayngen-Weier II, canton Schaffhausen, where some of the excavated buildings have been interpreted as stables, although this is a matter of debate (Ebersbach, 2002). All of them are dated to the early 4th millennium BC and are chronologically comparable to the Layers 6/5 of Zurich-Mozartstrasse. Hence, the low $\delta^{13}\text{C}$ values in these layers may be indeed explained by winter leaf foddering. However, other explanations for low carbon isotope values, such as woodland pasturing of domestic cattle, cannot be ruled out completely, especially for seasons other than winter. Woodland pasturing was a common land management system in historical times in Europe even though large grazing grounds were available (Ebersbach, 2002). Such grounds can certainly be regarded as one of the preconditions for increased cattle breeding efforts in the Neolithic (Schibler and Jacomet, 1999; Ebersbach, 2002), which is suggested for 2800 BC (Corded Ware period) onwards in the Lake Zurich area (Schibler et al., 1997). The association of relatively high $\delta^{13}\text{C}$ values and (man-made) open grazing grounds was postulated for other European regions and time periods (e.g. Noe-Nygaard et al., 2005; Drucker and Bocherens, 2009; Sommer et al., 2011). The high $\delta^{13}\text{C}$ values of domestic cattle compared to red deer in our study emphasize the importance and availability of open landscapes throughout the complete stratigraphic sequence of the settlement from the early 40th century BC onwards. We argue that domestic cattle management was always linked to specific niche use (Stewart et al., 2003) and seasonal herding strategies. Ongoing multi-isotope (strontium, oxygen, carbon, nitrogen) analyses on tooth enamel and dentin of the sampled individuals will shed light on seasonally varying feeding practices and herding strategies in the Lake Zurich region. Overall, it needs to be stressed that livestock management was certainly influenced strongly by cultural, social and individual human decisions. It is very likely that extensive land-use and diversified herding and feeding management increased the resilience of Neolithic farming communities (Doppler et al., 2012; 2013), factors that may have played key roles in opening the landscape and in changing cattle herding strategies over time.

6. Summary and conclusions

The wetland site of Zurich-Mozartstrasse, with its extensive stratigraphy and precisely dated settlement layers, offers a unique opportunity to observe diachronic changes in land-use and animal management at a local and regional scale. Our isotopic data set is one of the first of its kind for Swiss wetland sites, and one of the few applied to lakeshore settlements in general. We analyzed the carbon isotope composition of domestic cattle and red deer bone collagen, and observed shifts in the $\delta^{13}\text{C}$ between the early 4th millennium and the 2nd millennium BC. Trophic level shifts, suckling effects and metabolically differing fractionation processes can be excluded as explanations for differences in carbon isotope ratios between red deer and domestic cattle, and between different age groups. We rather suggest that the significant difference between the carbon isotope values of red deer versus domestic cattle points to different habitat use by these species, with cattle mainly grazing in open grasslands and red deer feeding in more closed woodlands. The increasing $\delta^{13}\text{C}$ trend of red deer over time is best explained by an opening of the landscape, and can be related to a reduction in the canopy effect. Our interpretation emphasizes the potential of stable carbon isotope measurements of herbivore bone collagen for tracking forest cover. This is consistent with archeobotanical and archeozoological data suggesting the existence of an opened landscape from 2800 BC onwards. In addition, we argue that relatively high $\delta^{13}\text{C}$ values for domestic cattle observed throughout the stratigraphic sequence of the study site indicate the importance and availability of pastures in open environments as early as the 40th century BC. The low $\delta^{13}\text{C}$ values of several non-adult cattle in the early 4th millennium BC imply a greater variety of animal management strategies compared to the younger periods, potentially linked to differing herding skills, specific niche use and leaf foddering. These conclusions underline the importance of carbon isotope analyses of collagen from domestic cattle and red deer bones in order to explore paleoenvironmental conditions and human-induced subsistence strategies, which certainly contributed to changes in forest cover over time.

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Figure 1
Location of Zurich-Mozartstrasse at the northern end of Lake Zurich in Switzerland.

Figure 2
Stratigraphic sequence of Zurich-Mozartstrasse with vertical wooden post remains visible in the profile. The numbered dark layers represent the settlement occupations while the white layers (lake marl) indicate phases of abandonment during lake transgressions. Each archeological layer differs in thickness within the excavated area. Photograph: Gross et al. 1987, supplemented.

Figure 3
Chronological scheme for the Neolithic and Bronze Age in Central Switzerland. Simplified after Rychner (1998), Hafner and Suter (2005), Stöckli (2009) and Denaire et al. (2011). Very little is known about the beginning and the end of the Early and the Middle Neolithic. The given numbers are approximations. Additionally, the temporal placement of the sampled archeological layers is shown.

Figure 4
Significance of domestic and wild animals in Neolithic lakeshore settlements of Central Switzerland. The chronological development (columns) is based on find densities (number of bone fragments per square meter and settlement phase; see Schibler et al., 1997, 329). The relative proportions of domestic and wild animals in single time periods (lines) are given in percentages (100% = number of all identifiable bone fragments). Graph: Schibler, 1997, modified.

Figure 5
Plot of $\delta^{13}\text{C}$ values of cattle and red deer bone collagen versus stratigraphic layers.

Figure 6
Plot of $\delta^{13}\text{C}$ values of cattle bone collagen according to age categories following IPAS (Altersbestimmung) versus stratigraphic layers. Non-adult and adult cattle are shown on different levels.

Table 1
Cattle and red deer samples with information on the stratigraphic layer, individual data on skeletal element, age (y = years, m = months), age group and results of isotopic measurements of bone collagen (mean of duplicate measurements for each sample).

Table 2
Tested differences in $\delta^{13}\text{C}$ values using Mann-Whitney statistics ($\alpha=0.05$).

Figure 1

Figure 2

Layer 1

Layer 2

Layer 3

Layer 4

Layer 5/6

Figure 3

Figure 4

BC	domestic animals	wild animals
2500
2750
2900	?	?
3250
3350	?	?
3660
3850
4200
4300

Figure 5

Figure 6

Table 1

Lab ID	Layer	Species	Skeletal element	Age	Age group	Coll%	%C	%N	C/N	$\delta^{13}\text{C}\text{‰}$ (vs. VPDB)
MOZ 19	1	cattle	mandible right	25-34 m	non-adult	10.3	43.1	15.3	3.3	-22.7
MOZ 33	1	cattle	mandible right	ca. 3 y	non-adult	12.4	43.5	15.5	3.3	-22.0
MOZ 1	1	cattle	mandible right	ca. 6.5 y	adult	12.0	43.9	15.6	3.3	-22.1
MOZ 3	1	cattle	mandible right	ca. 6.5 y	adult	10.9	43.8	15.7	3.3	-22.1
MOZ 5	1	cattle	mandible left	ca. 6.5 y	adult	12.3	43.7	15.6	3.3	-22.1
MOZ 2	1	cattle	mandible right	ca. 9 y	adult	11.0	44.6	16.0	3.2	-21.9
MOZ 16	1	cattle	mandible right	ca. 9 y	adult	15.3	42.4	15.1	3.3	-22.0
MOZ 18	1	cattle	mandible right	ca. 9 y	adult	15.3	43.5	15.4	3.3	-21.8
MOZ 20	1	cattle	mandible right	ca. 9 y	adult	13.3	42.7	15.1	3.3	-22.3
MOZ 21	1	cattle	mandible left	ca. 9 y	adult	11.4	41.9	14.4	3.4	-22.3
MOZ 22	1	cattle	mandible left	ca. 9 y	adult	9.1	41.1	14.4	3.3	-22.6
MOZ 24	1	cattle	mandible right	ca. 9 y	adult	4.8	39.3	14.1	3.3	-22.2
MOZ 4	1	cattle	mandible left	ca. 11.5 y	adult	10.1	42.3	15.1	3.3	-21.6
MOZ 17	1	cattle	mandible right	ca. 11.5 y	adult	10.7	42.5	15.2	3.3	-21.7
MOZ 23	1	cattle	mandible left	ca. 11.5 y	adult	10.2	42.3	15.0	3.3	-21.9
MOZ 36	1	red deer	mandible right	11-12 m	non-adult	13.7	43.2	15.3	3.3	-22.6
MOZ 35	1	red deer	mandible left	> 6 y	adult	15.2	43.6	15.5	3.3	-22.6
MOZ 6	1	red deer	mandible left	7-8 y	adult	13.0	44.9	16.0	3.3	-22.8
MOZ 7	1	red deer	mandible left	7-10 y	adult	12.8	42.7	15.1	3.3	-22.1
MOZ 34	1	red deer	mandible right	adult	adult	11.9	42.0	15.0	3.3	-22.3
MOZ 53	2	cattle	mandible left	7-14 m	non-adult	7.1	41.8	14.9	3.3	-22.2
MOZ 81	2	cattle	mandible left	7-14 m	non-adult	0.1	41.8	13.9	3.5	-22.2
MOZ 44	2	cattle	maxilla right	15-18 m	non-adult	9.0	41.5	14.8	3.3	-21.9
MOZ 86	2	cattle	maxilla left	15-18 m	non-adult	13.4	44.6	15.4	3.4	-22.1
MOZ 51	2	cattle	mandible left	19-24 m	non-adult	11.3	43.8	15.7	3.3	-21.4
MOZ 56	2	cattle	mandible left	19-24 m	non-adult	2.2	41.4	14.5	3.3	-21.7
MOZ 54	2	cattle	mandible left	4-6.5 y	adult	8.8	42.1	15.0	3.3	-22.2
MOZ 79	2	cattle	mandible right	6.5-9 y	adult	7.8	44.1	15.6	3.3	-22.4
MOZ 45	2	cattle	maxilla right	ca. 9 y	adult	17.1	43.1	15.5	3.2	-22.6
MOZ 55	2	cattle	mandible left	ca. 9 y	adult	1.0	41.3	14.5	3.3	-21.8
MOZ 83	2	cattle	maxilla left	ca. 9 y	adult	18.6	45.5	15.9	3.3	-22.7
MOZ 48	2	cattle	mandible left	9-11.5 y	adult	9.0	41.7	15.0	3.2	-22.3
MOZ 82	2	cattle	maxilla left+right	9-11.5 y	adult	16.3	45.7	16.1	3.3	-22.5
MOZ 52	2	cattle	mandible right	ca. 11.5 y	adult	13.0	42.5	15.3	3.2	-21.6

Table 2

Difference to be tested	p-value	Significance
cattle and red deer (all layers)	<0.0001	yes
adult and non-adult cattle (all layers)	0.223	no
adult and non-adult red deer (all layers)	0.369	no
cattle (layers 1 and 2)	0.835	no
cattle (layers 1 and 6/5)	0.111	no
cattle (layers 2 and 6/5)	0.122	no
red deer (layers 2 and 6/5)	0.582	no
red deer (layers 1 and 6/5)	0.008	yes
red deer (layers 1 and 2)	0.004	yes