

Potential short-term earthquake forecasting by farm animal monitoring

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Abstract

Whether changes in animal behavior allow for short-term earthquake predictions has been debated for a long time. Before, during and after the 2016/2017 earthquake sequence in Italy, we deployed bio-logging tags to continuously observe the activity of farm animals (cows, dogs, and sheep) close to the epicenter of the devastating magnitude M6.6 Norcia earthquake (Oct–Nov 2016) and over a subsequent longer observation period (Jan–Apr 2017). Relating 5,304 (in 2016) and 12,948 (in 2017) earthquakes with a wide magnitude range ($0.4 \leq M \leq 6.6$) to continuously measured animal activity, we detected how the animals collectively reacted to earthquakes. We also found consistent anticipatory activity prior to earthquakes during times when the animals were in a building (stable), but not during their time on a pasture. We detected these anticipatory patterns not only in periods with high, but also in periods of low seismic activity. Earthquake anticipation times (1–20 hr) are negatively correlated with the distance between the farm and earthquake hypocenters. Our study suggests that continuous bio-logging of animal collectives has the potential to provide statistically reliable patterns of pre-seismic activity that could yield valuable insights for short-term earthquake forecasting. Based on a priori model parameters, we provide empirical threshold values for pre-seismic animal activities to be used in real-time observation stations.

KEYWORDS

collective behavior, disaster, earthquake, emergent sensing, forecasting

ONE SENTENCE SUMMARY

A collective of domestic animals repeatedly showed unusually high activity levels before earthquakes, with anticipation times (1–20 hr) negatively related to distance from epicenters (5–28 km).

1 | INTRODUCTION

Earthquakes are a major threat as they strike unexpectedly, and unpredictably in exact space and time, causing large economic and societal losses (Davies, 1975; Hui & Kerr, 1997; Kerr, 2009; Oliver, 1964; Wenzel & Zschau, 2013). While the general location, time period, and expected magnitude range can be statistically forecasted for earthquakes in well-instrumented regions, accurate short-term predictions are considered impossible (Hough, 2016; Keilis-Borok, Knopoff, Rotwain, & Allen, 1988; Li et al., 2003). To prepare for earthquakes and their consequences, probabilistic seismic hazard assessment is used to estimate possible shaking levels for future earthquakes. Earthquake early warning systems provide automated short-notice local warnings to agencies and infrastructural systems about the imminent danger of strong shaking (Cyranoski, 2004; Wenzel & Zschau, 2013). However, reliable technical warning systems that anticipate the location, magnitude, and timing of an earthquake within minutes to hours do not exist (Hough, 2016; Service, 1994).

Since ancient times, abnormal animal behavior prior to earthquakes or volcanic eruptions has been described, with some animals showing “aberrant” or “strange” behavior in anticipation of natural disasters (Davies, 1975; Humboldt, 2006; Tributsch, 1982b). Most famously, the 1975 Haicheng earthquake (magnitude M 7.3) in China was anticipated based on human observations of animal behavior, such as snakes or rats leaving their burrows in winter (Wang, Chen, Sun, & Wang, 2006). Similar observations are rare (Whitehead, Ulusoy, Asahara, & Ikeya, 2004), but recently evidence accumulated that animals in earthquake areas may show aberrant behavior (Fidani, 2013; Fidani, Freund, & Grant, 2014; Freund & Stolc, 2013; Grant, Raulin, & Freund, 2015; Li et al., 2009; Whitehead et al., 2004; Yamauchi, Uchiyama, Ohtani, & Ohta, 2014; Yokoi, Ikeya, Yagi, & Nagai, 2003). Nevertheless, a recent review (Woith, Petersen, Hainzl, & Dahm, 2018) points out the sparsity of data and need for testable quantitative measures on animal-anticipated earthquake occurrence.

Assuming that measurable physical precursors for earthquakes exist, three conditions must be met for animal behavior to be possibly useful for short-term earthquake forecasting (Kenagy & Enright, 1980): i) The precursors must be perceived by animals; ii) animals must respond to precursors by showing measurable, quantifiable, and testable behavioral patterns; and iii) these behavioral patterns must be detected and clearly distinguished against the background of regular behavior. In many reports on anticipatory animal behavior, these three conditions have been met only partially (Buskirk, Frohlich, & Latham, 1981; Kirschvink, 2000; Logan, 1977; Lott, Hart, Verosub, & Howell, 1979; McClellan, 1980).

More recently, several approaches proposed to quantify animal behavior in accordance with the abovementioned conditions (Van Buskirk et al., 1981; Grant & Halliday, 2010; Grant et al., 2011, 2015; Ikeya, Furuta, Kajiwara, & Anzai, 1996; Kenagy & Enright, 1980; Kirschvink, 2000; Logan, 1977; Lott, Hart, Howell, & Verosub, 1978; Tributsch, 1982a, 1982b). Among others, the use of camera traps for birds and mammals and the use of locomotor sensors for mice have shown potential to be useful to detect behavioral changes in animal behavior prior to earthquakes (Buskirk et al., 1981; Grant & Halliday, 2010; Grant et al., 2011, 2015; Ikeya et al., 1996; Kenagy & Enright, 1980; Kirschvink, 2000; Logan, 1977; Lott et al., 1978; Tributsch, 1982a, 1982b).

In our study, we used bio-logging techniques (Kays, Crofoot, Jetz, & Wikelski, 2015), enabling remote, continuous observation of animals in unprecedented detail, particularly through continuous 3D accelerometer data (Brown, Kays, Wikelski, Wilson, & Klimley, 2013; Wilson et al., 2006). Moreover, recent advances in understanding animal behavior show that collectives of animals can have sensing abilities that outperform individuals (Berdahl, Torney, Ioannou, Faria, & Couzin, 2013). Collectives are defined here as interacting groups of animals, either within or between species. Thus, one may speculate that some animal collectives are able to detect and process physical signals (Couzin, 2007) for which currently no engineered recording devices exist. Correspondingly, our study is not only aimed at providing evidence for unusual animal behavior prior to earthquakes (as proposed in (Wikelski, Mueller, Heidrich, & Kuemmeth, 2015)), but also at verifying that animals continuously respond to changes in potential precursors of earthquakes. For this purpose, we measured the activity (as overall dynamic body acceleration, ODBA) of multiple cows, dogs, and sheep at a farm nearby the hypocenter of the M6.6 Norcia (Italy) earthquake and analyzed them in the context of the ongoing seismicity. We distinguish three time periods: (a) the Oct–Nov 2016 period shortly before and after the M6.6 Norcia shock where the animals were in a stable; (b) the Jan–Mar 2017 period of lower earthquake activity, where the animals were also in the stable; and (c) the Mar–Apr 2017 period, where the animals were on a pasture.

A number of possible precursory processes and associated physical signal have been suggested in the literature (Buskirk et al., 1981; Grant & Halliday, 2010; Grant et al., 2011, 2015; Ikeya et al., 1996; Kenagy & Enright, 1980; Kirschvink, 2000; Logan, 1977; Lott et al., 1978; Tributsch, 1982a, 1982b), but there is no consensus on which of them may explain changes in animal behavior. Our considerations are based on the conjecture that a diffusive process, possibly related to slow deformation processes in the rock volume near the future hypocentral region of the ensuing earthquake (Freund, 2003, 2011; Freund et al., 2009; Freund, Takeuchi, & Lau, 2006; Little & Freund, 2019) generates and emanates a physical measurable precursory signal. However, we refrain from speculating about the details of the potential mechanisms of this diffusive process, but for a valuable discussion see (Bleier et al., 2009; Freund, 2003; Keilisborok et al., 1988; Rydelek & Horiuchi, 2006; Yoshida & Ogawa, 2004). The goal of this study

is to measure and analyze the anticipatory patterns without relying on assumptions about a potential mechanism.

2 | METHODS

2.1 | Field site selection and tagging of animals

We approached the farm of the Angeli brothers in the village of Capriglia (Figure S1) and, upon consultation with local authorities, received oral permission and the help of the farmers to tag their domestic animals. All our experiments were carried out in accordance with relevant guidelines and regulations. The protocols were in accordance with Legislative Decree No. 146, implementing Directive 98/58/EC of 20 July 1998 concerning the protection of animals kept for farming purposes.

We chose to tag the animal species and individuals that were selected by the farmers as being potentially sensitive to earthquakes, based on the farmers previous experience. On Oct 28th, 2016, we tagged a total of 6 cows, 5 sheep, 1 rabbit, 4 chicken, 2 turkeys and 2 dogs who later experienced earthquakes within 3–30 kilometers (S1,2), using 54Hz-3D-acceleration loggers to near-continuously quantify their overall dynamic body acceleration (ODBA), a measure for animal activity (Brown et al., 2013). The loggers were synchronized to GPS time immediately before deployment and were set to start recording at 18 hr UTC on Oct 28th, 2016. We left the farm on Oct 28th, 2016, at 15 hr UTC. We then returned to the farm on Nov 18th, 2016, to retrieve the tags. Data were downloaded immediately, entered into Movebank (Dodge et al., 2013; Fiedler & Davidson, 2012; Kranstauber et al., 2011), and visually pre-analyzed.

We returned again to the farm on Jan 3rd, 2017, to record additional animal activity data; it turned out that earthquake activity was reduced in that period. We tagged the same individual animals again that were previously tagged, from Jan 17th until Apr 16th, 2017. During the winter period (Oct–Mar 11th, 2017), the cows were held in a stable, chained to one predefined location as is customary in traditional farms (Figure S1, S2). The dogs were generally kept inside the house or in the narrow courtyard, from which they could also enter the stables of the cows or sheep. Starting from Mar 11th, 2017, the animals were brought to the pastures that surround the farm (Figure S3) and could roam freely within their large enclosures.

The animals were tagged with nylon harnesses, according to standard procedures (Kenward, 1987; Wilson, Wikelski, Wilson, & Cooke, 2015). They appeared to tolerate the tag attachments well, based on reports from the farmers and the fact that no anomalies to the fur were found when retrieving the tags. We recorded the 3D acceleration of the tagged animals continuously at 54Hz during the Oct–Nov 2016 period and at 54Hz every 120 s for 3.5 s during the Jan–Apr 2017 period. We calculated the ODBA according to standard procedures (Qasem et al., 2012; Scharf, LaPoint, Wikelski, & Safi, 2016; Wilson et al., 2014). The two dogs (of 4 on the farm)

were initially restricted to a narrow farm yard, but later roamed the pastures with the sheep. A total of ca. 20 cows were chained by the farmer next to each other inside a stable during Oct 2016 to Mar 10th, 2017, but were free to roam on a pasture after Mar 11th, 2017. The sheep were kept free-running inside a stable (ca. 4 by 20 meters) in a group of about 100 animals from Oct 2016 to Mar 10th, 2017. Later, the same group was kept free-running in open pastures.

2.2 | Data description

We used 3D acceleration sensors to measure the activity of the animals (Figure 1c). As only cows, dogs, and sheep were available in all three time periods of the study (Oct–Nov 2016, Jan–Mar 2017, and Mar–Apr 2017; the other individuals (rabbit, chicken, turkeys) were consumed during the holidays), only these three species were considered in the analysis. For each of these individuals of the three species, we computed the 15 min average of their ODBA, that is, the average acceleration and the average over all tagged animals of the respective species.

Between Oct 29th and Nov 7th, 2016, the animals experienced a total of 5,304 earthquakes with $M > 0.4$ (maximum M 6.6) and from Jan to Apr 2017 a total of 12,948 (maximum M 4.2, Figures 2, 3, 4). The M 6.6 Norcia mainshock was felt throughout central Italy and into Rome (Figure 1a).

For each of the earthquakes, we used hypocenter information (latitude, longitude, depth) to compute the hypocentral distance between the farm and the respective earthquakes. The hypocentral distances of these earthquakes range from 5 to 28 km to the tagged animals, oriented mostly in a southerly direction (Figure 1b).

Figure 2 shows the time series of both aggregated animal activity (average over the species) and the earthquakes for the Oct–Nov 2016 period.

2.3 | Data preprocessing

Regarding the animal activity, we could directly use the ODBA time series (on 15-min intervals) of the three species during the three periods.

Regarding the earthquake activity, a measure for the actual earthquake activity at the farm was needed. The magnitude is a measure for the strength of the earthquake that does not consider the distance from the hypocenter. As measure for earthquake activity at the farm, we estimated the peak ground acceleration (PGA) at the farm for the available earthquake catalog ($0.4 < M < 6.6$) using a regional ground-motion prediction equation (Bindi et al., 2011)(S3).

The depth-dependent seismic wave speeds in the upper Earth crust range typically from 3 to 7 km/s for the primary P-waves, and 2–4.5 km/s for the secondary S-waves. Given that we measure animal activity in 15 min time intervals, the travel times of seismic waves from the earthquake's hypocenters and the farm are on the order of a few seconds, and hence negligible in our analysis.

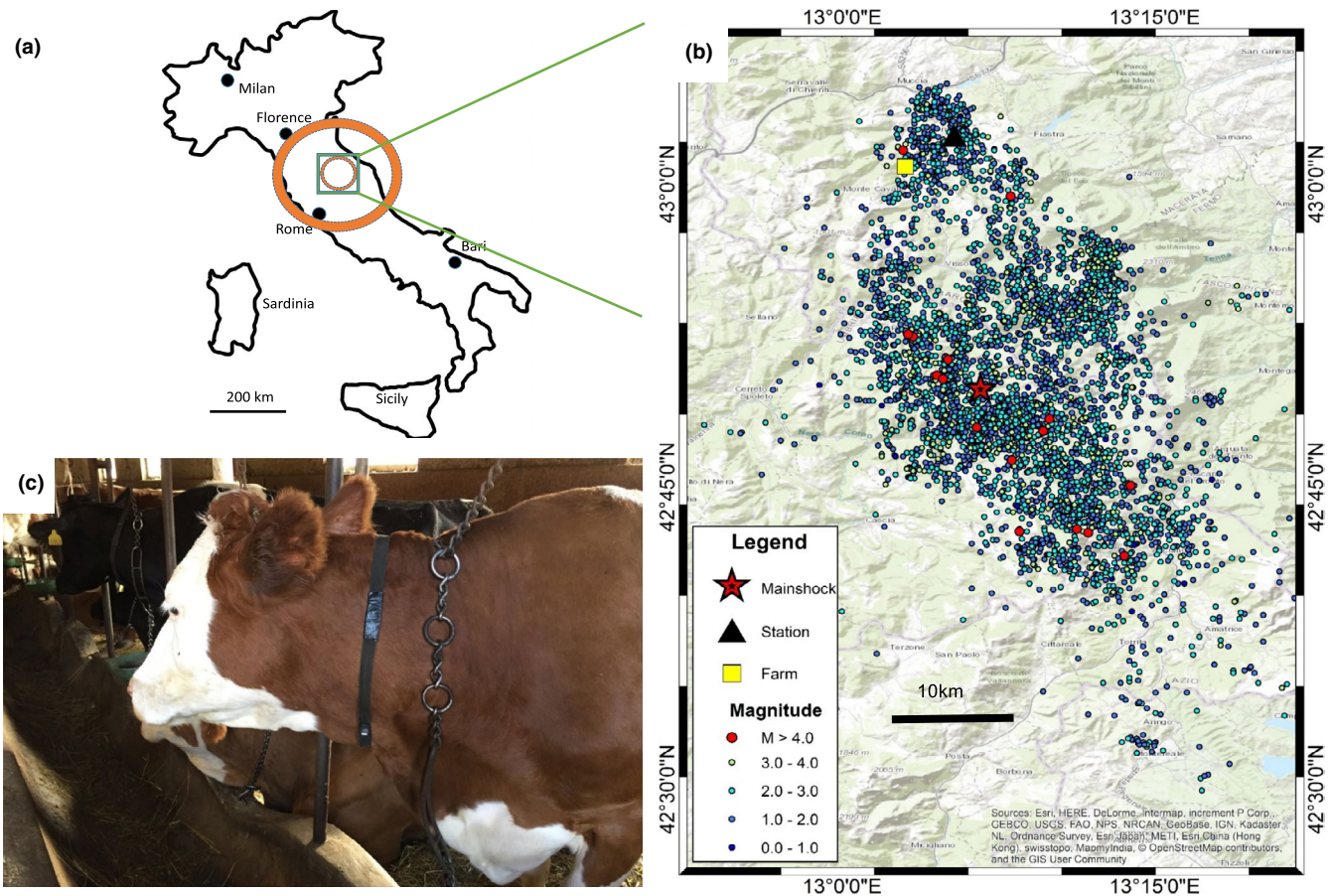


FIGURE 1 a) Map showing the locations of the Oct–Nov 2016 earthquakes in central Italy. Concentric circles show the area where the impact of the earthquake was perceived by people. The largest circle represents the M6.6 earthquake from Oct 30, 2016, at 6:40 UTC. Data from www.earthquaketrack.com/wileyonlinelibrary.com, based on original data from <https://earthquake.usgs.gov/wileyonlinelibrary.com>. b) Detailed map showing the epicenters of the earthquakes studied during the current investigation and the location of the farm where animals were studied. c) Example of a tagged cow inside a stable secured next to other cows. Electronic tag sits ventral on black neckband [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 3 visualizes the spatial distribution of the earthquakes, color-coding each earthquake event by the respective PGA at the farm.

The time series of estimated PGA events at the farm are depicted for Oct–Nov 2016 and Jan–Apr 2017 in Figure 4a and b, respectively.

To align the time-dependent earthquake-specific information with the animal activity data, we consider an aggregated measure of the estimated PGA value for each earthquake, using the highest PGA value estimated for any event that occurred in the respective time span. Note that the results of the study are robust against the choice of the aggregation method (alternatives were the mean and the sum of PGA events in the respective window).

After this processing, we obtain time series of animal activities and earthquake measures sampled at identical time intervals.

2.4 | Retrieving the daily patterns in animal behavior

The animal activity time series show daily patterns. We estimated the daily patterns separately for the three animal species and the

three periods, using Fourier series with 24 hr periodicity (Brockwell & Davis, 2000). Based on a Bayesian information criterion (BIC), we selected 16 discrete frequencies to quantify the daily patterns (Lütkepohl, 2005). However, the findings of our analysis are robust against the chosen number of frequencies used for the estimation of daily patterns (we tested 10–25 frequencies).

2.5 | Vector Autoregressive (VAR) Analysis

In a vector autoregressive model, the variable vector (here the ODBA values of the three animal groups and the PGA activity) at time t depends linearly on past (lagged) values of the variable vector at times $t-1$, $t-2$, ..., $t-p$, where p denotes the number of lags (Lütkepohl, 2005). Using this analysis allows to assess the mutual influence of the variables on each other, for example, via impulse response functions.

Based on the excess animal activity (observed activity–estimated daily activity) of cows, dogs, and sheep and the PGA time series, we estimated vector autoregressive processes for the three

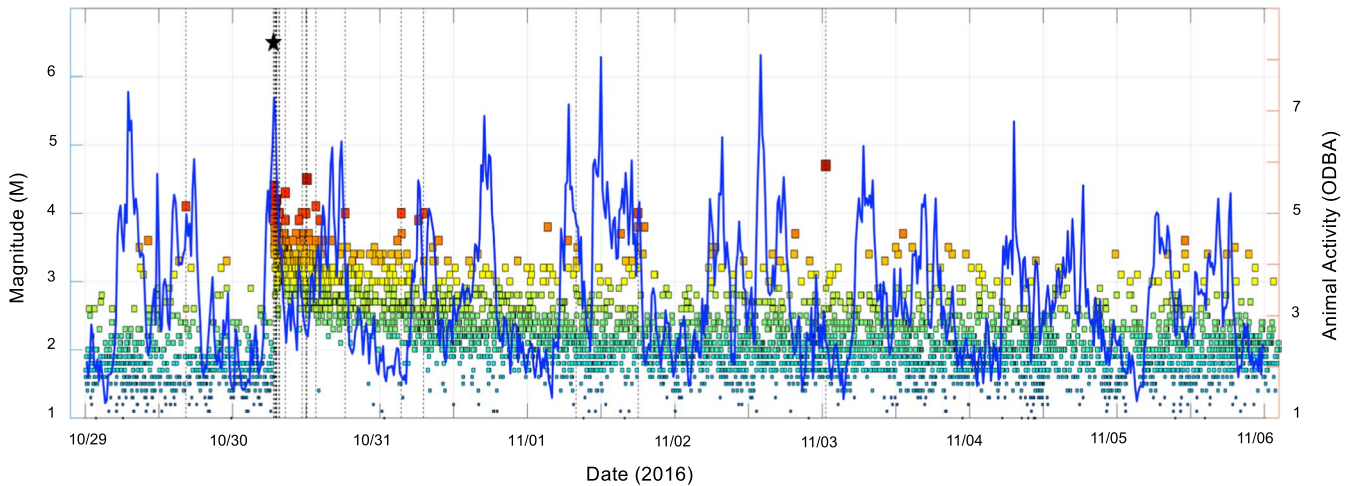


FIGURE 2 Animal activity in relation to earthquake activity. The blue line depicts the ODBA value summed over 15 min time intervals for farm animals during Oct 29th–Nov 6th, 2016. Colored symbols mark earthquake activity in the region (increasing with redness indicates higher magnitudes), dark red squares showing earthquakes above M4, and a black star indicating the M6.6 Norcia earthquake of Oct 30th, 2016 [Colour figure can be viewed at wileyonlinelibrary.com]

periods. The maximum number of lags suggested by BIC for any of the three periods was 6 (VAR(6)), so we used 6 lags in all three periods for comparative purposes. However, the results are robust with respect to the number of lags used in the VAR model (we considered 4–10 lags).

The VAR model and the resulting impulse response functions (IRFs) show the mutual influences of the animal species on each

other as well as the influence of earthquakes on the animal species (Figure S7, S8). The mutual influence of the animal species and the reaction to earthquakes is part of the normal behavior of the animals. To obtain the abnormal animal activity, in which we want to find anticipatory patterns, we subtract both daily patterns and the predictions of the VAR model from the observed animal activities.

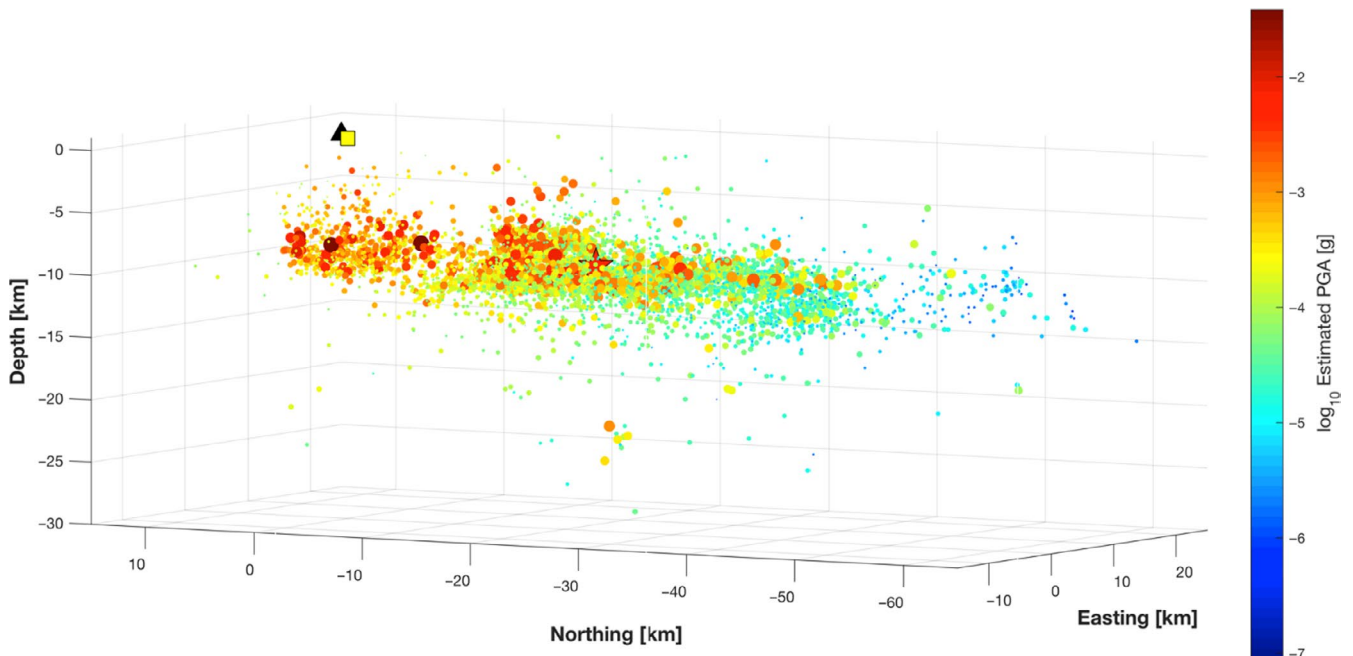


FIGURE 3 Spatial distribution of earthquakes during the Oct 29th–Nov 6th, 2016 period. Colored dots show estimated peak ground acceleration (PGA) at the farm (yellow square) for each event, computed using the empirical relations of (Bindi et al., 2011), considering magnitude, hypocentral distance, faulting style, and soil-site class (here class A, with VS30 = 800 m/s (Lucia Luzi, pers. comm.), measured at the station shown as black triangle). Larger far-distant events may cause stronger shaking than nearby small events [units in $\log_{10}(g)$, $g = 9.81 \text{ m/s}^2$; the Norcia main shock was about 0.1 g at the farm)] [Colour figure can be viewed at wileyonlinelibrary.com]

2.6 | Threshold Analysis

Consider the abnormal component of the animal activity, as defined in the previous paragraph, that is, abnormal activity = observed activity – daily patterns – VAR predictions. The following steps were applied for each of the animal species, as well as for the aggregate animal behavior (mean of animal species) in all three periods.

At first, each PGA event that exceeded a given threshold (2 standard deviations above the mean) was selected. For each of these PGA events, we selected all occurrences of “unusual” animal activity in a time span up to 20 hr before the respective PGA event that exceeded a second threshold (2 standard deviations above average “unusual” animal activity). In this way, we created pairs of unusually high PGA and animal activities.

For each pair of observations found in this manner, we compute the respective anticipation time (time of PGA event – time of abnormal animal activity event) and plotted it against the hypocentral distance between the farm and the respective earthquake event.

The results are robust with respect to the choice of the thresholds (Figure S13–S15) and with respect to outliers due to the use of median regressions (Koenker, 2005). We then estimate a linear relationship between anticipation time and distance.

2.7 | Informed consent

We received informed consent of all study participants for publication of identifying information/images in an online open-access publication.

2.8 | Data and modeling code repository

The original data and the python computer code to conduct the model calculations are deposited in the Dryad data repository (<https://doi.org/10.5061/dryad.q2bvq83gq>).

3 | RESULTS

3.1 | Daily patterns in animal behavior

To identify unusual animal behavior, one first has to identify and quantify the (daily) normal activity patterns. Therefore, we examined statistically robust daily activity patterns for three animal species (cows, dogs, and sheep); these are then considered in our analysis. For the time periods (a) and (b) when animals were in the

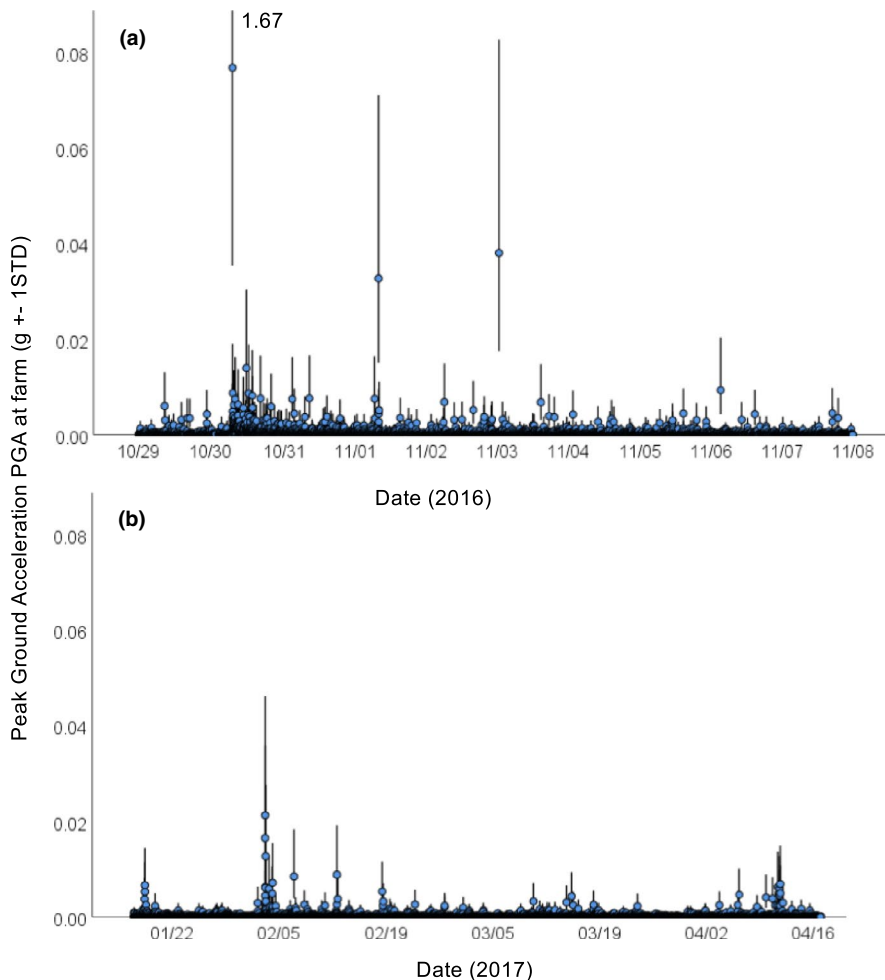
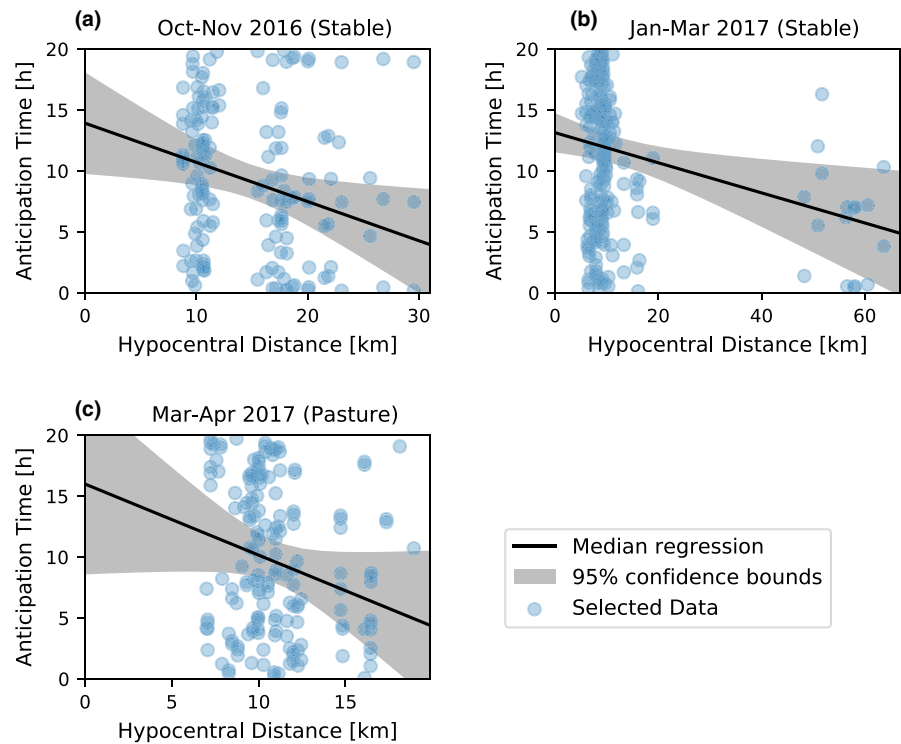


FIGURE 4 Time series of peak ground acceleration (PGA) at the farm, during (a) the Oct 29–Nov 06, 2016 and (b) the Jan 17–Apr 17, 2017 period. Blue dots indicate estimated PGA for each event as in Figure 5. Vertical lines highlight error estimates of one standard deviation. Please note the different x-axis time scales and the upper truncation of the highest PGA value (for graphical comparability between a and b) [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 5 Warning time before an earthquake event (time difference between earthquake event and increased animal activity) against the distance between the respective hypocenter and the farm. Assuming that physical precursors of earthquakes diffuse slowly from the respective hypocenter, we expect a relationship with negative slope when plotting anticipation time against hypocentral distance. (a) Oct–Nov 2016 period. (b) Jan–Mar 2017 period. Both periods when the animals were in a stable show a significantly negative relationship. However, this relationship is only robust for the Jan–Mar 2017 period (Figure S14). (c) Mar–Apr 2017 period. For this period, where the animals were on the pasture, the relationship is less significant (Figure S15) [Colour figure can be viewed at wileyonlinelibrary.com]



stable (Oct–Nov 2016 and Jan–Mar 2017), we find that all three species show high activity during the morning and afternoon, but lower activity during noon and at night (Figure S4). During period (c) on the pasture (Mar–Apr 2017), only cows showed a significantly reduced activity during noon (Figure S4).

3.2 | Mutual influence of the animal species

All tagged animals were held on the same farm, but cows and sheep in different buildings; thus, only dogs could directly interact with all species while animals were in a stable. To further understand the normal activity patterns of the animals, we studied the mutual influence of the three species on each other. During all three periods, cows and dogs significantly reacted upon each other; the sheep always reacted on dogs. However, during the period on the pasture (Mar–Apr 2017) the reaction is stronger, because the dogs guarded the sheep. The mutual reaction patterns are presented in Figures S7–S9 in the supplementary materials.

3.3 | Reactive animal behavior after earthquakes

In addition, we considered the reaction of the three animal species on earthquakes. We detected that the species differ in their sensibility toward earthquakes. Dogs were most sensible, followed by cows, while the sheep' activity hardly changed. Moreover, also the reactive patterns differ between the species. While dogs became hyperactive as response to earthquakes, cows initially became untypically calm, but then increased their activity in response to the

dogs' activeness. Notably, these reaction patterns were only found during the periods when the animals were in the stable (Oct–Nov 2016 and Jan–Mar 2017), but not during the time on the pasture (Mar–Apr 2017).

3.4 | Anticipatory animal behavior prior to earthquakes

Finally, knowing the normal activity patterns of the animal species, we analyzed the potential anticipatory behavior of the animals prior to earthquakes. Based on a threshold approach (see the Methods section), we identified the anticipation times (time difference between unusually high animal activity and the subsequent earthquake) of the animal species. For a slow diffusive process that generates the precursory signal that the animals react to, we expect the anticipation (or warning) times to depend inversely on hypocentral distance of the respective earthquake to the farm. The further away the earthquake, the shorter the animal warning time. We find this relationship to be robust and significant for the Jan–Apr 2017 period in which the animals were in the stable (Figure 5b, Figure S11, S14). For the period when the animals freely roamed on the pasture (Mar–Apr 2017), the pattern was less robust and significant (Figure 5c, Figure S12, S15). In the Oct–Nov 2016 period, we cannot find robust patterns despite the stronger earthquake activity (Figure 5a, Figure S10, S13), which likely results from the short observation period (6 days). Interestingly, aggregating the information from the three animal collectives helps to identify and establish the statistical significance of this inverse relationship (reflected by the negative slope in Figure 5a). The pattern was insignificant when considering the information on the individual

species (Figure S9). This indicates that the aggregation is likely to reduce background noise.

4 | DISCUSSION

Our observational study systematically quantifies the inter-relationships of complete time series of animal activity and earthquake occurrence (including large mainshocks and their aftershocks), as well as during a period of lower earthquake activity (Borre et al., 2003; Michele et al., 2016; Wenzel & Zschau, 2013). Our animal activity data are based on proven behavioral surveillance methods that quantify activity patterns of a collective of domestic animal species (Brown et al., 2013; Kays et al., 2015; Wilson et al., 2006).

The usual behavior of the animals is subject to a strong daily pattern and mutual interactions between the three observed species. Moreover, reactive patterns to seismic activity are observed during the periods when the animals were in a building (stable; Oct–Nov 2016 and Jan–Mar 2017).

The analysis of the anticipatory animal behavior provides evidence that the animals are steadily influenced by changes in the physical precursor of seismic events. Notably, the detection of the anticipatory patterns does not rely on the occurrence of a few strong and rare earthquakes, but it is also obtained for periods with medium size earthquakes. This might ease the detection of larger earthquakes against the background of noise in the animals' activity.

Both the reactive and the anticipatory behaviors of the animals were significant for the periods when the animals were in a stable (Oct–Nov 2016 and Jan–Mar 2017), but not when they were on a pasture (Mar–Apr 2017). This implies that the animals are more sensitive in closed buildings. However, our conjecture cannot rule out the possibility that there may exist simple seasonal differences in behavior. But as the reactive patterns are equivalent for the Oct–Nov 2016 and the Jan–Mar 2017 period, both with the animals held in a stable, the distinction between periods in a stable and periods on a pasture seems to be the decisive and most reasonable one.

Overall, the continuous monitoring of animal behavior over longer time spans at high temporal sampling (on the order of minutes) in the controlled setting of a stable provides evidence for anticipatory behavior, irrespective of the occurrence of large earthquakes. Our novel empirical approach (continuous bio-logging) and the a priori statistical and modeling approach significantly advance the way we can now study a possible anticipation of earthquakes by animal collectives.

Our findings indicate that the anticipation time depends inversely on hypocentral distance. This is consistent with a (slow) diffusion-like mechanism, originating in the rock volume around the earthquake nucleation region at depth (about 5–18 km, see Figure S5c) (Freund, 2003, 2011). This process seems qualitatively related to the pre-slip model for earthquake nucleation (Ellsworth & Beroza, 1995; Ohnaka & Shen, 1999; Rydelek & Horiuchi, 2006). The results indicate that the anticipation time might span up to 15–25 hr. Resulting from the large estimation uncertainty and non-earthquake related

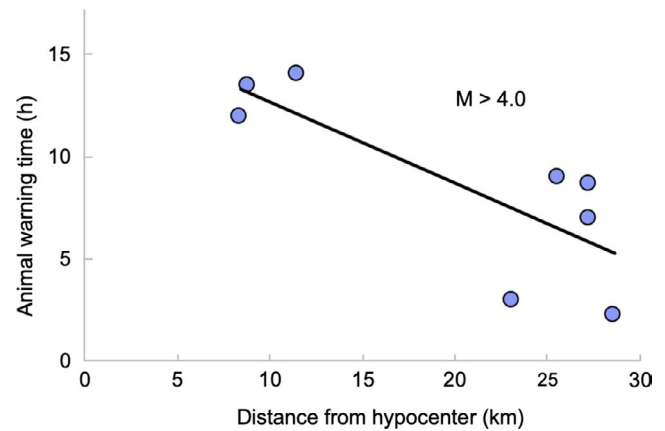


FIGURE 6 Plot showing excess animal activities ahead of 8 earthquake events with a magnitude >4 occurring within a 28 km vicinity of the farm animals. Each dot represents the anticipating or “animal warning time” (as in Figure 5). This time point is the mid-time when a threshold of sustained (>45 min) excess animal activity (>140% above the 99th percentile background average) was reached ahead of the subsequent earthquake. This animal warning time before an earthquake event is plotted against the straight-line distance between the respective hypocenter and the farm. The solid line indicates a significant linear regression ($y = -0.0174x + 0.7274$, $R^2 = 0.64$, $p = .018$) [Colour figure can be viewed at wileyonlinelibrary.com]

noise in the data, our results cannot be used for earthquake prediction at this stage. However, they provide evidence that, given that the maximum anticipation time and slope of the anticipation time–hypocentral distance–plot can be estimated more precisely in further large-scale experiments, these parameters might be useful to identify the actual precursors that the animals react to. One mechanism consistent with these model observations was proposed by (Freund et al., 2009; Freund & Stolz, 2013). The air ionizations at pressurized rock surfaces could slowly diffuse in the air toward the animals that then react toward this novel sensation (Bleier et al., 2009; Freund et al., 2006; Little & Freund, 2019; Yoshida & Ogawa, 2004).

Given that future work can quantify anticipatory behavior as our work suggests, and given that a sufficiently precise relation between warning time and distance can be estimated, an experimental test setup could be built: As a first step, we can derive an empirical threshold of excess animal activity that could serve as a trigger for a warning signal. Practically, this means that daily animal activity has to be quantified continuously for a period of time, at least for 2 weeks (Wikelski et al., 2015). In the current situation, whenever the farm animals were active for i) an extended period of time (>45 min) at ii) a level way beyond “regular,” that is, >140% above the 99th percentile background average, there was a very high likelihood of a follow-up earthquake activity of a high magnitude. Eight of nine earthquakes with a magnitude > 4.0 were anticipated by animal activity using this threshold, with no false positive (Figure 6).

However, in the threshold model discussed above, the animal activity at a single farm cannot identify in advance the time and distance of a future earthquake (Tributsch, 1982b). Either an

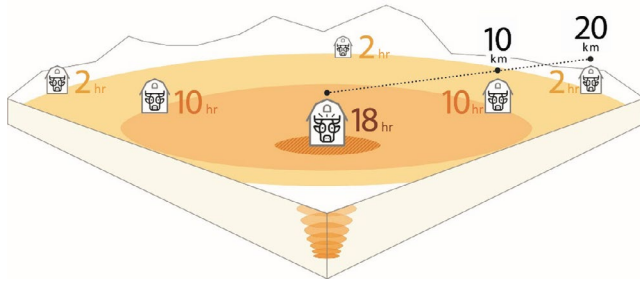


FIGURE 7 A potential test setup for an earthquake-forecast-by-animals scenario. Based on the information in Figure 5 (the ‘a priori model’) and Figure 6 (the ‘empirical threshold model’), one could set up animal activity monitoring sites across a landscape (e.g., the Italian Abruzzo mountains). If there are preparatory processes in the Earth crust indicating an imminent earthquake that could be perceived by animals, the animals on the central farm situated above the hypocenter should show activity ca. 18 hr ahead of the earthquake, but no other farm animals should show warning signs at this early time. Then, 8 hr later, farm animals at 10 km distance from the central farm should show warning signs. Another 8 hr later animals at farms 20 km away from the central farm should show warning signs. If correct, this would indicate an earthquake is imminent within the next 2 hr. Note that the time constants of 18 and 8 hr used in this schematic are indicative examples only. If this hypothesis is tested via experiments and theory involving a physical mechanism, these parameters are expected to change [Colour figure can be viewed at wileyonlinelibrary.com]

earthquake will occur at larger distance from the farm, but soon, or it will happen close by, but not as soon. To estimate both time and location of a future earthquake, a triangulation system is needed to forecast the most likely epicenter of an earthquake within approximately 20–30 km (Figure 7).

Our results indicate that many animals would have to be tagged at different locations over a long period under very controlled settings to obtain useful information. However, animals react to many different stimuli, which is beyond the ability of a single technical sensor. Despite the difficulties of using animals as sensors in this context, they could possibly provide the information necessary to search also for technical implementations of detection systems, which do not yet exist.

All in all, our findings provide motivation for a controlled, continuous monitoring of animal collectives at different locations to detect statistically reliable patterns of pre-seismic activity for short-time earthquake forecasting, while demonstrating the importance of additional noise reduction, long observation times, and controlled environments.

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AUTHOR CONTRIBUTIONS

M.W., U.M., M.B., L.D. and D.K. developed the concept, M.W., U.M., initiated the study and collected the animal data, P.M.M. contributed data and analysis, W.P., G.F. and M.W. analyzed the data and all authors contributed to the discussion and final write-up process.

CONFLICT OF INTEREST

The authors declare no competing interests.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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