—FULL PAPER—

Effect of advancing age on the reproductive performance of Japanese Thoroughbred broodmares

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Many studies have reported that advancing age in broodmares has a negative impact on the reproductive performance of horses. However, although the ages at first and last mating vary among broodmares, it is unknown how this variation affects the correlation between age and reproductive performance in mares. Here, in order to examine the effects of the ages at first and last mating, we analyzed all recorded mating events for Thoroughbreds in Japan from 1997 to 2017. We found that the live foal birth rate of mares with a younger age at first mating indeed declined at an earlier age than those with an older age at first mating and that the number of years since the first mating also contributes to the decline in the birth rate. We also found that the live foal birth rate and mean earnings of the produced foals are much higher for mares with an older age at last mating compared with mares with a younger age at last mating. Our results should aid breeders in assessing the value of broodmares and designing breeding strategies.

Key words: *birth rate, mare age, reproductive performance, Thoroughbred*

Improving reproductive efficiency is one of the main goals of horse breeding. One factor that is known to have a strong effect is the age of the mare at the time of mating [16]. Many studies have reported that the increase in the age of the mare has a negative effect on not only the pregnancy rate, gestation length, and birth rate [4, 8–10, 13, 15, 16, 18] but also the weight and racing performance of the foal [2, 15, 18]. This may be due to several factors, such as the ovulation rate, uterine blood flow, fetal development, birth weight of the foal, and high wastage element that occurs during breeding.

However, reproductive performance may be influenced by many other factors, which may affect the relationship between mare age and reproductive performance. For instance, some mares start mating when they are young, e.g., 3 years old, whereas others start when they are older, e.g., 7 years old. Yet, although the age at first mating is known to affect various reproductive traits in cows [5, 6], its effect has not been investigated in Thoroughbred mares. Likewise, some mares are retired when they are young, e.g., <10 years old, whereas others continue to be mated even after they are 20 years old. It is easy to imagine that those that are more successful in producing live foals and those whose foals have more successful racing careers are likely to be preferentially retained to mate until an older age. Thus, matings by old mares may be biased toward mares with high reproductive ability and mares whose foals show high racing performances, although this bias is often not considered when discussing the negative effect of advancing age.

Here, we analyzed all matings between Thoroughbreds recorded in Japan between 1997 and 2017. This dataset covering 21 years allowed us to examine not only the effect of advancing age in the mares but also how the ages at first and last mating affect the relationship between advancing age and reproductive performance.

Materials and Methods

Data extraction

Records of all matings between Thoroughbreds that took place in Japan between 1997 and 2017 were obtained from the database of the Japan Association for International Racing and Stud Book. Based on these records, a dataset was compiled that included the date of mating, name of the mare and sire, age of the mare at the time of mating, age at the first year of mating in Japan, and whether each mare produced a live foal for each mating event and each reproductive season. The total earnings of produced foals that had raced at least once at races organized by the Japan Racing Association (JRA) up to December 2020 were obtained from netkeiba.com.

Data analysis

The live foal birth rates per mating event and per season (i.e., per mare mated in that season) were calculated for each year, each mare age, and the number of years since the first mating. The rates were also calculated for each mare age and the number of years since the first mating, separated according to the age at the first year of mating and the age at the last year of mating. For the rates according to the age at the first year of mating and the number of years since the first year of mating, only matings of mares whose first year of mating in our dataset was between 2000 and 2017 were used in order to avoid including mares that had mated before 1997. In other words, only matings by mares that had not been mated for at least 3 years before their first year in our dataset were used. Matings by mares that were labelled as having been imported from overseas were also excluded. For the rates according to the age at the last year of mating, only matings of mares whose last year of mating in our dataset was between 1997 and 2014 were used in order to avoid including mares that had mated after 2017. In other words, only matings of mares that had not been mated for at least 3 years after their last year in our dataset were used. The mean earnings of foals were calculated per year and per mare age at the time of mating. As foals born in recent years were likely to continue racing and increase their earnings, only those produced based on matings that took place between 1997 and 2012 were considered.

Statistical analysis

Statistical tests were performed using the R statistical package [14]. The cor.test function, which tests for the association between paired samples, was used to calculate the correlation coefficients (r) between the outcome (born or not born) or the earnings of the foal and the age at first or last mating for each mating age from the ages of 4 to 15. The *P*-value was also calculated using the cor.test function. The glm function, which is used to fit generalized linear models, was used to estimate the logistic regression and its *P*-value for the live foal birth rate against variables such as the age at mating, number of years since the first mating (the age at mating minus the age at first mating), age at last mating, and year (number of years since 1997). Because the number of mares with data for age at both first and last mating was limited, the logistic regression between the birth rate and the number of years since the first mating was only estimated with mares for which the age at first mating could be determined. The logistic regression between the birth rate and the age at last mating was only estimated with mares for which the age at last mating could be determined.

Results

Birth rates and mean earnings for each year

We compiled a dataset consisting of a total of 364,724 mating events between Thoroughbreds in Japan from 1997 to 2017 (Table 1). Around 16,000–19,000 matings took place each year, of which 40–43% resulted in the birth of a live foal; 70–75% of the mares that were mated each year successfully produced a live foal. The number of matings and mares mated declined over the years, whereas the live foal birth rate remained similar both per mating and per season. Of the foals born each year, 4,300 to 4,700 went on to race at least once at a race organized by JRA and earn a total of approximately 13,000,000 to 15,000,000 yen on average throughout their careers. The mean earnings of the foals born each year were similar, although a slight increase was observed in the last few years. It should be noted that the distribution of the mean earnings was highly skewed, with a long tail; that is, many horses did not earn at all, whereas a small number of horses earned a lot, as indicated by the very small median value and large standard deviations [17].

Relationship between mare age and birth rates and earnings of foals

The ages of the mares at the time of mating ranged from 2 to 28 years old, although approximately 99% of the matings were by mares between 3 and 20, with a peak at 8 years old (Fig. 1A). Most (96%) mares were mated for the first time between the ages of 3 and 7, while the range for the age at last mating was much larger (Fig. 1B). The live foal birth rates, both per mating event (birth/mating) and per mare mated each season (birth/season), gradually decreased according to age ($r=-0.162$, *P*<2.2e-16 for birth/mating; $r=-0.201$, *P*<2.2e-16 for birth/season; Fig. 1C). The mean earnings did not show a linear relationship with the age at the time of mating. Foals produced by matings of 6-year-old mares earned the most on average, and the mean earnings declined from the age of 11 (Fig. 1D).

Table 1. Live foal birth rate and average earnings for each year

Year	Birth/mating[1]		Birth/season[2]		Earnings per raced foal (× 10,000 yen)			
	N	Rate	N	Rate	N	Mean	SD	Median
1997	19,042	0.426	11,048	0.733	4,506	1,365	3,912	128
1998	18,869	0.434	10,974	0.746	4,520	1,416	3,936	119
1999	19,126	0.432	11,036	0.749	4,317	1,410	4,247	90
2000	19,441	0.431	11,246	0.745	4,523	1,376	4,334	100
2001	19,525	0.419	11,130	0.735	4,563	1,350	4,223	100
2002	19,063	0.419	11,009	0.726	4,670	1,288	4,002	75
2003	17,960	0.431	10,529	0.735	4,717	1,331	4,140	75
2004	17,631	0.422	10,220	0.728	4,667	1,307	3,405	105
2005	16,887	0.428	9,890	0.731	4,562	1,390	4,095	125
2006	16,989	0.421	9,713	0.736	4,458	1,464	4,027	130
2007	16,946	0.412	9,667	0.723	4,408	1,478	4,429	120
2008	16,526	0.422	9,547	0.731	4,438	1,521	4,723	115
2009	17,472	0.395	9,805	0.704	4,326	1,411	3,961	130
2010	16,938	0.402	9,667	0.704	4,299	1,532	4,269	130
2011	16,162	0.412	9,322	0.715	4,381	1,486	4,788	130
2012	16,281	0.409	9,259	0.720	4,466	1,441	3,788	125
2013	15,781	0.427	9,253	0.728	NA	NA	NA	NA
2014	15,757	0.425	9,209	0.727	NA	NA	NA	NA
2015	16,031	0.422	9,348	0.724	NA	NA	NA	NA
2016	16,065	0.433	9,439	0.736	NA	NA	NA	NA
2017	16,232	0.433	9,554	0.735	NA	NA	NA	NA

[1]Number of mating events and rate of mating events that resulted in a live foal birth. [2]Number of mares mated that season and rate of mares mated that season that produced a live foal. NA, not applicable.

Effect of the age at first mating on the birth rate

The results of the live foal birth rate per mating at each age for the mares that started mating at the ages of 3 to 7, calculated according to the age at first mating, are shown in Fig. 2A. For each age at first mating, the birth rates were highest in the first year of mating, i.e., in maiden mares, and subsequently showed similar declines with age. When the results for the same mating ages were compared, the birth rate tended to be higher for matings by mares with an older age at first mating. To further confirm this, we estimated the correlation coefficient between the outcome (born or not born) and age at first mating for each mating age (Table 2). Indeed, the age at first mating showed a weak but positive correlation with the mating results at the mating ages of 4 to 15 ($P<$1e-05 for ages 4 to 11; $P<$0.05 for ages 12 to 15). Similar results were observed for the birth rate per season.

We also estimated the logistic regression between the outcome and the age at mating, the number of years since the first mating (age at mating minus the age at first mating), and the year at the time of mating (Table 3). An increase in the age at mating and the number of years since the first mating both decreased the log-odds of the live foal birth rate ($P<$1e-05 and $P<$1e-10, respectively). An increase in the number of years since the first mating resulted in a much larger decrease in the log-odds; that is, each additional age at mating resulted in the birth rate per mating and birth rate per season being multiplied by 0.984 (log-odds of -0.016) and 0.960 (log-odds of -0.040), respectively, whereas each additional year since the first mating resulted in the birth rate per mating and birth rate per season being multiplied by 0.940 (log-odds of -0.062) and 0.934 (log-odds of -0.068), respectively.

Effect of the age at last mating on the birth rate

The difference in birth rate per mating calculated according to the age at last mating is shown in Fig. 2B, where the results of the matings of mares with ages at last mating of <9, 9–13, 14–18, and <18 years old grouped together. Note that these groupings were for illustrative purposes only and not used in the analyses. The results clearly show that mares that were still mated when they were old have a much higher reproductive ability. As with the age at first mating, we calculated the correlation coefficient between the outcome and the age at last mating for each mating age. At each mating age, the age at last mating showed significant positive correlation ($P<$1e-10) with the mating result in terms of both the birth rate per mating and birth rate per season from the ages of 4 to 15 (Table 2).

We also estimated the logistic regression between the outcome and the age at mating, the age at last mating, and the year at mating. The results showed that an increase in the age at last mating significantly increased the log-odds for
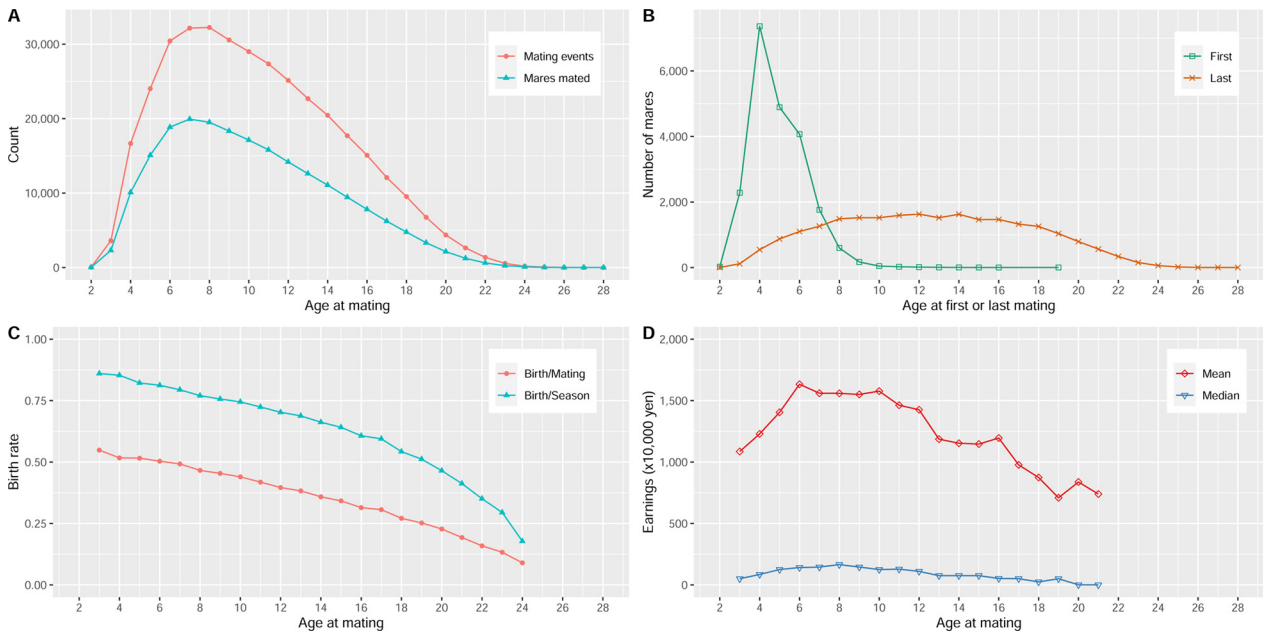
Fig. 1. (A) Numbers of mating events (red dots) and mares mated each season (blue triangles) according to the age of the mares at the time of mating. (B) Numbers of mares according to the ages at first (green squares) and last mating (orange crosses). (C) Live foal birth rates per mating event (red dots) and per mare mated in that season (blue triangles) according to the age of the mares at the time of mating. (D) Mean and median earnings of each foal produced by matings according to age at the time of mating in mares that raced at least once. Only data points based on 100 or more counts are shown for B and D.
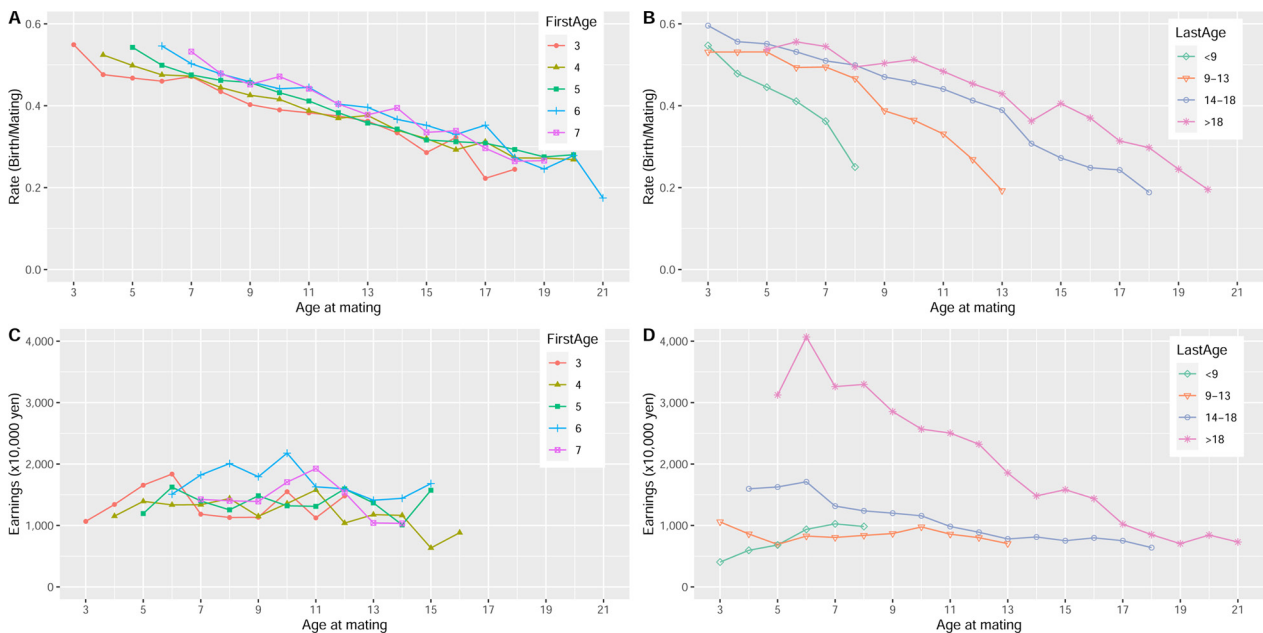
Fig. 2. (A) Birth rate per mating event according to the age at mating and grouped according to matings of mares with ages at first mating of 3, 4, 5, 6, or 7. (B) Birth rate per mating event according to age at mating and grouped according to matings of mares with ages at last mating of <9, 9–13, 14–18, or >18. (C) Mean earnings of foals produced by matings of mares according to age at mating and grouped according to matings of mares with ages at first mating of 3, 4, 5, 6, or 7. (D) Mean earnings of foals produced by matings of mares according to age at mating and grouped according to matings of mares with ages at last mating of <9, 9–13, 14–18, or >18. Only data points based on 100 or more counts are shown for A to D.

Table 2. Correlation coefficients (*r*) between the age at first or last mating and the birth rate or earnings

Mating age	Birth/mating vs. age at first mating		Birth/season vs. age at first mating		Earnings vs. age at first mating		Birth/mating vs. age at last mating		Birth/season vs. age at last mating		Earnings vs. age at last mating	
	N	r	N	r	N	r	N	r	N	r	N	r
4	15,582	0.040[3]	9,360	0.139[4]	3,672	−0.021	9,476	0.082[4]	5,702	0.141[4]	2,501	0.142[4]
5	20,955	0.052[4]	13,027	0.113[4]	4,979	−0.036[1]	13,751	0.102[4]	8,550	0.156[4]	3,794	0.192[4]
6	25,200	0.059[4]	15,506	0.091[4]	5,812	0.002	17,001	0.106[4]	10,379	0.171[4]	4,574	0.174[4]
7	25,061	0.036[3]	15,429	0.049[3]	5,443	0.037[1]	18,344	0.102[4]	11,256	0.169[4]	4,818	0.149[4]
8	23,226	0.037[3]	14,042	0.028[2]	4,814	0.027	19,253	0.112[4]	11,468	0.185[4]	4,893	0.180[4]
9	20,397	0.037[3]	12,147	0.030[2]	3,868	0.051[2]	18,695	0.117[4]	11,111	0.184[4]	4,649	0.139[4]
10	17,699	0.046[4]	10,401	0.035[2]	3,174	0.027	18,412	0.114[4]	10,747	0.178[4]	4,409	0.106[4]
11	15,129	0.040[3]	8,703	0.032[1]	2,456	0.022	17,998	0.110[4]	10,308	0.172[4]	4,085	0.159[4]
12	12,626	0.025[1]	7,080	0.023[1]	1,850	0.018	17,084	0.133[4]	9,588	0.214[4]	3,740	0.166[4]
13	10,267	0.023[1]	5,746	0.012	1,374	−0.005	15,894	0.133[4]	8,730	0.206[4]	3,336	0.165[4]
14	8,384	0.044[2]	4,538	0.051[2]	963	0.014	14,680	0.119[4]	7,880	0.188[4]	2,789	0.138[4]
15	6,644	0.024[1]	3,494	0.028	629	−0.014	12,852	0.122[4]	6,862	0.202[4]	2,356	0.146[4]

[1] $P<0.05$; [2] $P<0.001$; [3] $P<1e\text{-}05$; [4] $P<1e\text{-}10$.

Table 3. Log-odds and odds ratio for each variable in the logistic regression

	N	Age at mating		Years since first mating		Age at last mating		Year of mating	
		Log-odds	Odds	Log-odds	Odds	Log-odds	Odds	Log-odds	Odds
Birth/mating for mares with data for age at first mating	218,161	−0.016[3]	0.984[3]	−0.062[4]	0.940[4]	NA	NA	0	1
Birth/season for mares with data for age at first mating	128,715	−0.040[4]	0.960[4]	−0.068[4]	0.934[4]	NA	NA	−0.004[1]	0.996[1]
Birth/mating for mares with data for age at last mating	236,821	−0.127[4]	0.881[4]	NA	NA	0.069[4]	1.072[4]	−0.010[4]	0.990[4]
Birth/season for mares with data for age at last mating	134,504	−0.212[4]	0.809[4]	NA	NA	0.146[4]	1.158[4]	−0.012[4]	0.988[4]

[1] $P<0.05$; [2] $P<0.001$; [3] $P<1e\text{-}05$; [4] $P<1e\text{-}10$. NA, not applicable.

the mating that resulted in the birth of a live foal ($P<1e\text{-}10$). This suggests that mares that are mated at an older age are more likely to have higher reproductivity, and that when this bias is considered, the negative impact of the increase in age at mating on the birth rate becomes much larger (Table 3). For instance, when the age at last mating was not considered, each additional age resulted in the birth rate per mating and birth rate per season being multiplied by 0.944 (log-odds of −0.127 + 0.069 = −0.058) and 0.936 (log-odds of −0.212 + 0.146 = −0.066), respectively. However, when the age at last mating was considered, the birth rate per mating and birth rate per season were multiplied by 0.881 (log-odds of −0.127) and 0.809 (log-odds of −0.212), respectively.

Effects of the ages at first and last mating on the earnings of foals produced

We also examined the effects of the age at first and last mating on the relationship between the age at mating and the earnings of the foals produced. Figure 2C shows that the age at first mating did not have a strong effect on the

mean earnings of the foals, although the earnings of the foals produced by the first mating, i.e., by maiden mares, tended to be low. On the other hand, the age at last mating clearly had a strong effect. Figure 2D shows that the mean earnings of foals produced by mares that continued to be mated after the age of 18 were much higher than those of the foals produced by mares that were retired at a younger age. Indeed, the age at last mating and the earnings showed a significant positive correlation ($P<1e\text{-}10$) at each mating age from 4 to 15 (Table 2).

Discussion

The reproductive performance of horses is known to be influenced by many factors, such as differences in the age and fertility of individual mares and stallions, the reproductive status of the mare (i.e., whether the mare is maiden, barren, or foaled), and the number of days post-partum at time of covering [3, 9, 11, 12]. In particular, the age of the mare has been reported to be the most important factor in

Thoroughbreds in the U.S., U.K., Ireland, and Sweden [1, 3, 7, 9, 11, 12]. Consistent with these previous studies, we found that the advancing age of the mare is negatively correlated with the live foal birth rate in Japanese Thoroughbreds.

Although many of the aforementioned studies also reported the pregnancy rate per oestrous cycle, we were only able to collect data for the birth rates per mating event and per season. However, the birth rate and pregnancy rate are known to be highly correlated with each other, as are the rate per cycle and per mating event, and the birth rates per season in our study are similar to those reported by other studies (70–80%) [1, 3, 7]. Also, considering the fact that our dataset covers a much larger number of years and mating events than any of the previous studies, our results should make an important contribution to our understanding of the effect of mare age. Indeed, while most previous studies have only compared reproductive performance between different age categories (e.g., <9, 9–13, 14–18, and >18), our results showed a gradual decrease in birth rate according to age from as young as 3 years old [1, 3, 7, 9, 11, 12].

Importantly, we found two significant factors that influence the observed correlation between the age of the mare and both the live foal birth rate and the racing performance of the foal. One is the age of the mare at its first mating. Our results show that the increase in the number of years since the first mating contributes more to the decline in the birth rate than the increase in age. One possible explanation for this is that the increase in parity, which should be highly correlated with the number of years since the first mating, has a negative effect on the birth rate. Although parity is known to affect placental development and foal birth weight [8, 18], its effect on pregnancy or birth rate has not been fully examined. The effect of parity on pregnancy or birth rate should be examined in more detail in future studies. We also note that the mares that were 3 or 4 years of age at first mating likely included many mares that could not race at all, whereas mares that had a successful racing career are more likely to begin mating at an older age (e.g., 6 or 7). This difference may have contributed to the slight positive correlation between the age at first mating and the mean earnings of the foal, whereas its effect on the correlation between the age at first mating and the birth rate is unclear. Although the effect of the age at first mating was more pronounced at a younger mating age, this may have been partly due to limitations with respect to our dataset. In particular, limited data were available for the mating events of the mares for which we could determine the age at first mating. The narrow range for the age at first mating (mostly between 3 and 7) may have also restricted our ability to detect the effect of age at first mating at an older age.

Another important factor is the age of the mare at its last mating. Traits such as the live foal birth rate and the racing performance of the produced foal may vary among mares and are most likely to be prime targets of selective breeding. Although increased culling of barren mares was suggested as a cause for the decrease in the proportion of barren mares over the years in a previous study [11], to our knowledge, this process of selective breeding has not been considered in previous studies reporting the negative effect of the advancing age of mares. Indeed, our results suggest that this selection process introduces a bias into the dataset. The population of young mares consists of all mares, including those with poor performance that get removed from the population after a few years. On the other hand, the population of old mares typically consists of elite mares that produce foals with high racing ability at a high rate. Thus, as the logistic regression analysis suggests, when this bias was considered, the decline in the performance of each individual mare according to age became much larger. While it is possible that each mare was more likely to be retired from mating after an unsuccessful mating season, we note that the correlation between the age at last mating and the birth rate and earnings of the foals was still significant when the results for the last year of mating were removed. We also note that for the mares for which we could determine the age at last mating, the data for mating events at younger ages were only available for mares with a younger age at last mating. This means that the decline in the performance of mares with the advancing age based on this dataset may still be an underestimate.

The age of the mare is often considered when assessing its potential value. Here, we have shown that the ages at the first and last mating affect the correlation between age and reproductive performance in mares. Our results should help us to better understand the effect of the advancing age in mares and to design more effective breeding and management strategies.

Acknowledgments

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