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The coronavirus disease 2019 (COVID-19) pandemic can cause reverse zoonoses (i.e., human–animal transmission of COVID-19). It is vital to utilize up-to-date methods to improve the control, management, and prevention of reverse zoonoses. Awareness of reverse zoonoses should be raised at both individual and regional/national levels for better protection of both humans and animals.

Human Activities Exacerbate the Risks from Zoonotic Diseases
The COVID-19 has been the most widespread zoonotic pandemic to affect humanity in over a century, reflecting the problem of human activities exacerbating the risks of pathogen spillover, such as hunting, butchering, farming, deforestation, reforestation, irrigation, and traveling. Moreover, it has caused ecological feedbacks at local scales (e.g., bi-directional transmission of COVID-19 between animals and humans, which could augment the COVID-19 risk in both animals and humans). Understanding these feedbacks is crucial to mitigating zoonotic disease risks, which requires transdisciplinary collaborative research on pandemic risks among multiple fields, including epidemiology, virology, public health, geography, and ecology [1,2].

Reverse Zoonosis of COVID-19
Infection of animals with severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) from humans has highlighted the importance of understanding ‘reverse zoonosis’ (zooanthroponosis). Compared with three of the four possible routes of transmission for zoonotic diseases (i.e., animal–human, animal–animal, human–animal, human–human), which have been well studied and confirmed [3], human–animal transmission lacks sufficient research due to the rare occurrence prior to COVID-19 [4]. Once such reverse zoonosis occurs it may cause the further evolution of viruses and affect the effectiveness of potential COVID-19 vaccines [5]. Given the growing populations of livestock and other domesticated animals, increasing proximity between animals and humans in multiple settings (e.g., wet markets, home, and animal production facilities), and the relatively fewer resources assigned for animal testing during human outbreaks with zoonotic potential (particularly asymptomatic infections), new animal diseases may spread undetected. Proactive consideration of such reverse zoonosis enables the creation of management strategies. Therefore, reverse zoonoses require more rigorous and widespread macroecological and microbial studies.

As of 11 March 2021, the 1 year anniversary of the official declaration of COVID-19 pandemic by the World Health Organization (WHO), a total of 167 natural infections (i.e., SARS-CoV-2 positive) in 11 species of animals (excluding mink), both domesticated and captive, have been reported in 25 countries during the COVID-19 pandemic (Figure 1), with the origin of the infection probably being human COVID-19 cases in different settings (Table 1). Two peaks of reporting of pet infection were between July and August 2020 and between December 2020 and February 2021. Cat infection emerged 1 month later than dog infection, but has had a faster and stable increase and a larger total number of infections reported (86 versus 56). SARS-CoV-2 was mostly detected in their oral, throat, nasal, and rectal swabs. About 38% (64/167) of the infected animals showed digestive and respiratory symptoms and flu signs, with the remainder not showing any signs of illness. However, their contaminated fecal matter and urine could still transmit the virus to exposed humans if they are unaware of that risk [6]. Also, lions, pumas, and tigers at zoos, all belonging to the same family as cats (Felidae), were infected by asymptomatic and symptomatic patients in two countries (USA and South Africa), with SARS-CoV-2 detected in their fecal samples. About 73% of the infected zoo animals were reported in January and February 2021. In addition to pet and zoo animals, 138 infected mink farms were reported in 11 countries, with about 90% in Europe and 10% in North America (most in The Netherlands, 36%, followed by Denmark, 21%, and Greece, 20%). The mink in 15 out of 138 farms showed signs of illness, including respiratory symptoms and death, with SARS-CoV-2 detected in lung and throat/rectal swabs.

Scientists have also carried out several different animal model experiments of SARS-CoV-2 (Table 1). To date, ten species of animals have been exposed to SARS-CoV-2 to test their susceptibility, with more species being tested. It was found that cats, ferrets, golden hamsters, and rhesus macaques had high susceptibility to SARS-CoV-2, while dogs, rabbits, and fruit bats had relatively low susceptibility; chickens, ducks, and pigs showed no susceptibility, although some predictions suggested that pigs were likely to be susceptible to SARS-CoV-2 [7]. Therefore, more scientific evidence is needed to confirm these findings.

Building Resilience against Future Reverse Zoonoses
Reverse zoonoses may cause reduction and even extinction of the wild animal populations susceptible to viruses, which could destroy local biodiversity and ecological balance [8]. The risk factors for and transmission routes of reverse zoonoses vary by animal type (e.g., pet, livestock, wildlife), which may not be fully identified and prevented by traditional methods. It is vital
to take advantage of up-to-date methods to improve the control, management, and prevention of reverse zoonoses. Spatial and digital technologies, including location-based services, geographic information systems, and artificial intelligence, enable detection of pet owners’ history of contact with COVID-19 infection by monitoring and analyzing individual movement trajectories [9,10]. Once exposed to a COVID-19 risk, they should be notified via short message service and advised to monitor themselves and protect their pets from the risk. These technologies enable the chronology of infection to be determined, which, together with serosurveillance, may help reveal the direction of transmission between human and animal. Also, global positioning system and wearable sensors embedded in collars for farm livestock can monitor their daily activities and enable disease detection and monitoring of their health status [11].

Preventing reverse zoonoses also requires understanding pathogen feedback loops at the wildlife–livestock/pet–human interface. This will require greater capacities and commitments for pathogen discovery, mutation rate detection, and surveillance, in order to improve the prediction of pandemic potential, leading to management actions that interrupt possible pathways of spillover and transmission. Understanding these key evolutionary processes and ecological interactions calls for integrated virus–animal–human–environment surveillance systems. Spatial lifecourse epidemiology also provides a uniform analytical framework to link ecological surveillance to the national disease reporting system [12]. In the real world, the governance of all the key components (i.e., host, agent,
## Table 1. COVID-19 Natural Infections of Pet, Zoo, and Livestock Animals and Experimental Infections as of 11 March 2021

| Animal (Species)   | Reporting date | Region          | Source | Method (Samples) of initial diagnosis | Location of infection | Symptoms                                                                 |
|--------------------|----------------|-----------------|--------|--------------------------------------|----------------------|--------------------------------------------------------------------------|
| Cat (*Felis catus*)| 2020/03/27     | Belgium         | C      | PCR (feces, vomit)                   | Home                 | Diarrhea, nausea, and respiratory symptoms                              |
|                    | 2020/04/03     | Hong, China     | C      | PCR (oral cavity, nasal, rectal)     | Home                 | NA                                                                       |
|                    | 2020/05/22     | New York, USA   | C      | PCR                                  | Home                 | Ocular discharge and sneezing                                            |
|                    | 2020/05/01     | Paris, France   | C      | PCR (rectal)                         | Home                 | NA                                                                       |
|                    | 2020/05/08     | Catalonia, Spain| C      | PCR (nasal cavity, gastrointestinal tract) | Home | NA                                                                       |
|                    | 2020/05/12     | Bordeaux, France| C      | PCR (nasopharyngeal)                 | Home                 | Cough and respiratory symptoms                                           |
|                    | 2020/05/13     | Upper Palatinate, Bavaria, Germany | C | PCR (throat swab)                     | Home | Died                                                                    |
|                    | 2020/05/15     | The Netherlands | NA     | PCR, Ab                              | Mink farm            | NA (Seropositive but PCR negative)                                       |
|                    | 2020/05/15     | The Netherlands | NA     | PCR, Ab                              | Mink farm            | NA (Seropositive but PCR negative)                                       |
|                    | 2020/05/15     | The Netherlands | NA     | PCR, Ab                              | Mink farm            | NA (Seropositive but PCR negative)                                       |
|                    | 2020/05/21     | La Rioja, Spain | C      | PCR (oropharyngeal swab)             | Home                 | NA                                                                       |
|                    | 2020/05/26     | Moscow, Russia  | NA     | PCR (throat, nasal swab)             | NA                   | NA                                                                       |
|                    | 2020/05/01     | Minnesota, USA  | C      | PCR                                  | Home                 | Depression, fever, and harsh lung sounds                                 |
|                    | 2020/06/10     | Illinois, USA   | C      | PCR                                  | Home                 | Depression, fever, and harsh lung sounds                                 |
|                    | 2020/07/09     | California, USA | E      | PCR                                  | Home                 | Heart murmur, hyperthermia, respiratory symptoms, and tachypnea         |
|                    | 2020/07/22     | Utah, USA       | E      | Ab                                   | NA                   | NA                                                                       |
|                    | 2020/07/22     | Utah, USA       | E      | Ab                                   | NA                   | NA                                                                       |
|                    | 2020/07/22     | Utah, USA       | E      | Ab                                   | NA                   | NA                                                                       |
|                    | 2020/07/23     | Texas, USA      | C      | PCR                                  | Home                 | NA                                                                       |
|                    | 2020/07/24     | Hong Kong, China| C      | PCR (oral swab)                      | Home                 | NA                                                                       |
|                    | 2020/07/27     | South England, UK| C | PCR, Ab (oral swab)                  | Home                 | Respiratory symptoms of feline herpes virus                               |
|                    | 2020/07/30     | Texas, USA      | C      | PCR                                  | Home                 | NA                                                                       |
|                    | 2020/08/10     | Hong Kong, China| C      | PCR (swab)                           | Home                 | NA                                                                       |
|                    | 2020/08/10     | Hong Kong, China| C      | PCR (swab)                           | Home                 | NA                                                                       |
|                    | 2020/08/12     | New York, USA   | E      | Ab                                   | Shelter              | NA                                                                       |
|                    | 2020/08/12     | New York, USA   | E      | Ab                                   | Shelter              | NA                                                                       |
|                    | 2020/08/13     | Texas, USA      | E      | PCR                                  | Home                 | NA                                                                       |
|                    | 2020/08/19     | Hong Kong, China| C      | PCR, Ab (swab)                       | Home                 | NA                                                                       |
|                    | 2020/08/25     | Arizona, USA    | C      | Ab                                   | Shelter              | NA                                                                       |
|                    | 2020/08/27     | California, USA | C      | PCR                                  | Home                 | Very mild respiratory symptoms                                           |
|                    | 2020/08/27     | Georgia, USA    | C      | PCR (Mycoplasma felis)               | Home                 | Hyperthyroidism and respiratory symptoms                                 |
|                    | 2020/08/27     | Louisiana, USA  | C      | PCR                                  | Home                 | Mild respiratory symptoms                                                |
|                    | 2020/08/27     | Maryland, USA   | C      | PCR (oropharyngeal swab)             | Home                 | Mild respiratory symptoms                                                |
| Animal Reporting date | Region          | Source | Method (Samples) of initial diagnosis | Location of infection | Symptoms                                                                                     |
|-----------------------|-----------------|--------|--------------------------------------|----------------------|---------------------------------------------------------------------------------------------|
| 2020/09/02            | Texas, USA      | C      | PCR                                  | NA                   | NA                                                                                          |
| 2020/09/02            | Texas, USA      | C      | PCR                                  | NA                   | NA                                                                                          |
| 2020/09/18            | Spain           | C      | PCR, Ab (nasal swabs, nasal turbinate, mesenteric lymph node) | Home                 | Severe dyspnea                                                                               |
| 2020/09/24            | Kentucky, USA   | C      | PCR, Ab                              | Home                 | Congestion, cough, increased respiratory rate, sneezing, and vomiting                      |
| 2020/09/24            | New York, USA   | C      | Ab                                   | Home                 | NA                                                                                          |
| 2020/10/02            | Texas, USA      | C      | PCR, Ab                              | Home                 | NA                                                                                          |
| 2020/10/09            | Alabama, USA    | C      | PCR, Ab                              | Home                 | Upper respiratory symptoms, foaming from the nose, and neurologic symptoms, head pressing and staggering, in one case died |
| 2020/10/22            | Santiago, Chile | C      | PCR, Ab (nasal secretions, feces)    | Home                 | NA                                                                                          |
| 2020/10/28            | Cuiaba, Brazil  | C      | PCR                                  | Home                 | NA                                                                                          |
| 2020/10/31            | Pennsylvania, USA | C     | PCR, Ab                              | Home                 | Diarrhea and lethargy                                                                       |
| 2020/11/06            | Tokyo, Japan    | C      | PCR                                  | Home                 | NA                                                                                          |
| 2020/11/18            | Argentina       | C      | PCR                                  | Home                 | Nasal secretions and sneezing                                                              |
| 2020/11/18            | Argentina       | C      | PCR                                  | Home                 | Anorexia and weakening for 12 to 24 hours                                                   |
| 2020/12/04            | Hong Kong, China | C    | PCR                                  | Home                 | NA                                                                                          |
| 2020/12/09            | Italy           | NA     | PCR, Ab                              | Home                 | NA                                                                                          |
| 2020/12/18            | Texas, USA      | C      | PCR                                  | Home                 | Coughing and sneezing                                                                      |
| 2020/12/18            | Texas, USA      | C      | PCR                                  | Home                 | Coughing and sneezing                                                                      |
| 2020/12/18            | Texas, USA      | C      | PCR                                  | Home                 | NA                                                                                          |
| 2020/12/18            | Texas, USA      | C      | PCR                                  | Home                 | NA                                                                                          |
| 2020/12/18            | Wisconsin, USA  | C      | PCR                                  | Home                 | Congestion, lethargy, nasal discharge, sinus wheezing, and sneezing                        |
| 2020/12/21            | Ontario, Canada | C      | PCR                                  | Home                 | Mild respiratory symptoms                                                                  |
| 2020/12/23            | Thessaloniki, Greece | E     | PCR (pharyngeal, fecal)              | Home                 | NA                                                                                          |
| 2021/01/08            | Florida, USA    | C      | PCR                                  | Home                 | Respiratory symptoms                                                                       |
| 2021/01/08            | Hong Kong, China | C      | PCR                                  | Home                 | NA                                                                                          |
| 2021/01/08            | Virginia, USA   | C      | PCR                                  | Home                 | Progressive and severe respiratory distress                                                 |
| 2021/01/14            | California, USA | C      | PCR                                  | Home                 | NA                                                                                          |
| 2021/01/14            | Kansas, USA     | C      | PCR                                  | Home                 | Dry heaving, vocalizing, and vomiting                                                       |
| 2021/01/22            | Arkansas, USA   | C      | PCR                                  | Home                 | Mucopurulent nasal discharge, open-mouthed breathing, suspicious of toxin ingestion, and ulcerated oral mucosa |
| 2021/01/22            | Brazil          | C      | PCR                                  | Home                 | NA                                                                                          |
| 2021/01/22            | Brazil          | C      | PCR                                  | Home                 | NA                                                                                          |
| 2021/01/22            | Brazil          | C      | PCR                                  | Home                 | NA                                                                                          |
| 2021/01/22            | Brazil          | C      | PCR                                  | Home                 | NA                                                                                          |
Table 1. (continued)

| Animal | Reporting date | Region | Source | Method (Samples) of initial diagnosis | Location of infection | Symptoms |
|--------|---------------|--------|--------|--------------------------------------|----------------------|----------|
| 2021/01/22 | Tennessee, USA | C | PCR | Home | Febrile respiratory symptoms |
| 2021/01/28 | Switzerland | C | PCR | Home | NA |
| 2021/01/28 | Switzerland | C | PCR | Home | NA |
| 2021/02/03 | New Jersey, USA | E | Ab | NA | NA |
| 2021/02/03 | New Jersey, USA | E | Ab | NA | NA |
| 2021/02/05 | Connecticut, USA | C | PCR | Home | Upper respiratory symptoms |
| 2021/02/05 | Florida, USA | C | PCR | Home | NA |
| 2021/02/10 | British Columbia, Canada | C | PCR (rectal, nasal, oral swabs) | Home | NA |
| 2021/02/10 | Ontario, Canada | C | PCR | Home | NA |
| 2021/02/10 | Riga city, Latvia | C | PCR | Home | Mild depression |
| 2021/02/10 | Riga city, Latvia | C | PCR | Home | NA |
| 2021/02/12 | Texas, USA | C | PCR | Home | NA |
| 2021/02/12 | California, USA | C | PCR | Home | Mild respiratory symptoms |
| 2021/02/12 | Florida, USA | C | PCR | Home | Conjunctivitis, coughing, and nasal discharge |
| 2021/03/10 | Estonia | NA | PCR | NA | NA |
| 2020/02/28 | Hong Kong, China | C | PCR (nasal, oral swab) | Home | NA |
| 2020/03/20 | Hong Kong, China | C | PCR, Ab | Home | NA |
| 2020/05/15 | The Netherlands | C | PCR | Home | NA |
| 2020/06/02 | New York, USA | C | PCR, Ab | Home | Hemolytic anemia and severe lethargy |
| 2020/06/24 | New York, USA | E | Ab | NA | NA |
| 2020/06/24 | New York, USA | E | Ab | NA | NA |
| 2020/07/02 | Georgia, USA | C | PCR, Ab | Home | NA |
| 2020/07/03 | North Jutland, Denmark | C | PCR | Mink farm | NA |
| 2020/07/09 | Texas, US | C | PCR | Home | NA |
| 2020/07/17 | South Carolina, USA | C | PCR | Home | Chronic health condition and mild respiratory symptoms |
| 2020/07/22 | North Carolina, USA | E | Ab | Shelter | NA |
| 2020/07/22 | Utah, USA | E | Ab | NA | NA |
| 2020/07/22 | Utah, USA | E | Ab | NA | NA |
| 2020/07/22 | Wisconsin, USA | E | Ab | NA | NA |
| 2020/07/22 | Wisconsin, USA | E | Ab | NA | NA |
| 2020/07/23 | Arizona, USA | C | PCR | Home | Respiratory symptoms |
| 2020/08/03 | Louisiana, USA | E | PCR | NA | NA |
| 2020/08/10 | Hong Kong, China | C | PCR (swab) | Home | NA |
| 2020/08/10 | Hong Kong, China | C | PCR (swab) | Home | NA |
| 2020/06/13 | North Carolina, USA | C | PCR | Home | Respiratory distress |
| 2020/08/13 | Texas, USA | C | PCR | Home | NA |
| 2020/09/02 | Texas, USA | C | PCR | NA | Nasal discharge |
| 2020/09/02 | Texas, USA | C | PCR | NA | NA |
| 2020/09/25 | Tokyo, Japan | C | PCR, Ab | Home | NA |
| Animal              | Reporting date | Region                  | Source | Method (Samples) of initial diagnosis | Location of infection | Symptoms                                                                 |
|---------------------|----------------|-------------------------|--------|---------------------------------------|-----------------------|--------------------------------------------------------------------------|
| Ferret (Mustela putorius furo) | 2020/12/23 | Celje, Slovenia         | C      | PCR                                   | Home                 | Gastrointestinal tract                                                  |
|                     | 2020/10/02   | Texas, USA              | C      | PCR                                   | Home                 | Coughing and wheezing                                                   |
|                     | 2020/10/28   | Cuiaba, Brazil          | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2020/10/28   | Ontario, Canada         | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2020/10/30   | Texas, USA              | C      | PCR, Ab                               | Home                 | Crackling, increased respiratory rate, mild to moderate respiratory symptoms, and wheezing |
|                     | 2020/11/18   | Santiago del Estero, Argentina | C | PCR                                   | Home                 | Conjunctivitis, cough, dyspnea, and weakening                           |
|                     | 2020/11/18   | Santiago del Estero, Argentina | C | PCR                                   | Home                 | NA                                                                       |
|                     | 2020/11/18   | Santiago del Estero, Argentina | C | PCR                                   | Home                 | NA                                                                       |
|                     | 2020/11/27   | Hong Kong, China        | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2020/12/01   | Rhineland-Palatinate, Germany | C | PCR                                   | Home                 | High respiratory distress and apathy                                  |
|                     | 2020/12/11   | Hong Kong, China        | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2020/12/15   | Mexico                  | C      | PCR, Ab                               | Home                 | NA                                                                       |
|                     | 2020/12/18   | Florida, USA            | C      | PCR                                   | Home                 | Respiratory symptoms                                                   |
|                     | 2020/12/18   | Hong Kong, China        | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2020/12/18   | Kansas, USA             | C      | PCR                                   | Home                 | Nasal discharge                                                        |
|                     | 2020/12/18   | Pennsylvania, USA       | C      | PCR                                   | Home                 | Respiratory symptoms                                                   |
|                     | 2020/12/21   | Arizona, USA            | C      | Ab                                    | Home                 | NA                                                                       |
|                     | 2020/12/31   | Pennsylvania, USA       | C      | PCR, Ab                               | Home                 | Hemorrhagic diarrhea and lethargy                                       |
|                     | 2021/01/07   | Benito Juarez, Mexico   | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2021/01/08   | Florida, USA            | C      | PCR, Ab                               | Home                 | NA                                                                       |
|                     | 2021/01/21   | Toluca, Mexico          | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2021/01/22   | Curitiba, Brazil        | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2021/01/22   | Curitiba, Brazil        | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2021/01/29   | California, USA         | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2021/02/03   | Bosnia and Herzegovina  | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2021/02/05   | Florida, USA            | C      | PCR                                   | Home                 | Decreased appetite, lethargy, and productive cough                      |
|                     | 2021/02/05   | Iowa, USA               | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2021/02/09   | Hong Kong, China        | C      | PCR                                   | Home                 | NA                                                                       |
|                     | 2021/02/12   | Texas, USA              | C      | PCR, Ab                               | Home                 | NA                                                                       |
|                     | 2021/02/12   | California, USA         | C      | PCR, Ab                               | Home                 | NA                                                                       |
|                     | 2021/02/12   | Florida, USA            | C      | PCR, Ab                               | Home                 | NA                                                                       |
| Animal   | Reporting date | Region                  | Source | Method (Samples) of initial diagnosis | Location of infection | Symptoms                                                                 |
|----------|----------------|-------------------------|--------|---------------------------------------|----------------------|--------------------------------------------------------------------------|
| Gorilla  | 2021/01/12     | California, USA         | C      | PCR                                  | Zoo                  | Mild respiratory symptoms                                               |
| Jaguar   | 2021/01/29     | Texas, USA              | C      | PCR                                  | Zoo                  | NA                                                                       |
| Lion     | 2020/04/06     | New York, USA           | A      | PCR (fetal)                          | Zoo                  | Dry cough and wheezing                                                  |
|          | 2020/12/21     | Barcelona, Spain        | C      | PCR (nasal swab)                     | Zoo                  | Serous nasal discharge, sneezing, and coughing                         |
|          | 2021/01/15     | Sweden                  | NA     | PCR                                  | Zoo                  | Inappetence, neurological and severe respiratory symptoms              |
|          | 2021/01/22     | Estonia                 | NA     | PCR                                  | Zoo                  | Severe kidney failure and upper respiratory symptoms                    |
|          | 2021/01/29     | Texas, USA              | C      | PCR                                  | Zoo                  | Mild respiratory symptoms                                              |
|          | 2021/01/29     | Minnesota, USA          | C      | PCR                                  | Zoo                  | Cough, inappetence, and wheezing                                       |
|          | 2021/02/10     | Texas, USA              | C      | PCR                                  | Zoo                  | Cough, exercise intolerance, epistaxis, and wheezing                    |
| Pig      | 2021/01/08     | Florida, USA            | C      | PCR                                  | NA                   | NA                                                                       |
| Puma     | 2020/08/11     | Johannesburg, Gauteng, | C      | PCR                                  | Zoo                  | NA                                                                       |
|          | 2021/01/29     | Minnesota, USA          | C      | PCR                                  | Zoo                  | Cough, inappetence, and wheezing                                       |
|          | 2021/02/10     | Texas, USA              | C      | PCR                                  | Zoo                  | Cough, epistaxis, exercise intolerance, and wheezing                    |
| Rabbit   | 2020/02/12     | Texas, USA              | C      | PCR                                  | Home                 | NA                                                                       |
| Snow leopard | 2020/12/18   | Kentucky, USA           | C      | PCR                                  | Zoo                  | Occasional dry cough or wheezing and mild respiratory symptoms         |
| Tiger    | 2020/04/07     | New York, USA           | A      | PCR (fetal)                          | Zoo                  | Dry cough and wheezing                                                  |
|          | 2020/11/06     | Tennessee, USA          | C      | PCR                                  | Zoo                  | Inappetence, lethargy, and mild cough                                  |
|          | 2021/01/15     | Sweden                  | NA     | PCR                                  | Zoo                  | NA                                                                       |
|          | 2021/01/29     | Minnesota, USA          | C      | PCR                                  | Zoo                  | Inappetence, intermittent wheezing, and lethargy                       |
|          | 2021/01/29     | Texas, USA              | C      | PCR                                  | Zoo                  | NA                                                                       |
|          | 2021/02/10     | Texas, USA              | C      | PCR                                  | Zoo                  | Cough, exercise intolerance, epistaxis, and wheezing                    |
|          | 2021/02/12     | Indiana, USA            | C      | PCR                                  | Zoo                  | Dry cough                                                              |
|          | 2021/02/12     | Indiana, USA            | C      | PCR                                  | Zoo                  | Inappetence                                                            |
| Mink     | 2020/04/15     | North Brabant, The Netherlands | C  | PCR (conchae, lung, throat swab, rectal swab) | Farm | Respiratory symptoms                                                                 |
|          | 2020/04/20     | North Brabant, The Netherlands | C  | PCR (conchae, lung, throat swab, rectal swab) | Farm | Respiratory symptoms                                                                 |
|          | 2020/05/06     | North Brabant, The Netherlands | C  | PCR                                  | Farm | NA                                                                       |
|          | 2020/06/02     | North Brabant, The Netherlands | C  | PCR                                  | Farm | NA                                                                       |
Table 1. (continued)

| Animal          | Reporting date | Region                  | Source | Method (Samples) of initial diagnosis | Location of infection | Symptoms                                                                 |
|-----------------|----------------|-------------------------|--------|---------------------------------------|-----------------------|--------------------------------------------------------------------------|
|                 | 2020/06/09     | Limburg, The Netherlands| E      | PCR, Ab                               | Farm                  | NA                                                                       |
|                 | 2020/06/18     | Northern Jutland, Denmark| C      | PCR                                  | Farm                  | NA                                                                       |
|                 | 2020/07/03     | Northern Jutland, Denmark| C      | PCR                                  | Farm                  | NA                                                                       |
|                 | 2020/07/03     | Northern Jutland, Denmark| C      | PCR                                  | Farm                  | Respiratory symptoms                                                     |
|                 | 2020/08/12     | Limburg, The Netherlands| E      | PCR, Ab                               | Farm                  | NA                                                                       |
|                 | 2020/08/12     | North Brabant, The Netherlands| E      | PCR, Ab                               | Farm                  | NA                                                                       |
|                 | 2020/08/17     | Utah, USA               | C      | PCR                                  | Farm                  | Respiratory symptoms and sudden death                                    |
|                 | 2020/08/19     | Utah, USA               | C      | PCR                                  | Farm                  | Respiratory symptoms and sudden death                                    |
|                 | 2020/08/24     | Northern Jutland, Denmark| C      | PCR                                  | Farm                  | Inappetence and increased mortality                                      |
|                 | 2020/08/25     | Utah, USA               | C      | PCR                                  | Farm                  | Respiratory symptoms and sudden death                                    |
|                 | 2020/09/01     | North Brabant, The Netherlands| E      | PCR                                  | Farm                  | NA                                                                       |
|                 | 2020/09/01     | Gelderland, The Netherlands| E      | PCR                                  | Farm                  | NA                                                                       |
|                 | 2020/09/01     | Limburg, The Netherlands| E      | PCR                                  | Farm                  | NA                                                                       |
|                 | 2020/09/24     | Utah, USA               | C      | PCR                                  | Farm                  | Ill thrift and sudden death                                               |
|                 | 2020/10/01     | Northern Jutland, Denmark| NA     | PCR                                  | Farm                  | (23)                                                                     |
|                 | 2020/10/02     | Utah, USA               | C      | PCR                                  | Farm                  | NA                                                                       |
|                 | 2020/10/06     | Gelderland, The Netherlands| E      | PCR, Ab                               | Farm                  | NA                                                                       |
|                 | 2020/10/06     | Limburg, The Netherlands| E      | PCR, Ab                               | Farm                  | (7)                                                                      |
|                 | 2020/10/06     | North Brabant, The Netherlands| E      | PCR, Ab                               | Farm                  | (11)                                                                     |
|                 | 2020/10/09     | Michigan, USA           | C      | PCR                                  | Farm                  | Epistaxis, inappetence, respiratory distress, sudden death               |
|                 | 2020/10/09     | Wisconsin, USA          | C      | PCR                                  | Farm                  | Epistaxis, inappetence, respiratory distress, and sudden death in all cases, coffee-colored urine in black mink |
|                 | 2020/10/16     | Utah, USA               | C      | PCR                                  | Farm                  | Open-mouth breathing and sudden death                                    |
|                 | 2020/10/16     | Jutland, Denmark        | E      | PCR                                  | Farm                  | NA                                                                       |
|                 | 2020/10/29     | Blekinge, Sweden        | E      | PCR (oral cavity, pharynx swab)      | Farm                  | NA                                                                       |
|                 | 2020/10/30     | Lombardia, Cremona, Italy| NA     | PCR                                  | Farm                  | (9)                                                                      |
|                 | 2020/11/05     | Denmark                | NA     | PCR                                  | Farm                  | NA                                                                       |

(continued on next page)
| Animal                     | Reporting date | Region                        | Source | Method (Samples) of initial diagnosis | Location of infection | Symptoms                                                                 |
|----------------------------|----------------|-------------------------------|--------|---------------------------------------|-----------------------|--------------------------------------------------------------------------|
| Cat (*Felis catus*)        | 2020/11/06     | Blekinge, Sweden              | E      | PCR (oral cavity, pharynx swab)       | Farm                 | NA                                                                       |
| Chicken (*Gallus gallus domesticus*) | 2020/11/16     | Utah, USA                     | C      | PCR                                   | Farm                 | Inappetence, mild respiratory symptoms, and sudden death                |
| Dog (*Canis lupus familiaris*) | 2020/11/16     | Wisconsin, USA                | C      | PCR                                   | Farm                 | Inappetence and sudden death                                             |
| Duck (*Anas*)              | 2020/11/27     | Oregon, USA                   | C      | PCR                                   | Farm                 | Cough, inappetence, mild respiratory symptoms, and sneezing           |
| Ferret (*Mustela putorius furo*) | 2020/11/30     | Jonava, Lithuania             | C      | PCR                                   | Farm                 | NA                                                                       |
| French Domestic Goose      | 2020/12/01     | Blekinge, Sweden              | E      | PCR                                   | Farm                 | NA                                                                       |
| British Columbia, Canada   | 2020/12/09     | Oregon, USA                   | C      | PCR                                   | Farm                 | NA                                                                       |
| Western Macedonia, Greece  | 2020/12/15     | Western Macedonia, Greece     | C      | PCR                                   | Farm                 | NA                                                                       |
| Greece                     | 2020/12/19     | Greece                        | C      | PCR                                   | Farm                 | NA                                                                       |
| Ottawa, Canada             | 2020/12/21     | Ottawa, Canada                | C      | PCR                                   | Farm                 | NA                                                                       |
| British Columbia, Canada   | 2020/12/30     | British Columbia, Canada      | C      | PCR                                   | Farm                 | Diarrhea                                                                 |
| Siauliai, Lithuania        | 2020/12/31     | Siauliai, Lithuania           | C      | PCR                                   | Farm                 | NA                                                                       |
| France                     | 2021/01/06     | France                        | NA     | PCR, Ab                               | Farm (B)             | NA                                                                       |
| Limburg, The Netherlands   | 2021/01/06     | Limburg, The Netherlands      | E      | PCR, Ab                               | Farm                 | NA                                                                       |
| North Brabant, The Netherlands | 2021/01/06   | North Brabant, The Netherlands | E      | PCR, Ab                               | Farm                 | NA                                                                       |
| Athens, Greece             | 2021/01/12     | Athens, Greece                | C      | PCR                                   | Farm                 | NA                                                                       |
| Galicia, Spain             | 2021/01/21     | Galicia, Spain                | C      | PCR                                   | Farm                 | NA                                                                       |
| Navatalgordo, Castilla y Leon, Spain | 2021/01/26 | Navatalgordo, Castilla y Leon, Spain | C | PCR                                   | Farm                 | NA                                                                       |
| Lazeo, Poland              | 2021/02/03     | Lazeo, Poland                 | C      | PCR                                   | Farm                 | NA                                                                       |
| Western Macedonia, Greece  | 2021/02/06     | Western Macedonia, Greece     | C      | PCR                                   | Farm                 | NA                                                                       |
| Greece                     | 2021/02/14     | Greece                        | C      | PCR                                   | Farm                 | (23)                                                                     |

**Experimental infection**

| Animal                     | Method (Samples) of initial diagnosis | Symptoms                                                                 |
|----------------------------|---------------------------------------|--------------------------------------------------------------------------|
| Cat (*Felis catus*)        | PCR, Ab (nasal turbinate, soft palate, tonsil, trachea, lung, fecal) | High susceptibility to SARS-CoV-2                                         |
| Chicken (*Gallus gallus domesticus*) | PCR, Ab                               | No susceptibility to SARS-CoV-2                                           |
| Dog (*Canis lupus familiaris*) | PCR, Ab (rectal swab)                 | Low susceptibility to SARS-CoV-2                                           |
| Duck (*Anas*)              | PCR, Ab                               | No susceptibility to SARS-CoV-2                                           |
| Ferret (*Mustela putorius furo*) | PCR, Ab (nose swab, nasal turbinate, soft palate, tonsil, trachea) | High susceptibility to SARS-CoV-2, fever, and inappetence                  |
| Fruit bat (*Pteropodidae*) | PCR, Ab (nasal conchae, trachea, lung, tracheal lymph node, skin, duodenum tissue) | Low susceptibility to SARS-CoV-2 (potential reservoir hosts)               |
vector, environment) can be substantially strengthened by the participation of the United Nations Environment Program in the tripartite collaboration among the WHO, the World Organization for Animal Health, and the Food and Agriculture Organization of the United Nations, which would help countries implement the One Health approach.

There are several implications when considering and studying reverse zoonoses. At the individual level, awareness of reverse zoonoses should be raised for better self-protection, as it has extended our definition of population groups vulnerable to COVID-19, from those with closer and/or more frequent contact with people/patients (e.g., healthcare workers, safety guards, delivery service people) to those with closer and/or more frequent contact with animals (e.g., pet owners, farmers, zoo keepers), although the risk of pet-human transmission is currently considered to be low. More regulations should be prepared to raise awareness of COVID-19 risks among these vulnerable populations. At regional and national levels, due to limited resources for SARS-CoV-2 detection and containment measures for animals (especially for home pets), there could be a high likelihood of transmission, a lower recovery rate, and hence a large number of infections among animals, which would pose a severe threat to humans. Therefore, resources for SARS-CoV-2 detection should be reserved for testing animals that may be most at risk (e.g., pets of confirmed COVID-19 patients) and regulations should be made to manage infected and at-risk animals, especially at the farm. Attention should also be paid to animals on duty during the COVID-19, such as dogs that are used at airports in some countries to detect passengers infected with COVID-19. In addition, human–animal transmission would expand the total population in COVID-19 forecasting models to both humans and animals, the increased risk of which, together with animal–animal and animal–human transmission, should be considered in future COVID-19 forecasting models.

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Declaration of interests
No interests are declared.

Table 1. (continued)

| Animal                  | Reporting date | Region | Source | Method (Samples) of initial diagnosis | Location of infection | Symptoms                                      |
|-------------------------|----------------|--------|--------|--------------------------------------|-----------------------|-----------------------------------------------|
| Golden hamster (Mesocricetus auratus) | NA             | NA     | NA     | PCR, Ab (nasal turbinate, trachea, and lung) | NA                    | High susceptibility to SARS-CoV-2 and severe lung injury |
| Pig (Sus)               | NA             | NA     | NA     | PCR, Ab                              | NA                    | No susceptibility to SARS-CoV-2               |
| Rabbit (Oryctolagus cuniculus) | NA             | NA     | NA     | PCR, Ab (nose, throat swab, nasal turbinate) | NA                    | Low susceptibility to SARS-CoV-2             |
| Rhesus macaque (Macaca mulatta) | NA             | NA     | NA     | PCR, Ab (nose swab, oropharyngeal swab, throat swab, lung, bronchoalveolar lavage) | NA                    | High susceptibility to SARS-CoV-2, dehydration, inappetence, interstitial pneumonia, hunched posture, pale appearance, and piberection tachypnea |

*Data from https://www.oie.int/en/scientific-expertise/specific-information-and-recommendations/questions-and-answers-on-2019novel-coronavirus/events-in-animals/, https://www.avma.org/resources-tools/animal-health-and-welfare/covid-19/depth-summary-reports-naturally-acquired-sars-cov-2, and https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/SA_OneHealth/sars-cov-2-animals-us

Sources: A, asymptomatic infected owners of pet animals or close contacts of other animals; C, confirmed infected owners of pet animals or close contacts of other animals; E, exposure to a probable or confirmed COVID-19 human case.

Ab, virus-neutralizing antibody; NA, not available; PCR, real-time reverse transcription-polymerase chain reaction.

Values in the parentheses represent the number of farms.
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