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New Approaches to Anticipate the Risk of Reverse Zoonosis

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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–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 animals 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

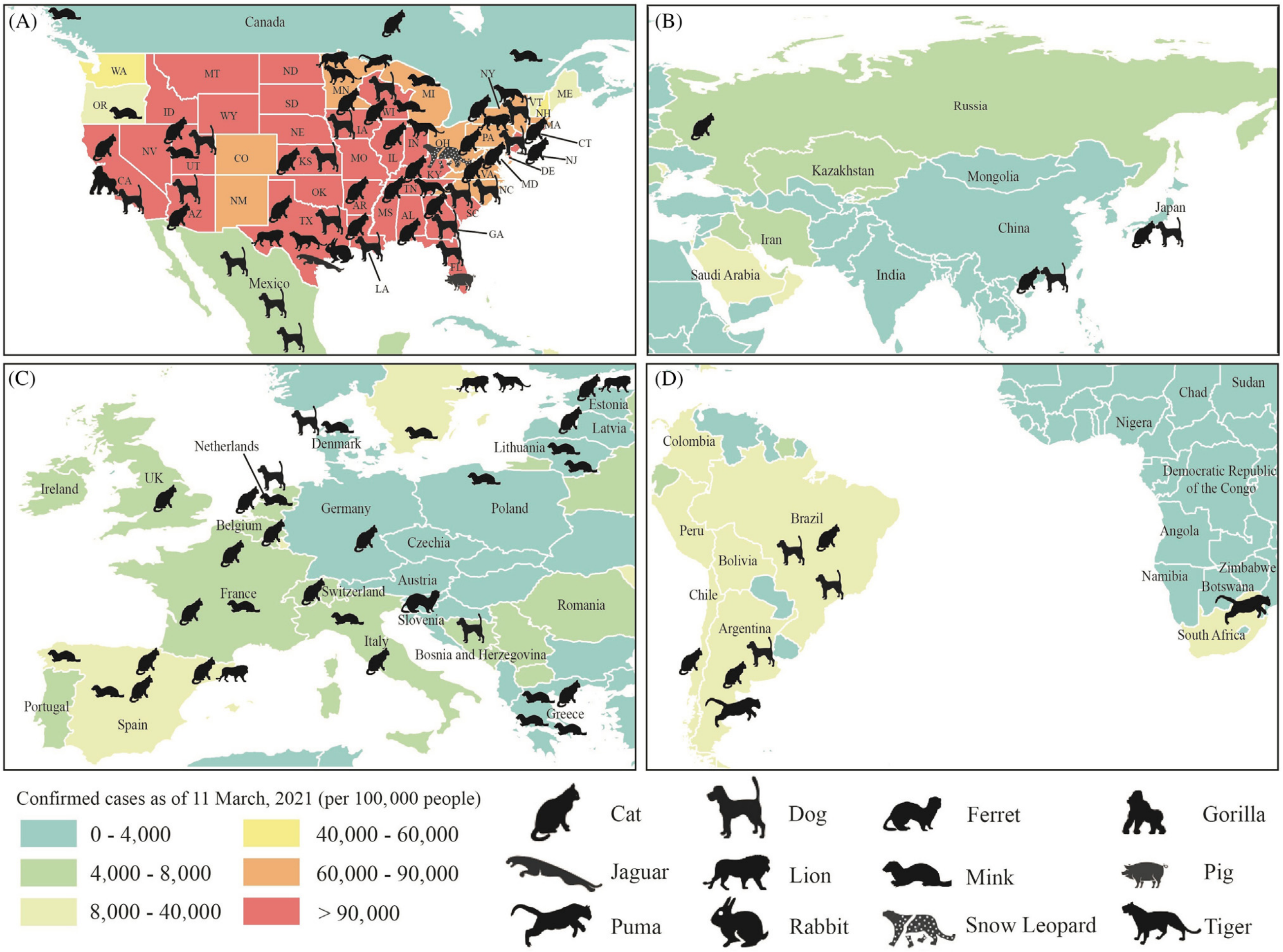

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Figure 1. Coronavirus Disease 2019 (COVID-19) Natural Infections of Pet, Zoo, and Livestock Animals as of 11 March 2021 Mapped onto Number of Confirmed Cases in the Human Population. Data for human confirmed cases from https://covid19.who.int/ and data for animal cases 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_One_Health/sars-cov-2-animals-us.

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[a]

Animal	Reporting date	Region	Source[b]	Method (Samples) of initial diagnosis[c]	Location of infection[d]	Symptoms
Cat (*Felis catus*)	2020/03/27	Belgium	C	PCR (feces, vomit)	Home	Diarrhea, nausea, and respiratory symptoms
	2020/04/03	Hong Kong, China	C	PCR (oral cavity, nasal, rectal)	Home	NA
	2020/04/22	New York, USA	C	PCR	Home	Ocular discharge and sneezing
	2020/04/22	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
	2020/06/01	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, hypothermia, 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
	2020/07/22	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
	2020/08/10	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

Table 1. (continued)

Animal	Reporting date	Region	Source[b]	Method (Samples) of initial diagnosis[c]	Location of infection[d]	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
	2020/11/18	Argentina	C	PCR	Home	NA
	2020/12/04	Hong Kong, China	C	PCR	Home	NA
	2020/12/09	Italy	NA	PCR, Ab	NA	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
	2021/01/22	Brazil	C	PCR	Home	NA

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Table 1. (continued)

Animal	Reporting date	Region	Source[b]	Method (Samples) of initial diagnosis[c]	Location of infection[d]	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
Dog (*Canis lupus familiaris*)	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
	2020/08/13	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

Table 1. (continued)

Animal	Reporting date	Region	Source[b]	Method (Samples) of initial diagnosis[c]	Location of infection[d]	Symptoms
	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
	2020/11/18	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	Florida, USA	C	PCR	Home	NA
	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
Ferret (*Mustela putorius furo*)	2020/12/23	Celje, Slovenia	C	PCR	Home	Gastrointestinal tract

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Table 1. (continued)

Animal	Reporting date	Region	Source[b]	Method (Samples) of initial diagnosis[c]	Location of infection[d]	Symptoms
Gorilla (*Gorilla gorilla*)	2021/01/12	California, USA	C	PCR	Zoo	Mild respiratory symptoms
Jaguar (*Panthera onca*)	2021/01/29	Texas, USA	C	PCR	Zoo	NA
Lion (*Panthera leo*)	2020/04/06	New York, USA	A	PCR (fecal)	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, wheezing
Pig (*Sus*)	2021/01/08	Florida, USA	C	PCR	NA	NA
Puma (*Puma concolor*)	2020/08/11	Johannesburg, Gauteng, South Africa	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, wheezing
	2021/02/18	Argentina	NA	PCR	Zoo	NA
Rabbit (*Oryctolagus cuniculus*)	2021/02/12	Texas, USA	C	PCR	Home	NA
Snow leopard (*Panthera uncia*)	2020/12/18	Kentucky, USA	C	PCR	Zoo	Occasional dry cough or wheezing and mild respiratory symptoms
Tiger (*Panthera tigris*)	2020/04/07	New York, USA	A	PCR (fecal)	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 (*Neovison vison*)	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
	2020/05/08	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[b]	Method (Samples) of initial diagnosis[c]	Location of infection[d]	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 (4)	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 (8)	NA
	2020/09/01	Gelderland, The Netherlands	E	PCR	Farm (5)	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)	NA
	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)	NA
	2020/10/06	North Brabant, The Netherlands	E	PCR, Ab	Farm (11)	NA
	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)	NA
	2020/11/05	Denmark	NA	PCR	Farm	NA

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Table 1. (continued)

Animal	Reporting date	Region	Source[b]	Method (Samples) of initial diagnosis[c]	Location of infection[d]	Symptoms
	2020/11/06	Blekinge, Sweden	E	PCR (oral cavity, pharynx swab)	Farm	NA
	2020/11/16	Utah, USA	C	PCR	Farm	Inappetence, mild respiratory symptoms, and sudden death
	2020/11/16	Wisconsin, USA	C	PCR	Farm	Inappetence and sudden death
	2020/11/27	Oregon, USA	C	PCR	Farm	Cough, inappetence, mild respiratory symptoms, and sneezing
	2020/11/30	Jonava, Lithuania	C	PCR	Farm	NA
	2020/12/01	Blekinge, Sweden	E	PCR	Farm	NA
	2020/12/09	British Columbia, Canada	C	PCR	Farm	NA
	2020/12/15	Western Macedonia, Greece	C	PCR	Farm	NA
	2020/12/19	Greece	C	PCR	Farm	NA
	2020/12/21	Ottawa, Canada	C	PCR	Farm	NA
	2020/12/30	British Columbia, Canada	C	PCR	Farm	Diarrhea
	2020/12/31	Siauliai, Lithuania	C	PCR	Farm	NA
	2021/01/06	France	NA	PCR, Ab	Farm	NA
	2021/01/06	Limburg, The Netherlands	E	PCR, Ab	Farm (6)	NA
	2021/01/06	North Brabant, The Netherlands	E	PCR, Ab	Farm	NA
	2021/01/12	Athens, Greece	C	PCR	Farm	NA
	2021/01/21	Galicia, Spain	C	PCR	Farm	NA
	2021/01/26	Navatalgordo, Castilla y Leon, Spain	C	PCR	Farm	NA
	2021/02/03	Lezno, Poland	C	PCR	Farm	NA
	2021/02/06	Western Macedonia, Greece	C	PCR	Farm	NA
	2021/02/14	Greece	C	PCR	Farm (23)	NA
Experimental infection						
Cat (*Felis catus*)	NA	NA	NA	PCR, Ab (nasal turbinate, soft palate, tonsil, trachea, lung, fecal)	NA	High susceptibility to SARS-CoV-2
Chicken (*Gallus gallus domesticus*)	NA	NA	NA	PCR, Ab	NA	No susceptibility to SARS-CoV-2
Dog (*Canis lupus familiaris*)	NA	NA	NA	PCR, Ab (rectal swab)	NA	Low susceptibility to SARS-CoV-2
Duck (*Anas*)	NA	NA	NA	PCR, Ab	NA	No susceptibility to SARS-CoV-2
Ferret (*Mustela putorius furo*)	NA	NA	NA	PCR, Ab (nose swab, nasal turbinate, soft palate, tonsil, trachea)	NA	High susceptibility to SARS-CoV-2, fever, and inappetence
Fruit bat (*Pteropodidae*)	NA	NA	NA	PCR, Ab (nasal conchae, trachea, lung, tracheal lymph node, skin, duodenum tissue)	NA	Low susceptibility to SARS-CoV-2 (potential reservoir hosts)

Table 1. (continued)

Animal	Reporting date	Region	Source[b]	Method (Samples) of initial diagnosis[c]	Location of infection[d]	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 piloerection tachypnea

[a] 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_One_Health/sars-cov-2-animals-us

[b] 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.

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

[d] Values in the parentheses represent the number of farms.

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.

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