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Original research paper

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Infrastructure of animal farms: key constructional elements in terms of biosecurity based on experience from Germany

Infrastruktur von Tierhaltungen: Bauliche Schlüsselelemente in Bezug auf Biosicherheit auf der Grundlage von Erfahrungen aus Deutschland

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Summary

The infrastructural design of an animal farm can significantly motivate or discourage adopting biosecurity measures in the daily routines. Proper planning and collaboration between architects, farmers and veterinarians is critical in the prevention of serious biosecurity issues, possible financial and animal losses. The consistent use of a uniform nomenclature that encompasses both, construction-functional and veterinary-epidemiological terms is therefore essential.
We developed a conceptual framework for key constructional elements in terms of biosecurity and characterize key concepts from both disciplines, architecture and veterinary epidemiology. From an epidemiological point of view, we focus on pathogens and vectors, and from a constructional perspective on biosecurity areas, barriers and locks. The central aspect of the framework is the capability of barriers and locks to prevent (uncontrolled) movement of vectors between different biosecurity areas, thus interrupting pathways of pathogen transmission. Concepts are abstracted and aggregated in such a way that they can be applied to any animal husbandry system, regardless of species or size, and independently of a particular disease. The aim is providing a common basis of terminology that facilitates cross-sectoral cooperation.

Keywords: agricultural building, livestock, veterinary hygiene, biosafety, biosecurity

Zusammenfassung

Die infrastrukturelle Gestaltung einer Tierhaltung kann die Umsetzung von Biosicherheitsmaßnahmen in den täglichen Routineabläufen maßgeblich unterstützen oder behindern. Eine sachgerechte Planung sowie die Zusammenarbeit von Architekten, Landwirten und Tierärzten sind unerlässlich, um wichtigen Biosicherheitsmängeln sowie möglichen finanziellen und Tierverlusten vorzubeugen. Dafür ist die Nutzung einer einheitlichen Nomenklatur wichtig, die sowohl baulich-funktionale als auch veterinär-epidemiologische Fachbegriffe umfasst. In diesem Artikel entwerfen wir einen konzeptionellen Rahmen der wesentlichen baulichen Elemente für Biosicherheit und charakterisieren Grundbegriffe aus den beiden Disziplinen Architektur und Veterinärepidemiologie. Aus epidemiologischer Sicht fokussieren wir uns auf Pathogene und Vektoren, aus baulicher Sicht auf Biosicherheitsbereiche, Barrieren und Schleusen. Die zentrale Eigenschaft, an der wir uns orientieren, ist die Fähigkeit von Barrieren und Schleusen, die (unkontrollierte) Bewegung von Vektoren zwischen unterschiedlichen Biosicherheitsbereichen zu verhindern und dadurch Infektketten zu unterbrechen. Die Begriffe werden so abstrahiert und aggregiert, dass sie für jede Art von Tierhaltung angewendet werden können, unabhängig von deren Größe und der Krankheit. Ziel ist die Schaffung einer einheitlichen Terminologie als Grundlage für eine erfolgreiche Sektor-übergreifende Zusammenarbeit.

Schlüsselwörter: Landwirtschaftliches Bauen, landwirtschaftliche Nutztiere, Veterinärhygiene, Biosicherheit

Introduction

Renovating, expanding or building a new animal farm make it necessary to consider several legal requirements to ensure functional and labor safety, animal welfare and environmental protection. Far less in the center of attention, but equally important, is the biosecurity perspective, one of the most important factors in protecting livestock against transmissible diseases (Council of the European Union 2019).

The term biosecurity is closely linked to the term biosafety and has received various definitions, depending on the context (Burnette et al. 2013). In this study, the term biosecurity is adopted from the European Animal Health Law (Regulation (EU) 2016/429), which defines it as the "sum of management and physical measures designed to reduce the risk of introduction, development and spread of diseases to, from and within an animal population, or an establishment, zone, compartment, means of transport or any other facilities, premises or location." Regarding animal farms, the term biosecurity usually refers to **operational biosecurity**, which describes management practices, such as personal hygiene, disease monitoring, medication regime, applying the all-in all-out principle or the closed-herd policy, manure and carcass removal, controlling vermin and birds, or cleaning and disinfection (Dewulf and van Immerseel 2019, Grabkowsky et al. 2020). In this study, we focus on **constructional biosecurity**, which includes building measures, such as building a quarantine stable or installing a washbasin. Both, operational and constructional measures may be further divided into those directed at preventing pathogens from entering a farm (external biosecurity) and those preventing the spread within a farm (internal biosecurity).

Animal farms are complex dynamic systems, and multiple infrastructural characteristics are relevant for biosecurity, from the geographic location and spatial layout to the features of each single constructional component. Therefore, constructional biosecurity needs to be included already at the planning stage, and it should involve architects, farmers and veterinarians. However, each of these disciplines has a different background and uses a different specific terminology, what can pose major challenges to collaboration.

The work described in this article is based on experience from Germany, but its results are meant to become widely applicable, also at the international level. In Germany, the Animal Health Law (§ 3 Tiergesundheitsgesetz) stipulates that the animal holder is responsible for implementing biosecurity measures to prevent disease introduction into and disease transfer from his or her farm. General measures are laid down in articles 3, 4 and 5 of the Regulation on protecting and keeping livestock (Tierschutz-Nutztierhaltungsverordnung). Biosecurity measures during transport are also required as stipulated in the Regulation on livestock movement (Viehverkehrsverordnung). Specific biosecurity measures for pigs are laid down in the Regulation on hygiene requirements in pig holdings (Schweinehaltungshygieneverordnung) and the Regulation on the protection against swine fever (Schweinepest-Verordnung). Measures for poultry are laid down in article 6 (cleaning and disinfection) of the Regulation on Avian Influenza control (Verordnung zum Schutz gegen die Geflügelpest) and in the Regulation on Salmonella in poultry (Geflügel-Salmonellen-Verordnung). Apart from these requirements, the design of an animal farm lies in the responsibility of the farmer, architect, or building professional, and the choice of the level of constructional biosecurity is ultimately left to the farmer´s judgement. Regarding cattle there is no legal framework that covers biosecurity issues in Germany.

Building companies, engineers and architects provide a large array of proposals for constructing animal farm buildings. Whilst they usually comply with size specifications and other animal welfare standards, most of them fail to consider biosecurity issues. From a farmer´s or veterinarian´s perspective, informal recommendations on biosecurity are given by various institutions, associations and stakeholders. Some apply to specific species, for example the reports of the Food and Agriculture Organization (www.fao.org), the Terrestrial Animal Health Code (OIE 2019), the recommendations of the Federal Ministry of Food and Agriculture for keeping ruminants (BMEL 2014) and various guidelines of the German Association for Technology and Structures in Agriculture (www.ktbl.de), the Agricultural Construction Association (www.bfl-online.de) or the German federal states (Anonymus 2009). Others are conceived at a more generic level, for example the biosecurity guide for endangered livestock breeds (Dorkewitz et al. 2018). However, only a few of them specifically address constructional aspects of biosecurity. One of the few exceptions is the Guideline on biosecurity in cattle farms of the German federal state of Lower Saxony (Anonymus 2016). Due to the lack of coordinated guidance, an increasing number of checklists is available online for evaluating the biosecurity level of a farm. In Germany, the quality assurance system for food (QS-system) provides checklists for poultry, pig and cattle (www.q-s.de), the Ministry for Agriculture and Environment of Sachsen-Anhalt issued checklists for different livestock including fish and bees (mule.sachsen-anhalt.de) and the University of Vechta has developed the "Risikoampel" for poultry and pigs together with the Friedrich-Loeffler-Institut, Federal Research Institute for Animal Health (https://risikoampel.uni-vechta.de). Similar checklists are also available in English, for example the risk-based "biocheck" scoring systems provided by Ghent University (https://biocheck.ugent.be/en/worldwide).

In the peer-reviewed literature, disease transmission routes and corresponding biosecurity practices from the individual farm to the international level are well documented, but hardly lead to recommendations on the construction of farms and stables. Most studies focus on particular diseases, e.g. avian influenza (Conraths et al. 2016, Glass et al. 2019, Robertson 2020; Ssematimba et al. 2013,). Others concentrate on specific species, e.g. pigs (Döring et al. 2019, Filippitzi et al. 2018), poultry (Carr and Howells 2018, van Steenwinkel et al. 2011), or cattle (Brennan and Christley 2012, Renault et al. 2018b, 2020). Some focus more specifically on certain production types, e.g. dairy cattle (Sibley 2010), veal calves (Damiaans et al. 2019), fattening pigs (Boklund et al. 2004), foie-gras ducks (Delpont et al. 2018) or fish in aquaculture (Delabbio 2006).

In Europe, modern animal husbandry is usually specialized on keeping cattle, pigs or poultry. Cattle farming is mostly represented by dairy and beef, pig production is usually subdivided into breeding and fattening, and poultry production mostly refers to chickens (eggs, broilers), ducks, geese and turkeys.

To gain an understanding of disease prevention measures that should be promoted, also by veterinary officials, several studies across Europe have assessed farmers´

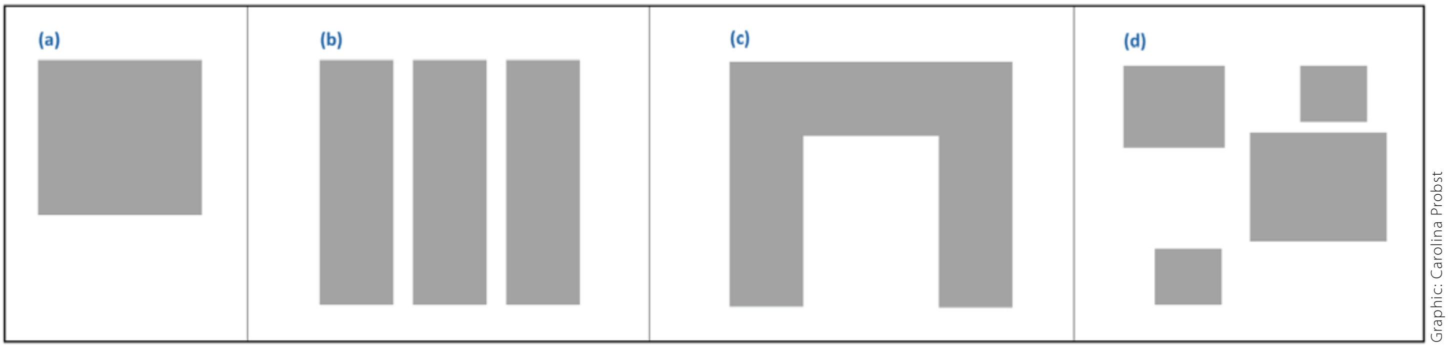


FIGURE 1: *Schematic overview of typical farm layouts. (a) One single animal building, (b) large identical buildings in parallel, (c) three-sided layout, (d) scattered buildings.*

knowledge and opinion about biosecurity. As outlined in several publications, there is room for improvement in all sectors including pigs (Laanen et al. 2010, Ribbens et al. 2008), poultry (Gelaude et al. 2014) and cattle (Laanen et al. 2014). The following example may illustrate this: Although badgers are known to pose a risk of transmitting bovine tuberculosis (bTB) to cattle (Donnelly and Nouvellet 2013), commercial cattle farms that had experienced herd breakdowns of bTB, had no biosecurity measures implemented several years after the outbreaks to prevent wild animals from entering the buildings and feed stores (Ward et al. 2008).

Others studies reported that the motivation to implement biosecurity measures mainly depends on the type and size of the farm (Nöremark et al. 2010, Sahlström et al. 2014, Simon-Grifé et al. 2013), the current epidemiological situation and the practicability of measures (Garforth et al. 2013, Renault et al. 2018a, Shortall et al. 2017). On the other hand, veterinarians suggested that on-farm conditions represented obstacles for keeping good biosecurity (Nöremark and Sternberg-Lewerin 2014) and perceived the education of farmers as the most important biosecurity measure (Kuster et al. 2015, Pritchard et al. 2015).

According to the FAO, the three main elements of biosecurity are segregation, cleaning and disinfection (FAO 2010). While cleaning and disinfection relate to management measures and therefore represent the "software" of biosecurity, segregation, i.e. the "creation and maintenance of barriers to limit the potential opportunities for infected animals and contaminated materials to enter an uninfected site" (FAO 2010) represent the "hardware" of biosecurity.

Within the BIPROC (Building Infection Protection Classification) project, architects and veterinary epidemiologists focus on the "hardware", i.e. the infrastructure of farms in the animal health context. The project is part of InfectControl 2020 funded by the German Federal Ministry of Education and Research. The aim of this interdisciplinary holistic approach to infection prevention is to analyze livestock farms from both, a construction-functional and a veterinary-epidemiological biosecurity perspective. In human medicine, a similar approach has already been used for the design of hospitals (Lateef 2009, Sunder et al. 2018, Tabori and Dettenkofer 2017). In this article, which reports results of the BIPROC project, we identify, define, and characterize key concepts of both disciplines, i.e. architecture and veterinary epidemiology, from a biosecurity perspective and develop a theoretical framework that includes the key constructional elements in terms of biosecurity.

Common farm layouts

The layout and infrastructure of an animal farm is influenced by a wide range of factors. Besides the type of business (hobby, family or commercial enterprise), animal species, specialization, production system, size etc. it is also always an expression of its localization (e.g. locality and topography), date of origin and subsequent evolutionary history. The arrangement of buildings is not subjected to a fixed set of rules, but systematic building patterns evolved over time due to similar tiers of influencing factors. These can be examined for example by using aerial photographs and used for the assessment of aspects of biosecurity.

Common types of farm layouts are: (a) one or two single stables, (b) several rectangular stables in parallel, (c) three-sided layout with an open front (alternatively four-sided layout, closed), and (d) several scattered buildings (Fig. 1 and 2).

FIGURE 2: *Examples of typical farm layouts. From left to right: (A) Farm with one single stable (in this case divided by an opening in the roof). (B) Turkey farm with four rectangular stables in parallel. (C) Three-sided and four-sided farms. (D) Mixed farm that has expanded through time. A public road leads straight across the farm; buildings are scattered across the premise, while carcasses are stored in the centre.*

Photos: Carolina Probst

FIGURE 3: *Examples of barriers around animal farms. From left to right: (A) Cattle farm (dairy, fattening): young cattle and calves are housed near the public road and can be accessed freely without any barrier or lock. (B) Water buffaloes kept outdoors surrounded by an electrical fence. (C) Perimeter fence around a chicken farm (fattening).*

The design of the so-called "Dreiseitenhof" or "Vierseitenhof" in Western Germany (Fig. 2C) is an expression of how a family farm was organized around the central farmyard. Farms of type (d) can be used to separate animals according to species (mixed farms), gender or age (e.g. cows, calves). However, they are mostly the result of farms expanding over time and consist not only of several animal buildings, but also of various feed and equipment storage areas located at different sites.

Due to the multiplicity of influencing factors mentioned above each farm remains unique, not only in terms of overall building infrastructure but also in the non-standardized treatment of functional components like fences, barriers, surfaces and access control measures. Figure 3 for example shows different perimeter fences, Figure 4 different barriers around stables or animals, Figure 5 barriers around feed/ bedding and Figure 6 different examples of locks. Consequently, a typology-driven approach to constructional biosecurity is impeded by the diversity of farms in general and their infrastructure in particular. A standardized, holistic approach hence needs to incorporate the individuality of farms into its methodology.

Pathways of pathogen transmission

To develop the methodological framework of our study, we used examples of notifiable contagious diseases (Table 1). Most of these pathogens, mainly viruses and bacteria, can be transmitted directly or indirectly (Thrusfield and Christley 2018). **Direct transmission** occurs, when a susceptible animal comes into direct contact with an infected animal. Infection can occur through the eyes, nose, mouth, the reproductive tract (e.g. brucellosis) or the placenta (e.g. bovine viral diarrhoea). **Indirect transmission** is relevant for pathogens that are resistant to environmental conditions. These pathogens can be spread via animated vectors (people, livestock, domestic or wild animals, arthropods, helminths) or inanimate fomites (vehicles, shoes, equipment, feed, water, bedding, air).

Typical routes of entry into the host are ingestion (e.g. *Salmonella*), through the skin (e.g. West Nile virus), or through the conjunctivae (e.g. *Moraxella bovis*). **Airborne** transmission is a type of indirect transmission that can happen through infectious aerosols or droplets. **Aerosols** are small particles of <10 µm diameter, and potentially capable of short and long-range transmission (Tellier et al. 2019) (e.g. foot and mouth disease). **Droplets** of diameters >20 µm fall mostly under the influence of gravity, so transmission happens only over short distances (Tellier et al. 2019). Intermediate particles of diameters in the range of 10-20 µm share properties of both aerosol-sized particles and large droplets. In both, aerosol and droplet transmission, the main route of entry into the host is inhalation (e.g. *Mycobacterium bovis*, influenza virus).

Material and Methods

To gain mutual understanding between architects and veterinarians and to create a common basis of knowledge and terms, a total of nine conventional and organic farms, which kept cattle, poultry and pigs and were

Photos: Carolina Probst

FIGURE 4: *Examples of barriers around stables/ animals. From left to right: (A) Ecological fattening pig farm with a double fence as required by law. (B) Ecological fattening pig farm. The first (and only) barrier can stop wild boar from walking through, but it is not high enough to stop them from jumping over. The sealed ground prevents wild animals from digging through. (C) Dairy farm. Calves are sheltered from rain and sun. (D) Turkey breeding farm. Turkeys are kept indoors with artificial light.*

TABLE 1: *Exemplary contagious livestock diseases and potential vectors by which the pathogens can enter a farm.*

Species	Disease (selection)	Autonomously moving vectors													Not autonomously moving vectors						
			Livestock		Domestic		Wildlife														
		Humans[a]	Conspecifics	Other species	Dogs	Cats	Rodents	Deer	Wild boar	Carnivores	Hares, rabbits	Birds	Arthropods[b]	Aerosols	Vehicles	Equipment[c]	Feed	Water	Bedding	Droplets	Feces
Multiple species	Foot- and mouth disease	x	x	x	x	x	x	x	x					x	x	x	x		x		
	Leptospirosis		x	x	x	x	x														
	Toxoplasmosis					x											x	x			
Cattle	Infectious bovine rhinotracheitis	x	x													x				x	
	Lumpy Skin Disease		x										x				x				
	Salmonellosis		x	x			x										x	x			x
	Tuberculosis	x	x							x											
	Chlamydiosis		x	x										x		x	x	x	x		
	Besnoitiosis		x										x								
	Paratuberculosis		x													x	x	x			
	Q fever		x			x								x		x	x	x	x		
	Schmallenberg												x								
	Toxoplasmosis			x		x											x	x			
Sheep, goats	Peste de petits ruminants		x														x	x	x	x	
	Sheep and goat pox		x											x	x		x		x		
Pigs	African swine fever		x						x						x	x			x		
	Aujesky´s Disease		x	x					x												
Poultry	Avian Influenza	x	x									x		x	x	x	x	x	x		x
	West-Nil Fever											x	x								
	Campylobacteriosis		x	x													x	x			
	Avian chlamydiosis		x											x							
	Listeriosis																x		x		
Rabbits	Myxomatosis										x		x								

[a] Humans: veterinarians, livestock traders, workers, maintenance personnel, consultants, visitors, etc.

[b] Arthropods: flies, mites, mosquitoes, lice, ticks, etc.

[c] Equipment: Needles, dehorning and castration instruments, etc.

located in different parts of Germany, were visited by an interdisciplinary team (two architects, two veterinarians, and one agricultural scientist). Additionally, an expert on agricultural building (Landgesellschaft Mecklenburg-Vorpommern) was interviewed. For the visits, three different data collection sheets were designed (dairy and poultry farms; agricultural building expert). The following aspects were addressed: Physical farm design, workflows and routine management practices, numbers and types of biosecurity areas, their spatial layout and physical separation. Based on this data, key constructional components with respect to biosecurity were delineated and defined.

Based on scientific literature and lessons learned from disease outbreak investigations in poultry (Conraths et al. 2016, Globig et al. 2018), pig (Schulz et al. 2017) and cattle farms (Beer et al. 2017, Gethmann et al. 2015, Probst et al. 2010), the available knowledge on pathogens and potential routes of entry into a farm was organized in a systematic way. All vectors were characterized and classified according to their size, types of locomotion and specific mobility abilities (crawl, dig, jump), allowing a differentiation into those that must be able to cross barriers in a controlled way (e.g. veterinarians, feed and equipment) and those that were to be kept out. Based on the find-

Photos: Carolina Probst

FIGURE 5: *Examples of barriers around feed and bedding. From left to right: (A) Feed storage in a dairy farm. (B) Hay ball storage in a poultry farm. The roof may protect the bedding from droppings of wild birds flying, but not from wild birds nesting. (C) Silo with corn silage located on a dairy farm.*

ings, relevant constructional components were identified. In this process, a common terminology for all relevant terms was established and eventually harmonized. The steps of this approach are illustrated in Figure 7.

Results

Movements

Constructional biosecurity aims at interrupting pathways of pathogen transmission by controlling the vectors that may spread them. Different from conventional veterinary terminology, we do not differentiate between animated vectors and inanimate fomites, but rather subsume them all under the term "vector", but differentiate between autonomously moving (e.g. aerosols) and not-autonomously moving (e.g. vehicles).

The matching of diseases to vectors and thus identifying hazard potentials therefore requires an examination of vector movements and characteristics.

Intended or desired movements are movements of potential vectors that are necessary, such as air, people, animals, consumable supplies (e.g. feed, bedding, pharmaceutical products), equipment (e.g. artificial insemination container), and certain vehicles.

Unintended or undesired movements (in the sense of external biosecurity: incursions) are movement of unwanted elements, such as contaminated aerosols, insects, rodents or wild animals.

To avoid unintended movements of autonomously moving vectors into a farm, i.e. to interrupt pathways of pathogen transmission in terms of external biosecurity, the physiognomy, types of locomotion and movement features of the vectors need to be assessed. The proposed framework distinguishes three locomotion types, namely walking (running), flying and swimming, and four specific movement features, namely climbing (e.g. goats, rats, geckos), digging (e.g. foxes), jumping (e.g. fleas, roe deer) and passive locomotion (e.g. tapeworms).

Constructional components of a farm

The emphasis of constructional biosecurity is the ability to **stop unintended** movements and to **control intended** movements. From this perspective, animal farms can be divided into three main components: **areas, barriers** and **locks** (Fig. 8 provides a schematic overview).

Area: The term **area** usually refers to a delimited space for a particular use or activity. **Functional areas** can be classified in two ways. (i) According to their dimensionality: buildings, other structures (e.g. shelters) or surfaces (e.g. car parking). (ii) According to their content: they can house animals (e.g. livestock barn, dog kennel) or animal sub-populations (e.g. according to their health, gender, age or reproduction status), store products (e.g. feed, bedding, eggs and equipment)

Photos: Ursula Gerdes

FIGURE 6: *Examples of locks. From left to right: (A) Dairy farm. The farm itself has no perimeter fence. Instead, the animals (directly behind the door on the left) can be accessed directly from the public road. (B) Hygiene lock in a turkey fattening farm. (C) Cattle farm: Barrier (brick wall, door on the right) and hygiene lock (behind the door on the left). (D) Turkey fattening farm: Trucks can collect and remove carcasses from the farm without trespassing the perimeter fence*

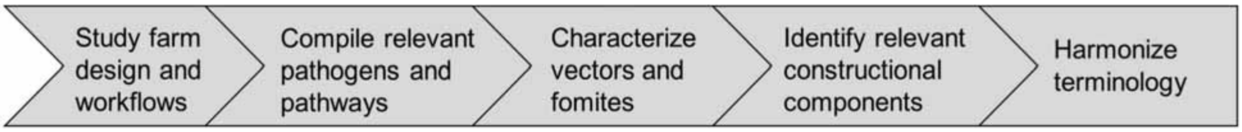


FIGURE 7: *Methodology: Working steps of the interdisciplinary approach to constructional biosecurity in animal farms.*

(Graphic: Carolina Probst)

or risk materials (e.g. carcasses) or harbor special-purpose processes (e.g. milking parlor). Individual functional areas can be grouped or combined. They may then form functional zones.

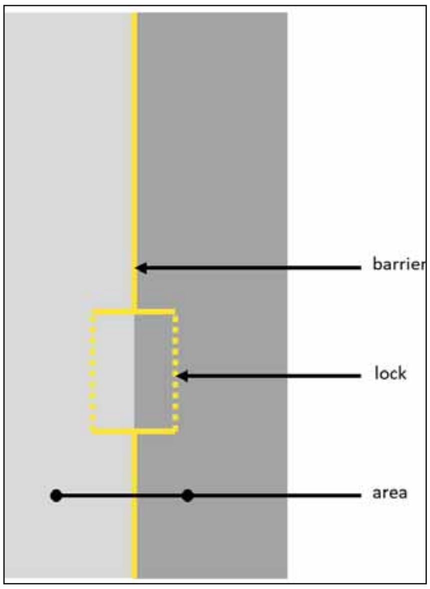
With respect to constructional biosecurity, areas need to be described and assessed according to their ability to provide a specific level of safety to its content. **Biosecurity areas** can be classified according to their hygienic level (e.g. "black and white" areas or epidemiological units), or according to their perceived biosecurity risk level: areas with increased risk usage (e.g. quarantine stable, calf kitchen) and areas with lower risk usage (e.g. social building).

Biosecurity areas may thus contain one or more functional areas and can be arranged independently or concentrically (Fig. 9).

Barrier: To control movement and prevent the unintended movement of specific vectors from an exposed ("black") to an unexposed ("white") area or between epidemiological units, biosecurity areas are separated from each other by barriers. Barriers remain fixed, once they are put in place, they function autonomously.

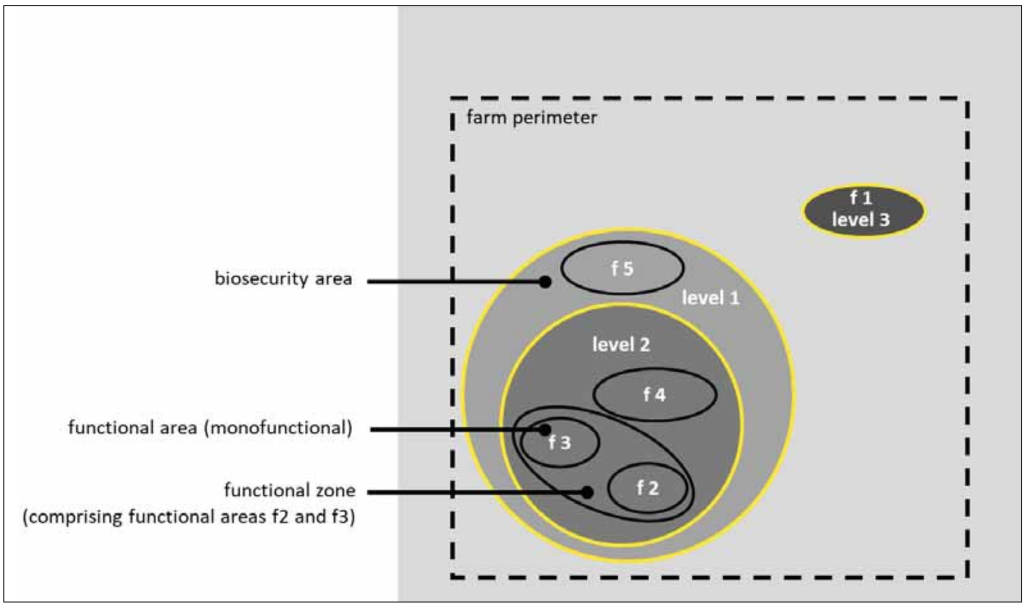
Barriers can be classified in two ways. (i) According to their position: horizontal (foundation, floor, ceiling) or vertical (wall). (ii) According to their materiality: visual (e.g. information sign that indicates the entry point to the farm), olfactory (e.g. repellent against wild boar) or physical (e.g. fence). Physical barriers are defined by their permeability and dimensionality. The permeability determines the size of the smallest vector prevented from crossing. Walls (made of stones, bricks, timber or blocks) have the lowest permeability, a single-wire fence the highest. The dimensionality (i.e. height, top and bottom) determines the type of locomotion prevented from crossing (Table 2).

Lock: An element in a barrier that can be opened and thus allows the controlled passage of selected vectors. This definition is broader than the traditional "hygiene lock" to cover the full range of lock types. Locks can be classified according to their features: They can be visual/virtual (e.g. line on the floor) or physical (e.g. locking



Graphic: Michael Bucherer

FIGURE 8: *Basic functional components of constructional biosecurity.*



Graphic: Michael Bucherer

FIGURE 9: *Possible arrangements of areas with different biosecurity levels: Independent, concentric.*

Graphic: Michael Bucherer

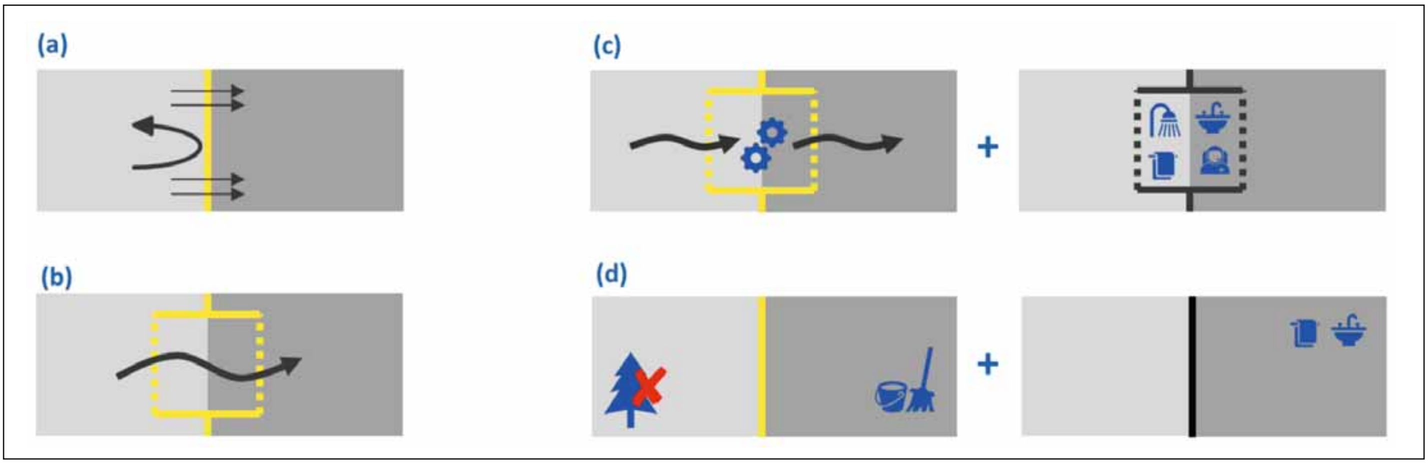


FIGURE 10: *Schematic overview of functional principles in animal farms. (a) Two areas with different biosecurity levels (lower level: light grey, higher level: dark grey) are separated by a barrier (yellow line). Depending on its permeability and framing, the barrier prevents certain vectors moving from one side to the other. (b) The barrier is interrupted by a lock (yellow box). Depending on its constructional elements, the lock allows the controlled passage of selected vectors. (c) The barrier is interrupted by a specific type of lock, namely a hygiene lock. The lock is equipped in such a way that particular lock-specific operational measures can be performed, e.g. washing hands, showering or changing protective clothing and shoes or boots. (d) Farm-specific management measures are implemented in various biosecurity areas.*

gate, hygiene lock). Opening devices can be doors, windows, shutters or similar. Closed locks usually have the same permeability as the corresponding barrier. Once the lock is activated – opened or penetrated – either a selection process (e.g. a chain that is opened by personnel but keeps visitors from passing) or a selection process in combination with certain operational measures that condition the vectors (e.g. by cleaning or changing clothes) takes place.

A special type of lock is the hygiene lock, which is a space integrated in the barrier. It contains specific equipment that helps ensure biosecurity compliance and allows performing specific operational measures. Another special type is the quarantine stable, which helps isolating and monitoring newly arrived animals over a certain period, before they join the rest of the herd or the target group in the animal farm.

While a barrier can interrupt infection chains physically, olfactory or visually, a lock can interrupt them physically, biologically or chemically (e.g. through disinfection) while still allowing physical access. The implementation of barriers and locks around defined areas, combined with operational measures, prevents the uncontrolled movement of selected vectors. To achieve an increased level of security biosecurity areas are usually not only protected by a single barrier, but by a sequence of areas and barriers with progressive biosecurity standards.

Measures

Operational measure: Specific biosecurity procedure performed at a lock to condition potential vectors with the aim of reducing the risk of pathogen introduction. Operational measures reduce the amount of infectious disease agents in or on a vector. They are sometimes laid down as standard operating procedures and may depend on the type of vector and the biosecurity level of the target biosecurity area.

Additional farm-specific management measure: Specific procedures performed in a biosecurity area with the aim of reducing the infection pressure on the premise as farm-specific management measures. Additional measures are also part of biosecurity plans, but in contrast to operational measures, they are not related to barriers or locks. They include the registration of visitors upon arrival, vaccination of animals, keeping areas clean and tidy, controlling the vegetation growth, measures to make the farm less attractive to wild birds and insects (e.g. by eliminating areas with standing water), rodent control, and discarding rubbish and debris in a timely manner. Similar to operational measures, additional measures may require special equipment (e.g. water supply) or constructional features (e.g. paved or sloped pathways).

Discussion

Building elements that support biosecurity measures are essential in the design of sustainable animal farms. Therefore, an interdisciplinary agreement on terms and definitions is necessary. The conceptual framework presented in this study aims overarching the two disciplines of architecture and veterinary epidemiology and hygiene. It considers three constructional elements (biosecurity areas, barriers and locks) that are crucial from a biosecurity perspective. The framework builds on the suitability of barriers and locks to prevent the uncontrolled movement of vectors, which may transmit pathogens between different biosecurity (black and white) areas or epidemiological units. While pathogens are characterized by the vectors that may spread them, vectors are described by their size or dimension and specific locomotion abilities.

The framework is neither species- nor disease- or context-specific. It applies equally well to different livestock sectors and equally well to small-scale producers and large commercial farms. In a future, it could also support human health, for example in infrastructures where many people come together. It can be integrated in the planning and design process of both existing and

TABLE 2: *Biological characteristics of the most relevant vectors which can move autonomously. Body size and type of locomotion of the most important autonomously moving vectors, by which pathogens can enter a farm. Vectors can spread pathogens either biologically via nasal secretions, saliva, blood, milk, faeces or urine, or mechanically via their feet or fur.*

Vector group	Vector species (selection)	Minimum vector size (approx.)		Vector type of movement / locomotion						
		Width (cm)	Height (cm)	Dig (cm)	Walk/crawl	Jump (cm)	Climb	Swim	Fly	Passive
Humans	Personnel	30	100							
	Stranger (obeyant)									
	Stranger (less obeyant)									
	Intruder					100				
Domestic animals	Dog (canidae)	20	40			60				
	Cat (felidae)	10	10			180				
Wild animals	Deer (cervidae)	30	60			220				
	Boar (suidae)	30	40	60		150				
	Fox (canidae)	20	30	60		180				
	Badger (mustelidae)	20	30	50						
	Marten (mustelidae)	5	10	50		180				
	Hare (leporidae)	5	20	30		100				
	Rabbit (leporidae)	5	10	30		100				
Rodents	Mouse (muridae)	2	2	100		30				
	Rat (muridae)	5	5	50		150				
Wild birds	Anseriformes	10	20							
	Larinae	10	10							
	Columbidae	5	5							
	Passeriformes	3	5							
Insects	Tabanidae	1.8	1.8							
	Muscidae	0.6	0.6							
	Culicidae	0.3	0.3							
	Culicoides	0.1	0.1							(wind)
	Acari	0.01	0.01							(host)
	Ixodida	0.1	0.1							(host)
Air	Droplet	<0.002	<0.002							
	Aerosol	0.002	0.002							(wind)

new farms and it may provide a good starting point for a set of building guidelines that combine both animal welfare and biosecurity management. Both subjects have been studied in isolation, but were so far not brought together.

Livestock farms are highly complex and variable in terms of size, animal species, production system, specialization, diversification, etc. (FAO 2018, Thorbeck 2017). For this reason, traditional attributes, for instance farm size or animal species, are not appropriate criteria for a holistic classification scheme. Yet, a holistic approach requires identifying the underlying principles of biosecurity, and definitions have to be based on fundamental principles and processes.

Our definitions are based on a scientific rationale and do not depend on definitions from remote fields. Whenever possible, we used conventional terminology to align with existing standards. However, on some occasions, we had to define terms slightly different to better fit with our objective. For example, veterinary literature usually differentiates between animated transmitters, called vectors, and inanimate carriers, called fomites. For our purposes, subsuming both under the term "vectors" and differentiating between vectors that can move autonomously (e.g. aerosols) and vectors that are passively moved (e.g. vehicles), is more relevant.

Many recommendations and checklists regarding operational biosecurity measures in animal farms are available. However, from our experience, prescriptive, itemized checklists often focus only on specific aspects (e.g. animal welfare) and do not consider constructional biosecurity in sufficient detail. On the other side, some checklists (e.g. QS) and vertical integrated companies consider the whole farm as one biosecurity area, where the level of hygiene measures increases towards the animals.

In our opinion, the evaluation of an animal farm from a biosecurity perspective should consider the following aspects:

(i) Configuration of biosecurity areas, barriers and locks. In principle, one could hypothesize, the more comprehensive the barriers and the lower the numbers of locks are, the lower is the risk of introducing a pathogen into a farm. Since areas, barriers and locks with completely different biosecurity levels may be mixed across the farm premise, the evaluation may involve several steps starting with each biosecurity area as an independent component. Then, the network of the different components can be analyzed to obtain an understanding of the interdependencies and of the performance of the complete system.

(ii) Optimized pathways. Not only areas, barriers and locks should be considered, but also the spatial layout and relation of the different components and spaces to each other. If possible, a one-way principle of different workflows should be implemented. From our experience, animal farms in Germany are often designed and constructed without considering this aspect. Especially in cattle holdings and farms that have grown over time, deficiencies in infrastructure design can impede or totally prevent the one-way principle of animal and human movements (e.g. starting daily work with the youngest animals and ending with the quarantine and sick stables). For example, the planning of a fattening farm may have included all mandatory requirements such as size, ceiling height, expected airflow from fans, a lock with a shower and a room for changing clothes, footwear etc. However, if the one-way corridor that leads to the shower loops back to the changing room with the street clothes, a certain risk of cross-contamination cannot be avoided. In the past, even large, industrial-scale breeding farms, which were perceived as maintaining a high level of biosecurity, experienced outbreaks of highly pathogenic avian influenza probably due to seemingly insignificant violations of the rules mentioned above (Conraths et al. 2016, Globig et al. 2018).

(iii) Operational measures. The proposed framework focuses on biosecurity management measures that require constructional elements to support their implementation. Purely functional characteristics of farms that contribute to general animal health, for example by providing adequate temperature, ventilation, moisture, lighting, drainage, non-slippery floors, or easy to clean surfaces are generally not considered within the framework, just as non-constructional features that improve the level of biosecurity, e.g. a shuttle cooler for semen to avoid that a courier has to enter a breeding farm. Likewise, drinking water and feed are assumed to be pathogen-free and safe when consumed. If the water supply comes from surface water (e.g. rivers, lakes or ponds), ingress into relevant biosecurity areas, which includes constructional conditioning procedures (e.g. filtering, treatment), will be assessed following the systematic approach of barriers and locks.

Conclusion

The proposed framework is currently used as the basis for the developing a classification system for farm biosecurity, which may provide architects, farmers and other stakeholders with a tool for improving biosecurity in the evaluation, planning and design of new farms.

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Ethical approval

The authors declare that no research interventions or experiment with animals or humans, neither clinical trials nor clinical research were conducted in the context of this study.

Conflict of interest

The authors declare that there is not conflict of interest.

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