Selected issues of risk management in livestock production

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Abstract

This article presents the findings of a review study conducted using the snowballing technique. Its primary goal is in-depth analysis of six important, in the author's subjective opinion, issues concerning risk management in livestock production. The starting point for consideration is the observation that livestock farmers are confronted with various risks that can ultimately (when they materialise) impair their economic and financial situation. However, the most serious threat lies in animal diseases and epidemics, which can also adversely affect the states' budgetary situation, as well as the supply of animal products and their quality and prices. In this context, both farmers and public authorities should have appropriate economic models in place to control animal health and diseases, an overview of which are provided in this article. However, for the models to be used effectively, all stakeholders should, at minimum, have general knowledge of the sources of risks, their perception and the attitudes of agricultural producers themselves towards them, so the article analyses these categories as well. We also present the formal aspect of production and price risk modelling to address, among others, the reasons for the low uptake of traditional insurance in livestock production. Following this, the practical and political recommendation that every country should have a holistic risk management system for livestock rearing and breeding, which is also the main conclusion of the analysis, is reliably documented. Of course, such system should be continuously improved, and it is also highly desirable that it is gradually supported by complex models of system dynamics.

Key words: economic models for livestock health and disease control, risk in livestock production, insurance in livestock production, risk management in livestock production.

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Introduction

It is estimated that an average of around 1.8 million livestock die each year in Poland due to diseases and epidemics, weather and environmental stress, accidents, as well as farmers' own mistakes[1]. If counted as LSUs, these deaths would account for over 23% of total livestock in June 2021[2]. The percentage is obviously overstated, yet we must bear in mind that animal deaths also occur in transportation to slaughterhouses and while waiting in lairage. If the figure could be reduced, it would result, for example, in increased commodity livestock production, which in 2021 amounted to more than PLN 59 billion, accounting for some 59% of the total commodity production of Poland's agriculture. Alternatively, therefore, less livestock could be kept in order to earn that PLN 59 billion, which is compounded by substantial budget savings on compensating farmers for diseases that are subject to ex-officio eradication. In this context, most researchers now emphasise that for the economic, environmental and climatic assessment of livestock rearing, control of their health and diseases, as well as welfare, is fundamental[3].

In addition to the risk of animal diseases and injuries, farmers are also faced with other price and production risks, collectively referred to as business or economic risks, as well as financial, property, personal, political and regulatory risks. They can be grouped into: internal vs. external; operational vs. strategic; chained vs. networked, etc. Accordingly, agricultural producers must be equipped with specific tools and strategies to manage risks and threats, uncertainty and ambiguity. Essentially, this can be reduced to risk control (avoidance, prevention, reduction) and financing (retention, insurance, non-insurance transfer). Thus, the measures can be active, but also passive. The selection is not a trivial issue, as it is determined by the type of risk (frequency and magnitude of losses), its perception and attitude towards it, as well as the technical and production, as well as economic and financial characteristics of farms and the state of their environment. It is undisputed that first the COVID-19 pandemic, followed by the war in Ukraine, have led to a huge increase in the uncertainty and

1. A. Sowa, *Zwierzę przemysłowe*, "Polityka" 2021, nr 20, pp. 21–24.
2. GUS, *Rocznik Statystyczny Rolnictwa*, Warszawa 2022, p. 164.
3. A.D. Hennessy, L.T. Marsh, *Economics of animal health and livestock disease* [in:] *Handbook of Agricultural Economics*, Vol. 5, ed. Ch.B. Barett, D.R. Just, Amsterdam, Elsevier, 2021, pp. 4233–4330; D. Läpple, W.O. Osawe, *Concern for animals, other farmers, or oneself? Assessing farmers' support for a policy to improve animal welfare*, "American Journal of Agricultural Economics" 2023, Vol. 105(3), pp. 836–860; A.K. Schaefer, P.D. Scheitrum, S. van Winden, *Returns on investment to the British bovine tuberculosis control programme*, "Journal of Agricultural Economics" 2022, Vol. 73(2), pp. 472–489; E.A. Weyori, *Returns to livestock disease control – a panel data analysis*, "European Review of Agricultural Economics" 2020, Vol. 47(2), pp. 654–683.

risk of agricultural operations. It is even said and written that the world has entered a polycrisis/multi-crisis era. A response to this should come in the development of a holistic/integrated approach to risk management, both at the level of individual farms and the entire agricultural sector and agribusiness. However, materialisation of the above systemic risks already shows that the holistic approach is going to become less and less applicable over time with regard to the evolving uncertainty and risks inherent in livestock rearing and breeding. Therefore, an attempt should be made to support this branch of agricultural production also with a risk management tool based on the philosophy of complex system dynamics.

In the above context, the primary purpose of this article is to undertake an in-depth analysis of six issues, that are important in the author's opinion, concerning risk management in livestock production, so that they can subsequently be seamlessly incorporated into a holistic view of the problem, which, in the process, is constantly evolving. This would provide other researchers with a reference point for their own analyses, and insurers with support for designing their products. Agricultural policy makers, in turn, can use this article as an aid in the construction of relevant programmes and in their evaluation. The considerations presented can also be applied in consultancy and in the self-education of agricultural entrepreneurs. They may also be of interest to veterinary services, by confronting, for example, the epidemiological models they use with economic models for animal disease and health control. To the best of the author's knowledge, the article is an original work, as no other text structured in an identical way could be found.

The selection of the six areas for in-depth analysis was based on two criteria: (1) their socio-economic importance for Polish agriculture, where the problem of ASF is still unresolved and the bird flu epidemic periodically recurs, (2) the transfer of risk from agriculture to the financial market, mainly through traditional insurance – its ex-post evaluation must be carried out by the Ministry of Agriculture and Rural Development in 2024. The latter is designed as theory-based evaluation. The article fits into this approach. This should then be supplemented with further justification, namely that in Poland the public authorities have so far not officially communicated how they intend to holistically (comprehensively) manage risk in livestock production.

The applied research method

The author of the article used the hand-searching method, also referred to as the snowballing method, which is also classified as systematic review[4]. This is a manual technique for searching through various resources, pre-defined and selected peer-reviewed articles, conference papers and unpublished material. For researchers who have a good level of knowledge of the issue, hand-searching can be a more effective method than online techniques. The author has already been dealing with the issues covered in the article, with varying intensity, for more than ten years, and is quite familiar with them.

Detailed use of the snowballing method, in turn, involved ongoing research into twelve English-language and two German journals. A prerequisite was that these would be titles with an impact factor and at least 70 points in a rating by the Ministry of Education and Science (MEiN). These were journals that are published, among others, by: Elsevier, Oxford University Press, Springer/SpringerGabler and Willey. Each text of interest to the author of the article is recorded on an ongoing basis and briefly characterised, which considerably simplifies its later use. However, this is not done without reflection or automatically, thanks to the knowledge and observations of reality gathered by the author, as well as the integration of other sources of information. This means that the article has the qualities of a critical systematic review. Last but not least, the snowballing technique used as described above allows the most up-to-date information to be incorporated much more quickly than is the case with online techniques of systematic review.

As already indicated, the range of issues related to risk management in livestock production is constantly evolving, which is reflected in their overview summarised in Table 1. The areas of research explored in more depth in this article are highlighted in bold.

4. B. Craane, P.U. Dijkstra, *Methodological quality of a systematic review on physical therapy for temporomandibular disorders: influence of hand search and quality scales*, "Clinical Oral Investigations" 2012, Vol. 16(1), pp. 295–303; F.D. Polman, H.P.M. Selten, N. Motowska et al., *A risk governance approach to mitigating food system risks in a crisis: Insights from the Covid-19 pandemic in five low – and middle – income countries*, "Global Food Security" 2023, Vol. 39, p. 100717.

Table 1. Main areas of research on risk management in livestock production

Research area	Representative researchers
Economic modelling of disease control	**J.P. McInevrey et al. (1992), A.D. Hennessy and L.T. Marsh (2021)**
Sources and types of risk, and perception of risk by farmers	**P.M. Meuwissen et al. (2021), A.K. Abay et al. (2019)**
Price and production risk	**G.C. Turvey (2003), E.M. Skidmore (2023)**
Traditional insurance	**S. Shaik et al. (2006), P. Liu et al. (2021)**
Index-based insurance	V. Bertram-Huemmer et al. (2018), F.E. Nordmeyer and O. Musshoff (2023)
Biosecurity, self-insurance and self-protection	O. Rat-Aspert and C. Fouridon (2010), T. Kompas et al. (2019)
Animal vaccination	L.A. Ugochukwu and W.P. Phillips (2019); J. Soak and J.A.E. Fischer (2020)
Budget compensation for emergency slaughter	B. Gramig et al. (2009), A.P. Barness et al. (2015)
Evaluation of government risk management programmes	T. Wang and A.D. Hennessy (2015), A.K. Schaefer et al. (2022)
Risk vs. animal welfare	E. Owusu-Sekyere et al. (2022), D. Läpple and W.O. Osawe (2023)
Animal health vs. trade	B.J.W. Zongo and B. Laure (2019), M.S. Ferguson (2023)
Animal health vs. public health	D. Heady (2018)
Animal diseases vs. economic and social welfare	R.P. Tozer et al. (2015), R.M. Benett et al. (2019)
Holistic risk management	**O. Melyukhina and W. Yoon (2015)**
Complex system dynamics and risk management	**R. Sarker et al. (2022), F.D. Polman et al. (2023)**

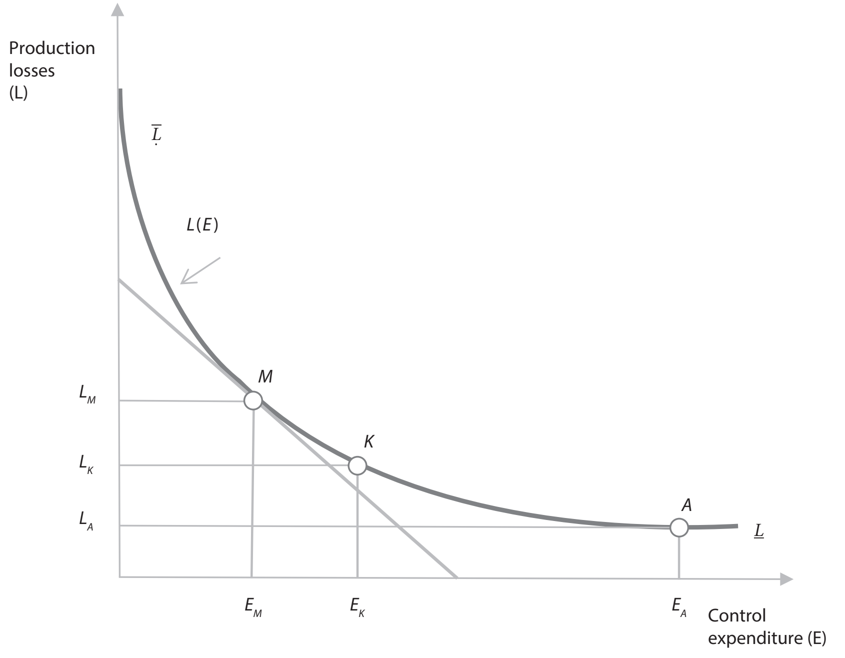
Source: Own elaboration.

Economic modelling of animal health and disease control

Virtually all researchers dealing with the above issues refer to the 1986 work by E. Lichtenberg and D. Zilberman, despite its subject being the optimisation of the use of plant protection products to control diseases and pests in crops[5]. It is noteworthy, however, that these two American agricultural economists introduced the concept of the damage function that is used in catastrophic risk modelling, which denotes the ratio of the expected cost of repairing the damage to the replacement value of the relevant asset. D.J. Panell, in turn, adopted the reasoning of E. Lichtenberg and D. Zilberman to modelling the optimum use of herbicides for weed control in fields[6], while R.M. Benett and G.Y. Miller addressed the estimation of direct damage caused by animal diseases, and A.A. Dijkhuizen constructed a model for optimising government programmes to combat animal disease epidemics[7]. More sophisticated models authored or co-authored by P.J. McInerney were published in 1992 and 1996[8], and their essence is illustrated in Figure 1.

5. E. Lichtenberg, D. Zilberman, *The econometrics of damage control – Why specification matters*, "*American Journal of Agricultural Economics*" 1986, Vol. 68(2), pp. 261–273.
6. D.J. Panell, *An economic response model of herbicide application for weed control*, "Australian Journal of Agricultural Economics" 1990, Vol. 34(3), pp. 223–241.
7. R.M. Benett, *The use of economic quantitative modelling techniques in livestock health and disease-control decision making. A review*, "Preventive Veterinary Medicine" 1992, Vol. 39, pp. 155–171; G.Y. Miller, C.P. Bartlett, E.S. Lance et al., *Costs of clinical mastis and mastis prevention in dairy herds*, "Food Animals Economics" 1993, Vol. 202(8), pp. 1230–1236; A.A. Dijkhuizen, M.B.R. Huirne, M.W. Jalvingh, *Economic analysis of animal diseases and their control*, "Preventive Veterinary Medicine" 1995, Vol. 25, pp. 135–149.
8. J.P. McInerney, K.S. Howe, J.A. Schepers, *Framework for the economic analysis of disease*, "Journal of Agricultural Economics" 1992, Vol. 47(3), pp. 137–154; J.P. McInerney, *Old economics for new problems – Livestock disease: Presidential address*, "Journal of Agricultural Economics" 1996, Vol. 20, pp. 173–179.

Figure 1. Graphical determination of the optimum animal disease control



Source: Presented on the basis of: J.P. McInerney, S.K. Howe, A.J. Scheper, A framework for the economic analysis of disease in farm livestock, "Preventive Veterinary Medicine" 1992, Vol. 47.

It can be seen that expenditure (E) to prevent the disease and/or mitigate its adverse effects results in a reduction of losses in production and income-generating potential (L). However, the total resulting loss, *C*, is the sum of *E* plus *L*. Figure 1 also shows the efficiency limit, $L(E)$, indicating the interchangeability (substitutability) between expenditure and losses. Correspondingly, with no control whatsoever ($E = 0$), the loss reaches a maximum $\overline{L}$. However, it must be noted that the increase of expenditure does gradually reduce losses, but only up to a limit $\underline{L}$, which means that the expenditure brings decreasing efficiency. The optimum control of the *C* parameter value is one for which a further increase in expenditure by a unit results in a decrease in loss lower than unity. In other words, this bioeconomic model assumes that the risk of disease is not completely eliminated, and/or does not seek its complete elimination, as seen from a private-economic perspective. With transition to the determination of the social optimum of control, the efficiency limit will move, although upwards. The implementation of new technology and various government programmes for livestock producers, on the other hand, may push this limit downwards.

The work of J.P. McInerney was referred to by G. Fox and A. Weersink, and by J. Chi et alia[9]. Their basic premise was that they could not be modelled in the same way that input-output relationships are modelled in traditional agricultural production economics, since in the case of diseases the function of these inputs is to control the level of damage, not to increase the production output. However, again there is a correlation in that the optimum for controlling animal disease is determined by the point at which the marginal costs incurred become equal to the marginal benefits gained, although this does not fully illustrate the problem. The primary focus of farmers are direct costs. The situation becomes much more complex when farmers' decisions are constrained by relevant administrative regulations, if public health and the interests of the entire industry in livestock production are at stake. In the cost-effectiveness calculus of prevention and cost control, this gives rise to new costs, but on the benefit side we can see government compensation and disaster relief payments. The decisions are further complicated by the purchase of livestock insurance by farmers.

Building mainly on the work by E. Lichtenberg and D. Zilberman (1986), and J.P. McInerney (1996), A.D. Hennessy and L.T. Marsh proposed what is essentially a system of animal health and disease economics, highly formalised and described in as many as 96 pages of text[10]. Here, we will only briefly outline the key elements of this construct. First, A.D. Hennessy and L.T. Marsh present their baseline model, then extend it to include the problem of externalities and farmers' reporting of diseases to government institutions and other stakeholders. The next section covers public management of animal diseases and their implications for international trade in animals and animal products. The final section looks at estimating social welfare through producer and consumer surpluses, budget expenditure, impact on food chain actors, and willingness to pay and risk reduction opportunities.

In the last decade, the economic modelling of animal health and disease control was also addressed by other researchers[11]. All these studies are highly formalised and often supported by various types of simulation.

9. G. Fox, A. Weersink, *Damage control and increasing returns*, "Journal of Agricultural Economics" 1995, Vol. 77, pp. 33–39; J. Chi, A. Weersink, J. VanLeeuwen et al., *The Economics Controlling Infectious Diseases on Dairy Farms*, "Canadian Journal of Agricultural Economics" 2002, Vol. 50(3), pp. 237–256.
10. A.D. Hennessy, L.T. Marsh, op. cit.
11. J.M. MacLachdan, R.M. Springhorn, L.P. Fackler, *Learning about a moving target in resource management: optimal Bayesian Disease Control*, "American Journal of Agricultural Economist" 2017, Vol. 99, pp. 140–162; A.D. Hennessy, A.Ch. Wolf, *Asymmetric Information Externalities and Incentives in Animal Disease Prevention and Control*, "Journal of Agricultural Economics" 2018, Vol. 69, pp. 226–242; E.A. Weyori, S. Liebenehm, H. Weibel, *Returns to livestock disease control – a panel data analysis in Togo*, "European Review of Agricultural Economics" 2020, Vol. 47, pp. 694–683.

Sources of risk and its perception by farmers

Some of the first advanced research on risk perception and management strategies in livestock production in Europe was conducted by M.P.M. Meuwissen, R.B.M. Huirne and J.B. Hardaker[12], becoming, so to speak, a standard in this area, and referred to by subsequent researchers. Let us, therefore, take a closer look at them.

P.M. Meuwissen et al. constructed a survey form that contained as many as 121 different variables and sent it to 2,700 farms in October 1997. A total of 612 forms were returned, with 59% of farms classified as dairy, 28% as pig farms and the rest as mixed. The authors of the article admit that they embarked on the task of identifying risk perception and handling strategies, although previous researchers had stressed that these categories are so strongly differentiated and highly dependent on the socio-economic characteristics of farmers, their farms and local conditions that it is difficult to be precise and objective. Consequently, one should avoid over-generalisations.

Conclusions about attitudes to risk were made on the basis of ranking of farmers' ratings of the sentence: "I am willing to accept higher risk than others with regard to: production, sales, finance and overall farming", ranked on a five-point Likert scale, with "1" indicating strong disagreement and "5" indicating strong agreement. It can be seen that the issue at stake was relative risk aversion.

P.M. Meuwissen et al. put forward 23 sources of risk for farmers to assess, six of which related directly to livestock production. Factor analysis was then applied to reduce this set to five groups: "family health", "financial situation", "legislation", "production", and "changes in the farm's standing". The same approach was used for the risk management strategy, with the starting point being a thirteen-element set, which was reduced by factor analysis to four groups: "price risk reduction", "purchase of property and personal insurance", "diversification", and "reliable income".

The entire analysis can be summarised as follows:

1. Price and production risks ranked as significant in all three farm groups, but the former was of greatest concern in dairy-type farms.
2. Insurance ranked quite low in risk management strategies. Interestingly, a closer look at preferences for this instrument revealed that farmers found that insurance rates and premiums did not reflect actual individual risks very accurately.

12. P.M. Meuwissen, M.R. Huirne, B.J. Hardaker, *Risk and risk management: an empirical analysis of Dutch livestock farmers*, "Livestock Production Science" 2001, Vol. 69, pp. 43–53.

In other words, farmers were convinced that they were subsidising other producers in this way.

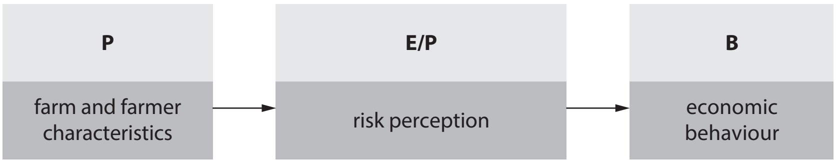
3. The relationship between insurance and legislation suggests that the former can be a substitute for withdrawing subsidies from certain agricultural activities. For insurers, an opportunity also arises to reduce price risk, for example in the form of revenue or surplus insurance, as farmers ranked futures low.

A very interesting study of risk perception, risk sources and risk management strategies was conducted on 363 conventional and 162 organic farms in Norway by O. Flaten et alia[13]. It should be explained that the Norwegian study was modelled on the 2001 survey by P.M. Meuwissen et al., which has already been commented here, with the source data collected in early 2003 through a dedicated questionnaire. The risk was identified on the basis of farmers' declarations regarding the indicative sentence: "I am willing to accept higher risk than others with regard to: (1) production; (2) marketing, finance and investment", with "1" on a seven-point Likert scale indicating strong disagreement and "7" indicating strong agreement. As for the sources of risk, initially there were as many as 33, but during the factor analysis this set was reduced to six categories. Of the 33 sources specified, ten explicitly referred to livestock production (including prices, disease risk, and public policy). In the case of risk management strategies, in turn, 25 were identified in the survey, to be later reduced to six groups in the factor analysis. Of the specific strategies, only two were directly related to livestock production, i.e. prevention of animal diseases and mitigation of their effects, use of veterinary services and consultations.

In the conceptual layer, O. Flaten et al. drew on the descriptive approach. In the first instance, they were looking for inspiration in behavioural microeconomics, namely in its assumption that in order to understand people's decisions under risk and uncertainty, it is necessary to refer to their perception of these categories. These requirements are accommodated by the model of F.W. van Raaij presented in an article titled "Economic psychology" published in the Journal of Economic Psychology, issue 1 of 1981. Its essence is presented in Figure 2.

13. O. Flaten, G. Lien, M. Koesling et al., *Comparing risk perceptions and risk management in organic and conventional dairy farming: empirical results from Norway*, "Livestock Production Science" 2005, Vol. 95, No. 1–2, pp. 11–25.

Figure 2. Decision-making in the van Raaij model



Source: Elaborated on the basis of: O. Flaten., G. Lien, M. Koesling et al., Comparing risk perceptions and risk management in organic and conventional dairy farming: empirical results from Norway, "Livestock Production Science" 2005, Vol. 95, No. 1–2, pp. 11–25.

The **P→E/P** component represents the impact of farm and farmer characteristics (**P**) on risk perception (**E/P**). The relationship **P→E/P→B**, in turn, reflects how **P** and **E/P** combined affect the economic behaviour of the agricultural producer, which is embodied in risk management strategies. The statistical analysis of the survey information was also governed by the above logic.

Let us summarise the main conclusions and recommendations of O. Flaten et al.:

1. Farmers on organic farms had, on average, lower relative risk aversion than those involved in conventional production. In the former group, the distribution of aversion was also more even. Organic farmers ranked institutional risk highest, while conventional farmers were concerned about purchase input prices and animal welfare.
2. Interestingly, the preferences of both groups of farmers regarding risk management strategies were very similar. In line with the above, all farmers, on average, considered financial strategies (focused on liquidity and cost management), prevention of animal and plant diseases, and purchase of business and personal insurance to be the most effective.
3. Among the farm and farmer characteristics, only the number of cows kept was related to livestock production. This variable was negatively correlated only with production and institutional risk, while the increase in cow herd size encouraged the purchase of insurance and a reduction in unit fixed costs.
4. The high importance attached to institutional (or: policy) risk by both groups of farmers can be seen as somewhat of a paradox. In fact, this should be interpreted as viewing changes in agricultural policy and sector regulation as a risk with long-term effects, whereas interim and annual fluctuations in primary natural and economic-financial categories are generally easier to absorb through internal and external risk management instruments. These correlations can also be interpreted to mean that it is institutional risk that is likely to lead to farm bankruptcy sooner. In this context, the issue of stability and predictability of agricultural policy and

of all socio-economic policy, in the part relating to the agricultural sector, is of paramount importance.

A key issue in understanding farmers' strategies to prevent and manage livestock diseases is the perception of the risk they pose. Foreign studies clearly show that this risk is handled differently for endemic diseases than for epidemics[14], with the former considered operational risk, and the latter falling into the category of catastrophic risk, i.e. one that is rare but has serious, even existential, negative consequences for individual farms, their regional groupings, and sometimes those with a global reach. Examples of the latter are ASF or bird flu.

However, the perceived risk, understood as the probability of a livestock disease, may in fact be under- or overestimated, as it may be subject to the psychological deformations of people's assessments and judgements[15]. This involves the farmers' use of various heuristics, the rejection of certain mechanisms, as well as highly individualised specific evaluation processes and the plasticity of human brains. However, heuristics are crucial here, especially for the perception and measurement of catastrophic risk. It appears that when dealing with such existential events, farmers for the most part try to use examples of past reactions and behaviour. The damage experienced determines the selection of strategies to prevent them in the future and to deal with such risk once it has materialised. Obviously, cognitive processes and behavioural responses are largely shaped by farmers' innate attitudes towards risk, self-protection and precaution. Certain other variables influencing farmers' behaviour are generally not directly observable from the outside, and their impact is also very often not fully recognised by the farmers themselves.

A very interesting tool for analysing the correlation between farmers' perceptions of animal disease risk and their preference for prevention and handling instruments and strategies is "The Health Belief Model' (HBM)[16], which is a socio-psychological model describing changes in people's behaviour towards diseases. Conceived in the 1950s in the US Public Health Service, it refers specifically to the ways in which health services are used, and is also used in health education. The model's focal point is the individual's perception of the disease, which also influences preventive measures. Perception is understood twofold here: (1) susceptibility to disease, specifically as

14. O. Flaten, op. cit.; J. Jansen, B.H.P. Van den Borne, R.J. Renes et al., *Explaining mastitis incidence in Dutch dairy farming: The influence of farmers' attitudes and behaviour*, "Preventive Veterinary Medicine" 2009, Vol. 92(3), pp. 210–223.
15. N.I. Valeeva, T.J.G.M. Lam, H. Hogeveen, *Motivation of Dairy Farmers to Improve Mastitis Management*, "Journal of Dairy Science" 2007, Vol. 90, pp. 4466–4477.
16. N.I. Valeeva, M.A.P.M. van Asseldonk, G.B.C. Backus, *Perceived risk and strategy efficacy as motivators of risk management strategy adoption to prevent animal diseases in pig farming*, "Preventive Veterinary Medicine" 2011, Vol. 102, No. 4, pp. 284–295.

the probability of contracting the disease; (2) and the severity of the disease's effects. By combining these two perceptions, we obtain the potential risk of disease; thus, the category of perceived risk emerges. In order to take appropriate action, an individual needs to also have an idea of the benefits they can expect, i.e. of the effectiveness of the measures taken to reduce the aforementioned risk of contracting the disease. They then compare these with the perceived monetary and psychological costs of taking appropriate action. All these categories can be moderated by certain indications of the direction and type of disease management procedure, as well as socio-psychological, demographic and structural variables. Overall, however, it can be assumed that a higher level of perceived risk of disease, combined with significant expected benefits from adopting desired behaviours, will be a strong motivator to take care of one's health and seek professional treatment when an individual becomes ill.

When transposing HBM into the field of livestock disease treatment, it is basically only necessary to incorporate strategies to manage this risk at some point. This was done by N.I. Valeeva et al., who designed a research programme for Dutch fattening pig producers[17]. The survey sample comprised 164 farms, with farmers asked to share their views on the effectiveness of biosecurity strategies and participation in animal health programmes. Porcine respiratory disease complex (PRDC) was adopted as an endemic disease, while classical swine fever (CSF) was an example of an epidemic. The information collected was transformed into structural modelling (SEM) equations, which is an advanced regression calculation that allows to investigate the direct and indirect effects of specific independent variables on the dependent variables (severity of effects of both diseases; susceptibility to disease; effectiveness of on-farm protection; animal health index). Consequently, SEM allows causal relationships between different variables to be quickly established. In general, N.I. Valeeva et al. concluded that biosecurity is definitely a more effective strategy for dealing with both types of diseases than participation in animal health promotion programmes. Regrettably, there is a significant issue with this strategy in Poland when it comes to tackling ASF.

The perception of participation in mandatory animal health checks, the acceptance of compensation for emergency slaughter of animals, and the impact of weather conditions on the decisions of agricultural producers were explored by several other researchers in the previous decade of this century[18].

17. Ibidem.
18. A.K. Abay, D.N. Jensen, *Access to markets, weather conditions on dairy production*, "Agricultural Economics" 2019, Vol. 50, pp. 165–175; W. Gilbert, J. Rushton, *Incentive Perception in Livestock Disease Control*, "Journal of Agricultural Economics" 2018, Vol. 69, No. 1, pp. 243–261; J. Madizimure, M. Chimonyo, K. Dzama et al., *Classical Swine Fever Changes the Way Farmers Value Pigs in South Africa*, "Journal of Agricultural Economics" 2015, Vol. 66, No. 3, pp. 812–831; A.J. Perez-Mendez, D. Rosbes, A. Wall, *The influence of weather conditions on dairy production*, "Agricultural Economics" 2019, Vol. 50, pp. 165–175.

The issue of production and price risk

Livestock production is exposed to disease epidemics, which, being systemic, create a serious threat, the most obvious manifestation being the drastic fall in the price of products sold. The market sometimes even collapses completely and price quotations are stopped[19]. Therefore, it is vital to take a closer look at the risks faced by livestock farmers. An interesting approach to the issue is presented by C.G. Turvey, who distinguishes the following types of risk:

- production risk;
- price risk, both on the side of the products sold and the inputs purchased, in particular feed;
- catastrophic risk.

Production risk arises from the possibility of various pathogens and environmental hazards. C.G. Turvey models it using a simple example of corn-fed fattening pigs. The net revenue *R* per LSU can be expressed with a simple formula:

$$R = \theta p - \omega f,$$

where: p – price obtained per pound of fattening pig, f – price of one pound of corn, θ – weight of fattening pig in pounds, ω – quantity of corn fed.

If we consider *R* in the convention of expected value, then, after applying an exact differential equation, we obtain the impact of all sources of risk on this parameter.

$$dR = \theta\, dp + p\, d\,\theta - \omega\, df - f\, d\,\omega.$$

Assuming that $d\theta=0$, $d\omega=0$, *adp i df* are random variables with expected values equal to zero, and standard deviations σ_p and σ_f and covariance σ_{pf}, the variance of net revenue will be:

$$VAR\left(dR\right) = \theta^2\sigma_p^2 + \omega^2\sigma_f^2 - 2pf\sigma_{p,f},$$

and its joint distribution, or expected value, will amount to:

$$E\left(R\right) = \iint\left[\theta p - \omega f\right]g\left(p, f\right)dp\, df,$$

where: g(·) is the joint distribution of fattening pig and corn prices.

19. G.C. Turvey, *Conceptual Issues in Livestock Insurance*, The State University of New Jersey RUTGERS, May 2003.

The formal approach outlined above referred to a situation where the risks did not lead to the premature death of the fattening pig. Yet, in reality, the animal's potential death should be taken into account. A more general specification of the expected value is therefore needed, with the requirements met by the following notation:

$$E(R) = \begin{cases} \iint [\theta p - \omega f] g(p, f)\, dp\, df & tening\ pig\ survival = 0 \\ 0 & death = 1. \end{cases}$$

When insuring the production risk in livestock production, three aspects of the risk should be covered in each case:

– frequency, i.e. the probability of a risk event, particularly a disease, in a given period;
– duration, i.e. the length of time over which a risk has an adverse effect on the animal's health;
– intensity, i.e. the severity of the adverse impact in relation to its duration.

Frequency and intensity represent randomness, i.e. they should be modelled as random variables. In fact, however, considered indirectly, duration is also random, as it depends on stochastic factors. Hence, the following loss function can be proposed, which directly relates to the previous presentation of expected net revenue:

$$V(f, \lambda, \beta) = 1000 f(t) \int \lambda^{(-\beta)} g(\lambda) d\lambda,$$

where: $f(t)$ is the probability of risk, equivalent to the frequency aspect; λ represents duration, and its probability density function is $g(\lambda)$, usually corresponding to a negative exponential or gamma distribution; $\lambda^{-\beta}$ represents the intensity aspect, with $\beta = 0$ usually assumed to mean no loss from a pathogen outbreak, $\beta = 0.5$ shows moderate intensity, and $\beta = 2$ is equivalent to high intensity. It follows that the insurance premium rises as the parameter β increases.

It is further evident from the loss function that the insurance premium rises when the risk occurs more frequently, lasts longer, and has a more intense negative impact on the animals. This also shows the importance of prevention in livestock production, i.e. ensuring optimum rearing and breeding conditions and proper veterinary care, including vaccination. In this context, it is also worth noting that some rearing systems focused on deep ecology may, paradoxically, be riskier and consequently imply higher insurance premiums than traditional systems. This conclusion is becoming increasingly common when comparing cage and free-range rearing of poultry in the context of bird flu.

When modelling price risk, C.G. Turvey assumed that no production risk would be involved, which allowed him to focus on the time path of changes in net revenue and match it with more sophisticated revenue insurance products, i.e. standard and exotic option contracts. The latter allow for a combined reflection of the product's price risk distribution. In general, their payouts do not depend on the prices of the product sold or the input purchased on a particular date, but are derived from averaging (arithmetically or geometrically) their value over a given period of time. Hence, such contracts are referred to in financial engineering as path-dependent options.

The starting point of this part of the considerations is, again, the formula for the expected value of net revenue:

$$E(R) = \iint [\theta p - \omega f] g(p, f)\, dp\, df,$$

although the difference is now that θ and ω are constants. Assuming further that p and f are consistent with the correlated geometric Brownian motion, we obtain two differential equations:

$$df = \alpha_f f dt + \sigma_f f dw_f$$

$$dp = \alpha_p p\, dt + \sigma_p p\, dw_p,$$

where: α_f and α_p are drift rates; σ_f and σ_p symbolise the volatility of corn and beef livestock prices; dw_f and dw_p are Wiener processes, i.e. so-called random walk over the time from t = 0 to T (when the option expires).

Covariance between maize and livestock prices will amount to:

$$\text{cov} = \rho \sigma_f \sigma_p.$$

By applying Itô's lemma now, one finally arrives at the change in net revenue:

$$dR = \left(\theta \alpha_p p - \omega \alpha_f f\right) dt + \theta \sigma_p p dw_p - \omega \sigma_f f dw_f$$

and its expected value will be equal to, for the particular T moment selected, such as, for example, the option expiry date:

$$E(dR) = \left(\theta \alpha_p p - \omega \alpha_f f\right) T,$$

while covariance:

$$VAR(R) = \left(\theta^2 f^2 \sigma_f^2 + \omega^2 p^2 \sigma_p^2 - 2\theta\omega f p \rho \sigma_f \sigma_p\right) T.$$

It is worth noting that stabilising corn consumption virtually eliminates the moral hazard in the option contract that is so widespread in traditional insurance, which should imply a lower cost of net revenue protection. In turn, the positive correlation of maize and livestock prices should reduce the total variance. Symmetrically, a negative correlation will push the variance even higher. As usual, the compensation function/ rule will, of course, be described as:

$$E\left\{MAX\left[0, X - R(T)\right]\right\},$$

where: X refers to actual net revenue.

To analyse catastrophic risk, i.e. an event that is unlikely but has strong negative consequences, C.G. Turvey uses the poisoning probability model. This risk can lead to a sudden, steep drop in the price of an agricultural product. This is reflected in the following stochastic partial differential equation:

$$\frac{dp}{p} = \alpha_p dt + \sigma_p dw_p - dq,$$

where: $dq = \begin{Bmatrix} 0 & probability = 1 - \lambda\, dt \\ \theta & probability = \lambda\, dt \end{Bmatrix}.$

It can be seen that the occurrence of an event with a probability of λdt leads to a loss of θ_p. In the opposite scenario (probability 1-λdt), the price path follows the Brownian motion equation. Hence:

$$\frac{dp}{p} = \left(\alpha_p - \lambda\theta\right)dt + \sigma_p dw_p,$$

whereby the drift of the price process is:

$$E\left(dp\right) = \left(\alpha_p - \lambda\theta\right) p\, dt.$$

Under normal market conditions, the average price change equals α_p, while with catastrophic risk a factor of $\lambda\theta$ – a steep downward drift – is involved. For complete modelling, we also need variance:

$$VAR\left(dp\right) = \left[p^2\sigma_p^2 + p^2\theta^2\lambda\right]dt.$$

Its first term describes the instantaneous impact of normal price processes, while the second one indicates the additional impact of a probable price shock.

Production and price risk modelling was also explored by C.E. Hart et al., who applied the concept of profit risk[20]. This technique focuses on the activities that make the greatest contribution to net profit generation, a concept that was later applied by J.E. Belasco et al. to simulate the variability of cattle feeding profits in Nebraska and Kansas[21]. In a sense, this research was continued by S.G.M. McKendree et al., who expanded the research sample to include farms from Iowa and Texas, but at the same time included profit as a stochastic category, which allowed them to progress to utility maximisation[22].

Traditional insurance in livestock production

At the outset, it is worth noting that private livestock insurance tends to be expensive and is most often structured on the basis of the specialisation principle, so it only protects against named risks[23]. This may be due to the complexity of the disease process, but it may also be a consequence of the lack of adequate demand, which in turn is due to information asymmetry and its consequences in the form of adverse selection and moral hazard. In the case of epidemics, however, a very important factor comes into play, i.e. the systemic dimension of such risk. The infection transmission rate plays a substantial role here, and is compounded by interim effects, and at the level of the specific livestock production and processing sector depends on the speed of disease outbreak disclosure and the ability to trace the disease back to its source. For farms, these effects can be manifested in a drop in the prices obtained, and the time and financial expenditure involved in herd recovery or total production restructuring. In contrast, for example, to drought, which is practically uncontrollable, some

20. C.E. Hart, A.B. Babcock, J.D. Hayes, *Livestock Revenue Insurance*, "Journal of Futures Markets" 2001, Vol. 21, pp. 21–32.
21. J.E. Belasco, R.M. Taylor, K.B. Goodwin et al., *Probabilities Models of Yield, Price and Revenue Risks for Feed Cattle Production*, "Journal of Agricultural and Applied Economics" 2009, Vol. 41.
22. S.G.M. McKendree, T.G. Tonsor, L.L. Schulz, *Management of Multiple Sources of Risk in Livestock Production*, "Journal of Agricultural and Applied Economics" 2021, Vol. 53, pp. 75–93.
23. W.J. Green, L.J. Driscoll, L.M. Bruch, *Data Requirements for Domestic Livestock Insurance* [in:] *The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies*, ed. S.R. Koontz, D.L. Hoage, D.D. Thilmany et al., Walligford, Cambridge, CABI Publishing, 2006; Ch. Hart, *The Current State of US Federally Supported Livestock Insurance* [in:] *The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies*, ed. S.R. Koontz, D.L. Hoage, D.D. Thilmany et al., Walligford, Cambridge, CABI Publishing, 2006.

animal diseases can be prevented through professional management, if we disregard cases of bioterrorism.

In line with the technical insurance orthodoxy and the actuarial techniques of risk insurability, S. Shaik et al. and K. H. Coble et al. proposed a matrix for integrating animal disease risk with the possibilities and conditions for risk transfer from agriculture to the insurance sector[24]. The matrix is shown in Table 2.

24. S. Shaik, B.J. Barnett, K.H. Coble et al., *Insurability conditions and livestock disease insurance* [in:] *The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies*, ed. S.R. Koontz, D.L. Hoage, D.D. Thilmany et al., Walligford, Cambridge CABI Publishing, 2006; H.K. Coble, R.T. Hanson, H.S. Sempier et al., *Investigation the Feasibility of Livestock Disease Insurance: a Case Study in US Agriculture* [in:] *The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies*, ed. S.R. Koontz, D.L. Hoage, D.D. Thilmany et al., Walligford, Cambridge, CABI Publishing, 2006.

Table 2. Conditions for animal disease risk insurability

Farmer's exposure to losses	Risk characteristics	Insurance conditions						Potential risk management instrument
		defined and measurable losses	random and unintentional losses	sufficient information to classify risk	sufficient information to calculate premiums	uncorrelated losses to build a portfolio	economically acceptable premiums	
Production losses	Fully controlled by the manager	Difficult when caused by management errors	No	No	Sometimes, however, special studies are needed	Yes	No	Unjustified solution – neither public nor private
	Ex officio compensation	Typically	Typically	Possible but very expensive	Sometimes, however, special studies are needed	Often not	Often not	Package insurance for valuable animals
	No ex officio compensation	Typically	Typically	Possible but very expensive	Sometimes, however, special studies are needed	No	Often not	Public insurance
	Local coverage without ex officio compensation	Typically	Typically	Possible but very expensive	Sometimes, however, special studies are needed	Yes	Possibly	Public or private insurance
	Endemic disease with lasting losses	Typically	No	Yes, because high risk for all	Yes	No	No	Government support for withdrawal from the sector

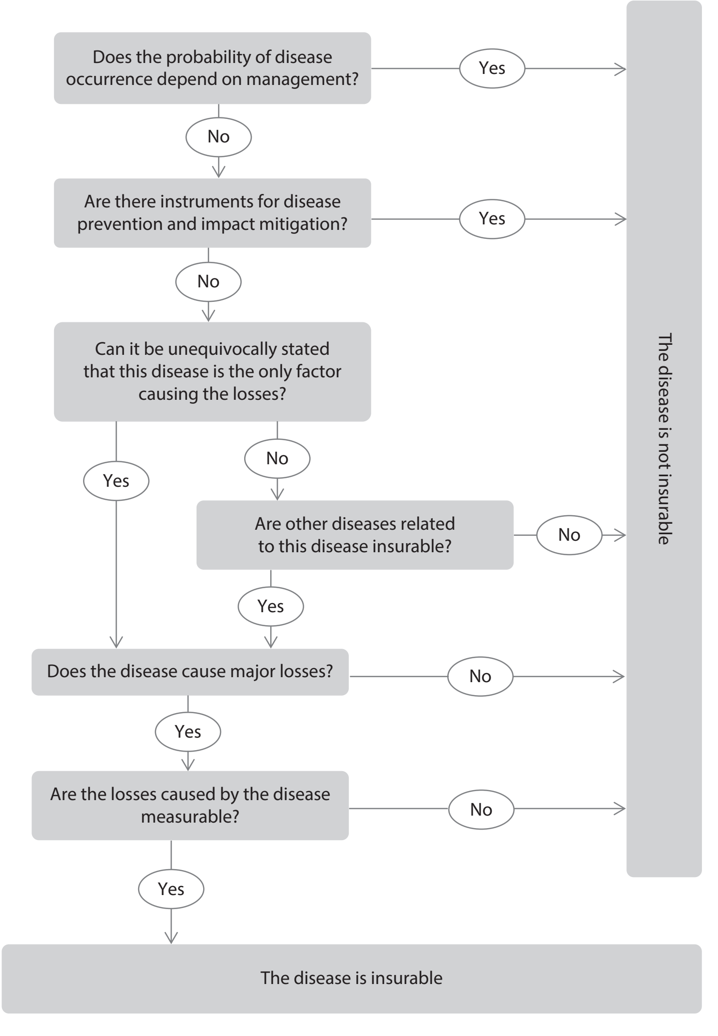
Continued on the next page.

Farmer's exposure to losses	Risk characteristics	Insurance conditions						Potential risk management instrument
		defined and measurable losses	random and unintentional losses	sufficient information to classify risk	sufficient information to calculate premiums	uncorrelated losses to build a portfolio	economically acceptable premiums	
Market losses	Depopulation, delayed herd recovery	Yes	Dependent on the disease	Dependent on the disease	Difficult	Dependent on the disease	Dependent on the disease	Private lost profits insurance
	Quarantine	Yes	Yes	Yes	Difficult	Depends on the quarantine time	Possibly	Private lost profits insurance
	Local short-term price drops	Yes, if prices are observable	Yes	Yes	Difficult	Yes	Possibly	Private insurance
	Geographically expanding short-term price drops	Yes, if prices are observable	Yes	Yes	Difficult	Yes	No	Government programmes for permanent market loss
	Long-term market loss due to endemic diseases	Yes, if prices are observable	No	Yes, because high risk for all	Yes	No	No	Government support for withdrawal from the sector

Source: Presented on the basis of: S. Shaik, J.B. Barnett, H.K. Coble et al., "Insurability Conditions and Livestock Disease Insurance" [in:] The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies, ed. S.R. Koontz, D.L. Hoag, D.D. Thilmany et al., Wallingford, Cambridge, CABI Publishing, 2006.

In contrast, K.H. Coble et al. proposed a pragmatic procedure for classifying a disease as "uninsurable", "potentially insurable" and "conditionally insurable"[25]. Its essence is illustrated in Figure 3.

Figure 3. Decision flowchart of animal disease insurability



Source: Presented on the basis of: H.K. Coble, R.T. Hanson, H.S. Sempier et al., Investigation the Feasibility of Livestock Disease Insurance: a Case Study in US Agriculture [in:] The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies, ed. S.R. Koontz, D.L. Hoag, D.D. Thilmany et al., Wallingford, Cambridge, CABI Publishing, 2006.

25. H.K. Coble, op. cit.

The issue with the animal disease risk insurability and its adverse effects is also due to the fact that in the case of around $^1/_4$ of the diseases we are not sure which agents cause them[26]. This makes it difficult to accurately estimate the scale and probability of disease occurrence and spread, and therefore to price the risk, which translates into generally high insurance premiums[27].

The ability to insure risk associated with a specific animal disease, as well as the calculation of budget compensation for affected farmers, is heavily dependent on access to reliable historical data, in particular relating to animal mortality and value, and direct and indirect losses/damages. Obviously, the quantity of data and its quality also matter, which has important implications for the coverage and depth of any insurance subsidies[28]. Without this data, private insurers generally face serious difficulties in determining rates and premiums. Consequently, their use of reinsurance, which is in fact indispensable for major risks, is also very problematic. Furthermore, both the government and private underwriters are always faced with the so-called residual risk, a term that is variously defined. Most often, however, it is the difference between normal risk, i.e. its level before any action is taken to reduce the probability of its occurrence and the effects of its materialisation, and the effects of its control. In the situation of interest for us, this will be the risk that remains after the intervention of the farmers themselves and that of the public authorities. All participants in the animal disease risk management process are also interested in how a tracking system for animals and animal products works.

H.K. Coble et al. take a very interesting approach to the situation where there is no adequate historical data on the probability of animal disease occurrence and the severity of associated damage, pragmatically proposing two possible lines of action:

1) asking appropriately structured questions to agricultural producers about past production trends and declines;
2) a survey on a group of insurance experts, especially actuaries and risk pricing and underwriting specialists, based on the current situation and relating to the frequency and size of losses[29].

The latter method can be followed in two ways: either the experiment is continued until the experts reach a consensus on the statistical characteristics of a given risk, or

26. OIE, *Animal Health: A Multifaceted Challenge*, 2014.
27. P.M. Meuwissen, op. cit.
28. W.J. Green, op. cit.; M.P.A.M. Van Asseldonk, P.M. Meuwissen, M.B.R. Hurine et al., *Designing Epidemic Livestock Insurance* [in:] *The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies*, ed. S.R. Koontz, D.L. Hoage, D.D. Thilmany et al., Walligford, Cambridge, CABI Publishing, 2006.
29. H.K. Coble, op. cit.

each of them gives their estimates in isolation. In turn, two specific techniques can be used in both methods:

1) a fractal approach, where the interviewees are asked to assign probabilities to specific situations, with the interval set at [0, 1];
2) the three-point technique, in which the interviewers use percentage ranges of the chances of a particular event occurring, which should ultimately enable them to draw up a histogram and, on its basis, the distribution function of a random variable; of course, one should always bear in mind that these will be subjective assessments, but this is what insurers very often deal with in practice.

Effective public intervention leading to the maintenance of the desired health status of livestock is of fundamental importance for the insurability of other risks in livestock production and the preservation of disease-free status in related food chains[30]. Let us, therefore, analyse in more depth the issue of insurability of risks in this division of agricultural production.

Insurance against disease risk and other risks encountered in livestock production, as well as public intervention in the risk management process, should always take into account the motivations of farmers to try to prevent disease outbreaks, for example using biosecurity, and to treat and/or cull their animals if necessary in accordance with the law. The state, in turn, should analyse the possible increase in costs for farmers and compensate them in an acceptable way, while striving to reduce as much as possible the period of return of the food chain in question to the disease-free status[31]. It should always be borne in mind that any public intervention carries the threat of so-called "derived externalities', which are often significantly delayed. Firstly,

30. H.A. Seitzinger, L.P. Paarlberg, G.J. Lee, *Economic Impacts of Eradication Scrapie, Ovine Progressive Pneumonia and Johne's Disease on US Sheep, Lamb, Sheep Meat and Lamb Meats Markets* [in:] *The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies*, ed. S.R. Koontz, D.L. Hoage, D.D. Thilmany et al., Walligford, Cambridge, CABI Publishing, 2006; J. Pritchett, D. Thilmany, K. Johson, *Understanding Broader Economic Effects of Livestock Insurance and Health Management: Impacts of Disease Outbreak on Allied Industries* [in:] *The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies*, ed. S.R. Koontz, D.L. Hoage, D.D. Thilmany et al., Walligford, Cambridge, CABI Publishing, 2006; L.J. Grannis, L.M. Bruch, *The Role of USDA-APHIS in Livestock Disease Management within the USA* [in:] *The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies*, ed. S.R. Koontz, D.L. Hoage, D.D. Thilmany et al., Walligford, Cambridge, CABI Publishing, 2006.
31. B.G. Neumann, C.R. Keogh, *Managing the Risks and Impacts of Animal Diseases in the Australian Livestock Sector* [in:] *The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies*, ed. S.R. Koontz, D.L. Hoage, D.D. Thilmany et al., Walligford, Cambridge, CABI Publishing, 2006; B. Stephen, T. Epps, *Livestock Industry Insurance: Canada* [in:] *The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies*, ed. S.R. Koontz, D.L. Hoage, D.D. Thilmany et al., Walligford, Cambridge, CABI Publishing, 2006; A.Ch. Wolf, *Livestock Disease Eradication Programmes and Farm Incentives: the Case of Bovine Tuberculosis* [in:] *The Economics of Livestock Disease Insurance. Concepts, Issues and International Case Studies*, ed. S.R. Koontz, D.L. Hoage, D.D. Thilmany et al., Walligford, Cambridge, CABI Publishing, 2006.

it restructures the motivation system for farmers and other chain players to undertake and implement preventive investment in animal health, referring, in the first place, to any budget subsidies. Secondly, governments sometimes allow farmers to combine compensation from private insurers with government and even regional compensation. Such cases are referred to in the literature as "double dipping". Paradoxically, this could reduce interest in private insurance or cause so-called underinsurance. Thirdly, governments do not always compensate farmers for indirect disease-induced damage. Fourthly, budget subsidies and compensation alter the risk exposure of farms, exacerbate the issue of moral hazard, and weaken the incentives of private underwriters to refine their procedures for pricing and classifying risks transferred from agriculture, which is sometimes reflected in a tendency to overcharge rates and premiums, or undercompensate. Fifthly, the additional investment of farmers in animal disease prevention results from negative and network externalities, which can lead to some farmers behaving as free-riders, i.e. benefiting from an investment made by their neighbours[32].

Although agricultural insurance can mitigate production and price risks, and can also sometimes limit the use of agrochemicals and lead to a better crop structure, the positive impacts are most often not very significant, as few farmers choose to purchase policies. Farmers' participation in the animal insurance segment is particularly low. In this connection, Y. Liu et al. constructed a theoretical model to explain the main determinants and mechanisms of this low demand, and then verified it empirically[33]. Let us take a closer look at its essence.

With c_i relating to the insurance premium and I the compensation, and, further, T standing for the waiting time for the compensation payout, and R for the additional payout conditions, we can look at how a livestock farmer will seek to maximise their net benefit from the purchase of a policy by selecting the number of insured animals q. When the probability of no loss is π, the farmer can make a profit equal to $pq-(1/2)c_0(\theta)g^2-c_iq-Rq$, where p is the price of the product and the term $-(1/2)c_0(\theta)g^2$ denotes the unit other costs (per LSU), with the parameter θ reflecting the cost variation between farmers and $\theta \in \left[\underline{\theta}, \overline{\theta} \right]$. As θ increases, unit costs increase and, in addition, $c'_0(\theta)>0$. If, in turn, damage occurs with a probability of $1-\pi$, the profit amounts to: $(1-\delta)\beta^T Iq+\delta pq-(1/2)c_0(\theta)q^2-c_iq-Rq$, where $\delta(0\leq \delta<1)$ denotes the percentage of loss covered by insurance and $\beta(0< \beta< 1)$ is the discount factor. We can, therefore, express the function of the farmer's expected net benefits (ENB) as:

32. OECD, *Producer Incentives in Livestock Disease Management*, Paris 2017.
33. P. Liu, L. Hou, D. Li et al., *Determinants of Livestock Insurance Demand: Experimental Evidence from Chinese Herders*, "Journal of Agricultural Economics" 2021, Vol. 72, No. 2, pp. 430–451.

$$ENB = \pi\left(pq - \frac{1}{2}c_0(\theta)q^2 - c_i q - Rq\right) + (1-\pi)\left((1-\delta)\beta^T Iq + \delta pq - \frac{1}{2}c_0(\theta)q^2 - c_i q - Rq\right).$$

If this function is to maximise the expected utility, then we need to find a suitable value for the parameter q, which leads us to:

$$\frac{\partial ENB}{\partial q} = 0,$$

or

$$((1-\pi)\delta+\pi)p+(1-\delta)(1-\pi)\beta^T I-(c_i+R)-c_0(\theta)q^*=0.$$

Let us now move on to the impact of the above contract attributes on utility. First, however, we need to convey the relationship between the optimum size of the protected stock q^* and the cost characteristics of the farmer:

$$G(q^*)=((1-\pi)\delta+\pi)p+(1-\delta)(1-\pi)\beta^T I-(c_i+R)-c_0(\theta)q^*.$$

The first order condition for a maximum and the implicit function theorem yield:

$$\frac{\partial q^*}{\partial \theta} = \frac{\frac{\partial G}{\partial \theta}}{\frac{\partial G}{\partial q^*}} = -\frac{c'(\theta)q^*}{c_0(\theta)} < 0,$$

because $c_0(\theta)>0$. Thus, if a breeder has a higher θ (their production costs are higher), they should insure fewer animals. The same applies when the insurance premium increases, as shown by the partial derivative below:

$$\frac{\partial q^*}{\partial c_i} = \frac{\frac{\partial G}{\partial c_i}}{\frac{\partial G}{\partial q^*}} = -\frac{1}{c_0(\theta)} < 0.$$

An equivalent finding is also that, for a given minimum insurance coverage level, fewer breeders will purchase a policy.

We have yet to present the impact of the T, as well as and I and R attributes on the optimum number of insured animals q^*. Let us therefore write down the corresponding partial derivatives:

$$\frac{\partial q^*}{\partial T} = -\frac{\frac{\partial G}{\partial T}}{\frac{\partial G}{\partial q^*}} = \frac{(1-\partial)(1-\pi)\beta^T I \ln\beta}{c_0(\theta)} < 0$$

and

$$\frac{\partial q^*}{\partial I} = -\frac{\frac{\partial G}{\partial I}}{\frac{\partial G}{\partial q^*}} = \frac{(1-\partial)(1-\pi)\beta^T}{c_0(\theta)} > 0.$$

This shows that lengthening the waiting time for compensation will reduce the level of protection, while increasing compensation has the opposite effect. The partial derivative $\partial\theta^*/\partial R$ is similar to the effect of the derivative $\partial\theta^*/\partial c_i$. We can conclude from this that tightening the conditions for coverage by underwriters, with other conditions remaining constant, will reduce the demand for policies.

The vast majority of work on traditional livestock insurance refers to the expected utility theory. This theory, however, provides an inadequate explanation of the behaviour of farmers and insurers when faced with extreme events and systemic risks. Hence, for more than forty years, attempts have been made to modify it, drawing mainly on the work of behavioural economics and, more recently, neuroscience. The most promising alternative remains the prospect theory, which, among others, attempts to identify the reasons for farmers' low interest in traditional insurance, even when it is subsidised. A good example in this context can be the article by H. Feng et al., in which the third-generation prospect theory is applied[34].

Comprehensive characteristics of the development of livestock production insurance by R.M. Hohl, as presented in Table 3[35], can be used as a kind of partial summary of this section of the article. It should be noted that this is a very relevant account of the problem in the international literature.

34. H. Feng, X. Du, A.D. Hennessy, *Depressed demand for crop insurance contracts, and rationale based on third generation Prospect Theory*, "Agricultural Economics" 2020, Vol. 51, 2020, pp. 59–73.
35. M.R. Hohl, *Agricultural Risk Transfer. From Insurance to Reinsurance to Capital Markets*, Wiley, Chichester, 2019.

Table 3. Overview of the main types of animal insurance

Insurance product	Characteristics	Risks insured	Advantages	Disadvantages	Recommended use
Standard	– For a specific farm, protection of individual animals (small farms) or entire herds (larger units) – Basic coverage – Liquidation of damage on the farm	– Animal deaths due to non-communicable diseases, fire, lightning, explosion, falling aircraft, electrocution, injury, flood and storm	– Standardised contract options for small farms – Customised contracts for mid-sized and large entities	– Moral hazard and adverse selection – High administrative, distribution and damage liquidation costs – Limited options in standardisation – No coverage for damage caused by communicable diseases	– Small and large farms in developed countries – Small farms protected by policies prepared at an aggregated level (e.g. China)
Extended coverage	– Broader protection than standard insurance – However, it can be standardised for small farms and customised for others – Liquidation of damage on the farm	– Animal deaths resulting from equipment failure, perinatal problems, and during transport and shows – Loss of revenue and income as a result of communicable diseases, including indirectly – Impaired fertility	– Additional coverage as an extension of standard policies – Possibility of covering indirect losses resulting from communicable diseases, supplementing, among others, state compensation	– Moral hazard and adverse selection – High administrative, distribution and damage liquidation costs – Problems with estimating damage, especially indirect damage, resulting from communicable diseases	– For individual breeders who follow the biosecurity rules, and as a supplement to state compensation

Continued on the next page.

Insurance product	Characteristics	Risks insured	Advantages	Disadvantages	Recommended use
Indexes based on regional mortality rates	– Mortality indexes before and after catastrophic losses (e.g. drought, flood) – Indexes for similar regions	– All risks leading to animal deaths	– Addressing the underdevelopment of the insurance infrastructure – Reducing moral hazard and adverse selection – Low cost, as long as the state collects reliable animal mortality data	– Rising costs when new data on animal deaths needs to be collected – Baseline risk – Problems in determining the causes of deaths	– For very extensive grazing systems and underdeveloped weather measurement systems
Satellite-based animal mortality indexes	– Natural risks (mainly drought) closely linked to mortality caused mainly by feed shortages – Indexes are based on network models – Similar natural and risk management conditions – Interdisciplinary knowledge needed for index construction	– All risks leading to mortality	– Addressing the underdevelopment of the insurance infrastructure – Reducing moral hazard and adverse selection – Low cost, as long as the state collects reliable animal mortality data	– Baseline risk – Difficult perception of the index by breeders – Necessity to develop a contingency plan when data for index construction is lacking	– Individual breeders with extensive knowledge of price quotations for animal products – Supply chain managers (meso-level risk transfer) – Government institutions (macro-level risk transfer)
Livestock production revenue and income insurance	– Use of the index formula – Price volatility in livestock production – Gross margin in selected activities – Adaptation to the cyclical pattern in livestock production (protection usually up to 1 year, but can be up to 3 years)	– Price risk – Gross margin	– Extensive coverage – Limiting moral hazard and adverse selection – No damage liquidation costs	– Limited number of protectable activities – Feed consumption standardisation problems – Difficulties in selecting feed-to-product conversion ratios – Baseline risk	– Individual breeders with extensive knowledge of price quotations for animal products – Supply chain managers (meso-level risk transfer) – Government institutions (macro-level risk transfer)

Source: Presented based on: M.R. Hohl, Agricultural Risk Transfer. From Insurance to Reinsurance to Capital Markets, Wiley, Chichester 2019.

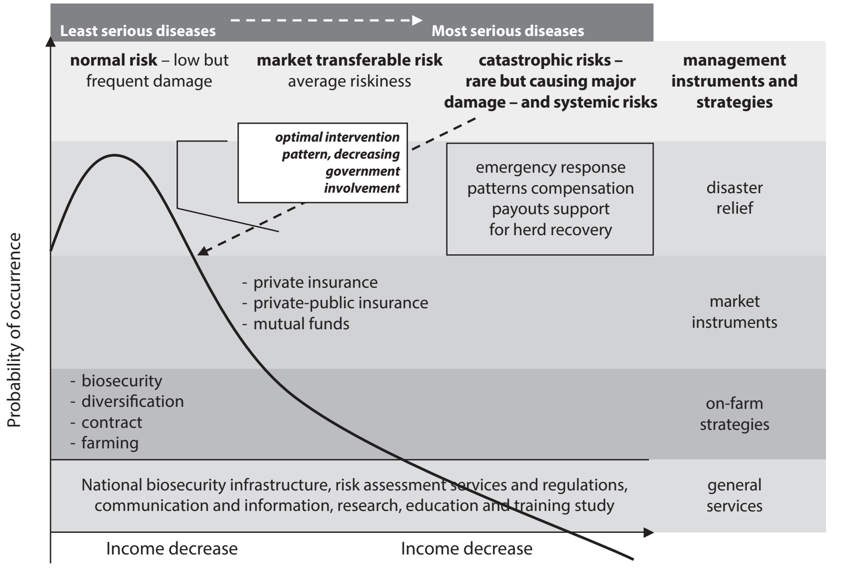
Holistic system of risk management in livestock production

The management of livestock disease risk is important in terms of the significance of the division's contribution to the overall volume of agricultural production and the functioning of sectoral supply chains, as well as the potential for transmission to humans, as we indirectly experienced with COVID-19. However, unfortunately, according to a study by the World Organisation for Animal Health (founded as OIE), in about ¼ of the cases we are not sure of the type of pathogen causing the epizootic. The management of the aforementioned risk is also difficult, because negative externalities can be generated in this case, and farmers often do not have the adequate motivation to take full account of social costs in this area. This is an important premise for the rationale behind the involvement of governments in animal disease prevention and control. On the other hand, this also justifies the advisability of designing an animal disease risk management system following a holistic convention, as demonstrated by researchers working for the Organisation for Economic Co-operation and Development (OECD), and shown in Figure 4[36].

O. Melyukhina and W. Yoon also distinguished three types of risk: (1) normal, which must primarily be handled by the farmers themselves; (2) transferable to the insurance and/or financial markets; (3) catastrophic, where public authorities very often have to get involved. The researchers also included two standard dimensions of risk, i.e. the probability of disease occurrence and its impact in terms of a possible decrease in agricultural income. Let us further note that the very bottom of the above matrix comprises public services, i.e. the type of infrastructure needed to prevent the outbreak of diseases and to deal with the consequences once they have occurred. The state is primarily responsible for its type, functioning and quality. However, the state's role does not end there, and its tasks in internalising external costs and creating the public good represented by proper animal health are no less important. This is a difficult issue, as it is necessary to construct motivation systems that satisfactorily match farmers' microeconomic goals with the social optimum, which is the appropriate level of their investment and effort in disease prevention. This is compounded by coordination and optimisation issues within sectoral supply chains, the food sector as a whole, consumer satisfaction and safety, and public health. As always with risk management, there is a moral hazard to be reckoned with among the main players, and farmers in particular.

36. O. Melyukhina, W. Yoon, *Producer incentives in livestock disease management: a synthesis of conceptual and empirical studies. Draft Report*, OECD Conference Centre, Paris 2017.

Figure 4. Holistic system of livestock disease risk management



Source: Elaborated on the basis of: O. Melyukhina, W. Yoon, Producer incentives in livestock disease management: a synthesis of conceptual and empirical studies. Draft Report, OECD Conference Centre, Paris 2017.

Regarding the overall experience to date of the management of animal diseases by farmers under risk and uncertainty, O. Melyukhina and W. Yoon highlight the following:

1) in the simplest theoretical models, farmers prevent and combat animal diseases until the expected marginal benefits equal the marginal costs of these activities;
2) animal disease prevention and control expenditure has diminishing marginal benefits, so on purely economic grounds preventing all possible damage caused by diseases is not optimum;
3) due to the possibility of external costs, farmers' investment and effort in the prevention and disease control phases may be lower than the social optimal;
4) technical and technological progress and/or government action in the area of disease prevention always lead to a higher social cost-loss boundary than in the microeconomic approach;
5) farmers managing animal diseases need to understand their various biological aspects and be familiar with relevant policy actions and administrative regulations;

6) the primary public policy task related to optimising farmers' income is to provide them with knowledge and cost-effective technologies for disease prevention and control;
7) biosecurity is a fundamental strategy for the prevention of animal diseases and the channels (vectors) of their transmission. The correct perception of these benefits by farmers can encourage them to investment more and commit to key biosecurity practices;
8) the dynamic relationships between farmers' choices and decisions and the increase in animal diseases may lead to a situation where seeking to eradicate them completely may be a non-optimal solution.

The vast majority of farmers only consider epidemic diseases to be a major risk, with other diseases regarded as low risk[37]. Hence, the question of classifying the risk itself is of central importance, as it determines the response to its materialisation. Under these conditions, it is the task of governments to facilitate farmers' accurate identification of risks by, among others, providing them with timely and relevant information on animal diseases, the channels and dynamics of their transmission, and the expected consequences. At this point, the systematisation of risks proposed by A. Mikes et al.[38] can be very helpful, as these researchers distinguished: (1) risks that can be prevented by ongoing and routine measures, such as vaccination and good zootechnical practices; (2) risks in a strategic area, i.e. associated with the pursuit of higher profits and profitability. An example of this is the purchase of animals with higher genetic production potential, although with higher needs. This risk can be managed to a certain extent, but it is always possible that some residual part of it will remain beyond the farmers' ability to make an effective impact. This can be referred to as baseline risk. There is also a third risk: external, over which agricultural producers have no direct control, but they can seek to build the resilience of their farms to future shocks. This group includes animal epidemics.

Each risk should be analysed from the perspective of the probability of its occurrence and the severity of the consequences of its materialisation. As always, however, we should bear in mind that farmers most often use subjective rather than objective probabilities. This circumstance should be taken into account in the design of the various government programmes and in the choice of risk management strategies by the farmers themselves. The latter set is standard and includes: risk avoidance, adoption of less risky practices, diversification, flexibility and insurance, therefore including

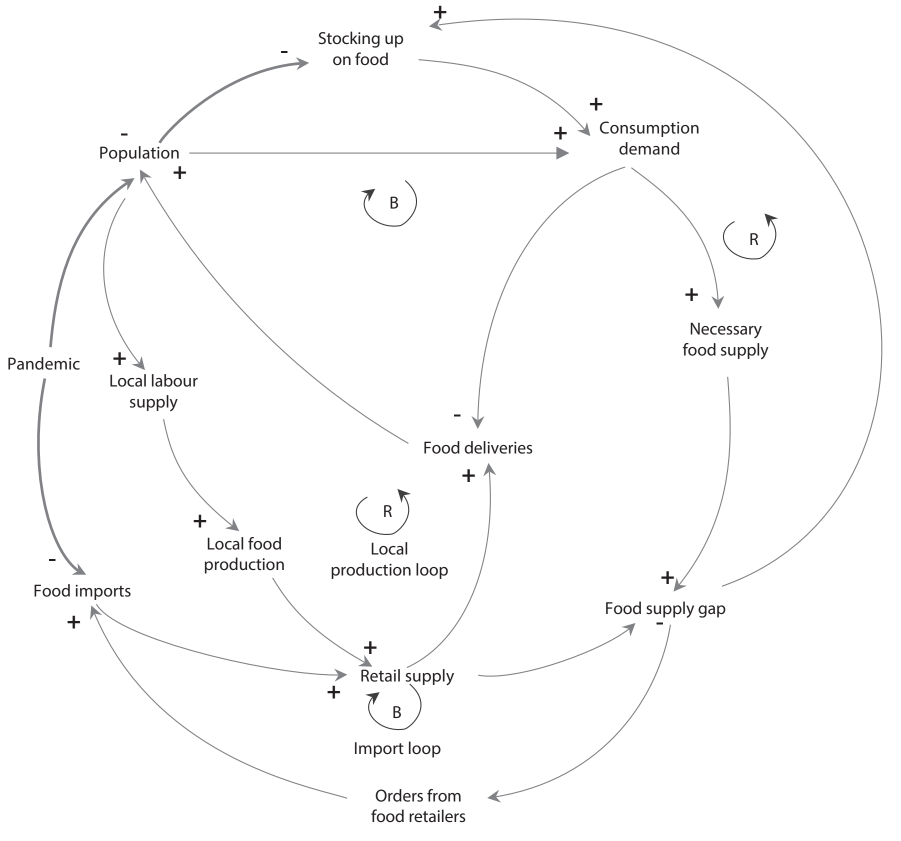
37. O. Rat-Aspert, C. Fouridon, op. cit.
38. A. Mikes, H. Lavsanne, R. Kaplan, *When one size doesn't fit all: Evolving directions in the research and practice of enterprise risk management*, "Journal of Applied Corporate Finance" 215, Vol. 27, pp. 210–227.

preventive and active measures aimed at minimising the negative consequences of risk materialisation. There are various relationships between risk management instruments and strategies, but substitutability and complementarity predominate. This must be borne in mind at all times when analysing insurance, which can sometimes be substituted by self-protection (an effort to reduce the probability of loss) and self-insurance (measures to limit the magnitude of damage).

Even though it is possible to attempt to improve the holistic system by extending it to include cognitive risk maps and orienting it specifically towards strengthening the resilience of livestock farms, i.e. improving their capacity to absorb risks/shocks, adapting to them, and thoroughly transforming their operations to be resilient to them also in an ex-ante sense, it will still be a static concept that does not accurately reflect the phenomena of multiplicative and additive risks, and the materialisation of extreme events[39]. In view of the above, it is worth taking a closer look at the convention used in complex system dynamics, which involves three basic elements: (1) levels which, by means of instantaneous values, define the state of a distinguished element of the system; (2) flows, i.e. fluxes that provide information on the rate of change of level values; (3) decision variables aimed at regulating the size of flows as a function of the instantaneous states of the system[40]. Feedback loops, which are supposed to reflect cause-and-effect relationships, play a fundamental role in system dynamics. There are already some first proposals to apply continuous simulation to food chains and sectors following the convention of system dynamics. This is exemplified in Figure 5.

39. P.A. Kerr, *Risk management in Canada's agricultural sector in light of COVID-19*, "Canadian Journal of Agricultural Economics" 2020, Vol. 68, pp. 251–258; P.A. Kerr, S. Biden, *Canada's agricultural sector in light of COVID-19: Considerations one year later*, "Canadian Journal of Agricultural Economics" 2021, Vol. 69, pp. 299–305; R. Sarker, T. Phan, N.Y. Lee et al., *Business Risk Management Program and risk-balancing on Ontario hog sector: An empirical analysis*, "Canadian Journal of Agricultural Economics" 2022, Vol. 70, pp. 287–304.
40. R. Hoffmann, T. Protasowicki, *Modele dynamiki systemowej w modelowaniu złożonych systemów i procesów*, „Biuletyn Instytutu Systemów Informatycznych" 2013, nr 12, pp. 19–28.

Figure 5. The causal loop of the impact of a pandemic on local food chains (presented in the convention of system dynamics)



The lines and arrows in bold indicate direct impacts, R – positive feedback, B – negative feedback.

Source: Own elaboration on the basis of: S. Song, L.C.J. Goh, W.T.H. Tan, Is food security an illusion for cities? A system dynamics approach to assess disturbance in the urban food supply chain during pandemics, "Agricultural Systems" 2021, Vol. 189, p. 108203.

Summary

Although the six areas of research in the field of risk management in livestock production were selected mainly with regards to the needs of Polish agriculture, it is clear from the in-depth analysis that they also remain a subject of interest to researchers from all over the world. This is obvious, since they are the basis of this management. The article's emphasis on the economic modelling of livestock health control, which is commonly treated as a process of creating this specific public good, was, however, conceived as a link to proceed – in a separate paper – to contemporary important relationships between risks, uncertainty and ambiguity and animal welfare, public health, trade and socio-economic well-being.

Risk management in livestock production should be holistic, as only then will it be possible to identify the most comprehensive set of risks and threats, and consequently rank them according to the probability of occurrence and the expected financial impact of their materialisation. Holism also provides an opportunity to clearly clarify the place and responsibility in the overall system encompassing farmers, market players and the state/policy. This broad perspective also greatly facilitates the process of reconciling the microeconomic motivations of agricultural producers with the processes of dealing with the external costs caused by animal rearing and breeding, and the creation of the public good in terms of the adequate health of livestock. The holistic convention is in fact necessary in order to ensure complementarity between the various risk management instruments, to avoid overcompensation of damages, and to reduce adverse selection and moral hazard. However, agricultural policy makers need to properly recognise the interactions between risk management tools and strategies, shaping the broad framework of their impacts while understanding how this affects the motivations, decisions and behaviour of agricultural producers. The development of a holistic concept, which nevertheless has its limits, therefore requires more sophisticated integration of the achievements of neoclassical microeconomics with those of behavioural microeconomics, and thus, consequently, the delineation of areas for the effective use of expected utility theory/hypothesis and proposals for its extension or even replacement, with prospect theory currently and in the future playing an increasingly important role in the latter case.

First the COVID-19 pandemic, and then the war in Ukraine, showed that holistic risk management in livestock production was not adapted well enough to deal with such global systemic risks, as it is overly static. However, it can be improved towards strengthening the resilience of livestock production and constructing cognitive risk maps. In parallel, however, there should be a stronger focus on the analytical and

utilitarian possibilities offered by modelling and continuous simulation embedded in complex system dynamics. However, researchers themselves, as well as agricultural policy makers and producers, should shift their thinking from narrowly defined agriculture towards sectoral food chains and networks, and whole food sectors. With time, this type of modelling and simulation probably also needs to gain a transnational dimension.

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