

## Supplemental Appendix S2

to

### Using an adaptive modeling framework to identify avian influenza spillover risk at the wild-domestic interface

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## **Supplemental Appendix S2: Poultry Sector Risk Literature Review**

The goal of the following exercise is to provide reasonable estimates for the different levels of risk faced by different types of poultry operations. To generate these estimates we sought to identify risk values from the literature and apply them to U.S. poultry categories. This was selected over a formal meta-analysis as there are only a handful of relevant literature sources, the majority of which rely on the same underlying dataset. Instead, we seek to make reasonable estimates of risk from a more qualitative approach given that stronger estimates are not available for the United States. What follows is a description of the steps taken to reach these estimates, beginning with a review of the current literature, and is followed by a summary of this literature based on European data, transferring these values into the categories used in the United States, and a set of caveats for these estimates.

### **Literature Overview**

Four central publications are relevant to setting values for avian influenza virus (AIV) risk by poultry type. Three (Bouwstra et al., 2017; Gonzales et al., 2010, 2012), are by the same research group, largely re-analyzing the same surveillance data from the European Union/ Netherlands with additional information in each publication based on an updated data set and each taking a different modeling approach. Galletti et al., (2018), does a similar analysis for data collected in Italy. In general, these four studies agree that chickens are less likely to experience initial outbreak events than turkeys (Table 1). In addition, they tend to point to an increase in risk for birds kept outdoors. It should be noted that because of the small sample size, all duck estimates for the four papers have wide confidence intervals. Our model does not include ducks, making this large error irrelevant for the current project.

These values are largely supported by AIV challenge studies (Aldous et al., 2010; Mutinelli et al., 2003; Spackman et al., 2010). General findings are that chickens are far less susceptible than turkeys, but that susceptibility in ducks is highly variable depending on strains. As such, it is reasonable to assume that the trends found for these four European studies are not Europe-specific, but are more broadly applicable. That leaves us with the task of combining these studies in the best way possible.

Table 1. Risk of initial outbreak events by poultry farm type. RR = “relative risk” OR = “odds ratio.” Colors range from lowest risk (dark blue) to highest risk (dark red). Missing values represent poultry categories not included in a given paper.

| Farm Type |                   | Risk of initial outbreak |                    |                    |
|-----------|-------------------|--------------------------|--------------------|--------------------|
| Species   | Flock             | Gonzales 2010 (RR)       | Gonzales 2012 (RR) | Galletti 2018 (OR) |
| Chicken   | Breeders          | 1                        | 0.3                |                    |
|           | Breeder (layer)   |                          |                    | 0.5                |
|           | Breeder (broiler) |                          |                    | 0.4                |
|           | Pullets           |                          | 0.7                |                    |
|           | Layers            | 1.08                     |                    |                    |
|           | Layers (indoors)  |                          | 1                  | 0.72               |
|           | Layers (outdoors) |                          | 11.1               | 6.3                |
|           | Broilers          | 0.25                     | 0                  | 0.2                |
| Turkey    | Turkey            | 1.64                     | 7.7                | 1.2                |
|           | Meat              |                          |                    | 12                 |
|           | Breeder           |                          |                    | 11.3               |
| Mixed     | Backyard          | 0.46                     |                    | 3.4                |
| Duck      | Duck/Geese        | 18.82                    |                    | 1.81               |
|           | Meat Duck/indoors |                          | 12.8               | 39.5               |
|           | Breeders/outdoors |                          | 24.5               | 25.5               |
| Other     | Game birds        | 6.98                     |                    | 0.41               |
|           | Ratites           | 4.8                      |                    |                    |
|           | Others            | 12.8                     |                    |                    |

The available data to generate risk estimates by poultry type. Hill et al. (2019) generated a poultry risk map for Great Britain. This study uses values from the Gonzales et al., 2010, and 2012 papers (Table 2). Hill et al. (2019) categorizes poultry inputs by species and housing (indoor/outdoor). Although decisions made for indoor birds look reasonable, it should be noted that there are missing data for indoor geese, with their value set to be the same as indoor ducks. Based on AIV surveillance in wild birds, this is likely an overestimate and that they should be at lower risk than ducks. Additionally, the risk of outdoor game birds varies greatly by study, and it is not clear that this estimate is accurate, with limited data comparing the risk of backyard birds to larger operations. However, we do not explicitly include ducks, geese, or game birds in our model. Perhaps the biggest challenge with these estimates is the lack of data for outdoor turkeys. The reasoning behind the value in Hill et al. (2019) is that if indoor turkeys are at greater risk than indoor chickens, then outdoor turkeys must be at least as at risk as outdoor chickens. As such, this is almost certainly a considerable underestimate.

Table 2. Risk values taken from Hill et al., 2019.

| Poultry type      | Relative Risk     | Notes                                                  |
|-------------------|-------------------|--------------------------------------------------------|
| Indoor chicken    | 1                 | Reference category                                     |
| Indoor turkey     | 7.7               | Direct from Gonzales 2012                              |
| Indoor duck       | 12.8*             | Direct from Gonzales 2012                              |
| Indoor goose      | 12.8 <sup>a</sup> | Assumed to be the same as duck                         |
| Outdoor chicken   | 11.1              | Direct from Gonzales 2012                              |
| Outdoor turkey    | 11.1 <sup>b</sup> | Likely an underestimate. Matched with outdoor chickens |
| Outdoor duck      | 24.5*             | Direct from Gonzales 2012                              |
| Outdoor goose     | 24.5 <sup>a</sup> | Assumed to be the same as duck                         |
| Outdoor game bird | 11.1 <sup>c</sup> | Mix of Chickens from Gonzales 2012 and game birds      |
| Backyard birds    | ??                | No estimate given                                      |

\*. In all studies, ducks have a very large CI.

a. Goose estimates are taken to be the same as duck estimates.

b. No estimate for outdoor turkey. Used estimate for outdoor chicken. Likely an underestimate.

c. This is the value for outdoor chicken, which is similar to that estimated by Gonzales et al., 2010, for game birds.

Overall, this leaves us with two unresolved decisions that apply to the hybrid model estimates. 1) How should we incorporate outdoor turkeys, and 2) how to assess the risk of backyard birds in general.

### Poultry Risk Estimates - European categories

We begin with our best estimates for relative risk by poultry type (Table 3) based on the literature reviewed above, followed by a justification for each. Here we provide a relative risk score that we believe is a reasonable estimate of the actual relative risk, a range of scores that could be easily justified, and notes on a few categories, mostly indicating which categories lack direct measures or otherwise strong evidence behind them. A more detailed justification for these numbers follows the table.

Table 3. Risk value for European poultry categories.

| Poultry Type            | Relative Risk | Range     | Notes                  |
|-------------------------|---------------|-----------|------------------------|
| Indoor layer/breeder    | 1             | 1         | Reference category     |
| Indoor broilers         | 0.2           | 0-0.25    |                        |
| Indoor turkey           | 7.7           | 1.64-12   |                        |
| Indoor ducks            | 12.8          | 39.5      |                        |
| Indoor geese            | 12.8          | <12.8     | No direct metric given |
| Outdoor layers/breeders | 11.1          | 6.3-11.1  |                        |
| Outdoor broilers*       | 2.2 (11.1)    | 0-11.1    | No direct metric given |
| Outdoor turkey          | 18            | 11.1-24.5 | No direct metric given |
| Outdoor ducks           | 24.5          | 24.5-25.5 |                        |
| Outdoor geese           | 24.5          | <24.5     | No direct metric given |
| Game birds/other        | 11.1          | 6.98-?    |                        |

\*. Commercial and backyard outdoor broilers likely have different risks, see below for details. A value of 2.2 will be used for commercial birds while 11.1 for backyard birds.

### *Indoor layer/breeder chicken*

Indoor layers and breeder chickens are sometimes separated but often combined in studies of risk. Because of this inconsistency, here we are treating them the same. It is reasonable to assume that breeder farms would have stricter biosecurity, so it may be appropriate to lessen their risk. For the main poultry risk studies they are treated as the reference category, so their relative risk is set to 1. We apply the same approach. Pullets are another indoor chicken type not posted above, but one study (Gonzales et al., 2012) found them to be comparable (RR = 0.7). It could be justified to split them out, though we chose not to do so.

### *Indoor broilers*

The Europe/Dutch papers clearly show broilers to be at lower risk than layers/breeders. Gonzales et al., (2012) found no outbreaks that started with indoor broilers – leading to complete separation, while Gonzales et al., (2010) and Bouwstra et al., (2017) found a small handful, giving relative risks of 0.25 and 0.2 respectively. The latter paper has a more robust analysis, so here we used that value of 0.2. All three papers conclude that this is likely due to the short lifespan of broilers, giving them less time to become infected and spread disease, as well as for a LPAI strain to mutate to HPAI prior to the time of slaughter.

### *Indoor turkey*

The three Gonzales papers find turkeys to be more likely to become infected than chickens. Gonzalez et al., (2010) and (2012) did not separate turkeys by production type and found relative risks of 1.64 and 7.7 respectively. Bouwstra et al., (2017), split turkeys into meat and breeder birds, finding little difference between the two, but a greater overall risk level than in the previous papers (12 and 11.3 respectively). We use the value from Gonzales et al., (2012) because it appears to be the more robust analysis, however, one could justify a higher value. Though not statistically significant, Galletti et al., (2018), found a similar trend where turkey farms were at a greater risk than chicken farms. This finding is further supported by the challenge study literature, which universally concludes that turkeys are more likely to become

infected when exposed to AIV than chickens (Aldous et al., 2010; Spackman et al., 2010). Additional literature points to turkeys having more severe infections (Mutinelli et al., 2003) and have found a lower minimal infectious dose for turkeys than chickens or ducks (Pantin-Jackwood et al., 2017; Pillai et al., 2010)..

#### *Indoor ducks*

All estimates for ducks have wide confidence intervals because of the small number of farms, and so some caution is warranted here. However, they do regularly show greater risk than chickens or turkeys. Ducks are identified as higher risk in all three European/Dutch papers (Bouwstra et al., 2017; Gonzales et al., 2010, 2012), and Galletti et al., (2018) shows a similar trend in Italy. There is a wide range of possible explanations given, including the frequency at which indoor ducks may still be allowed outside, the storage of bedding for indoor ducks outside, and their phylogenetic proximity to wild ducks. This pattern is not fully backed up by the challenge studies, which typically find that the susceptibility of ducks is highly strain specific (Aldous et al., 2010; Spackman et al., 2010). However, their lack of clinical signs even when infected (Pillai et al., 2010) may allow for undetected circulation in domestic duck farms (Verhagen et al., 2021). As such, these domestic duck farms may allow for circulation and mutation, especially of LPAI strains to HPAI strains, before then passing it along to another poultry farm (Verhagen et al., 2021).

#### *Indoor geese*

We have no direct measure for this as geese are rarely studied, and when included they are typically pooled with ducks. Hill et al., (2019), reused the value from ducks. We have no additional information to adjust the metric, but perhaps it could be shifted down some since we know that wild geese at least are less likely to be infected than wild dabblers (Kent et al., 2022). For our model purposes, we do not use geese in subsequent analyses.

#### *Outdoor layers/breeders*

It is clear from the literature that outdoor birds are at greater risk than indoor birds as there is less biosecurity preventing either direct contact with wild birds or from aerosolized viruses. In addition to both Gonzales et al., (2012) and Bouwstra et al., (2017), finding greater risk for outdoor chickens than indoor chickens (11.1 and 6.3, respectively), in Italy, Galletti et al., (2018), found a strongly significant increase in risk for birds that are kept outdoors, though this paper does not include a species interaction.

#### *Outdoor broiler*

There is no information on outdoor broilers, as at least in Europe these are generally kept inside. The same is generally true for the United States, though free range, pasture fed, and organic birds may be allowed access to the outside. It is likely they should be at a lower risk for commercial birds than layers/breeders for the same reasons as indoor birds, i.e., a shorter lifespan. However, this is likely not true for backyard birds, as these are generally kept for a longer time and harvested slowly as needed. As such, we revised this down for commercial birds ( $11.1 \times 0.2 = 2.2$ ) and maintained it as the same for layers/breeders at 11.1.

### *Outdoor turkeys*

As most European turkeys are housed inside, there is not a good value given for outdoor turkeys. Similarly, the bulk of U.S. turkey production has been moved indoors in response to what used to be yearly mass LPAI outbreaks in the Midwest on outdoor turkey farms (personal communication, Patyk). However, organic, pasture raised, and free-range birds are kept outdoors. Hill et al., (2019), use the value for chickens, though this is almost certainly an underestimate, as indoor turkeys are clearly at an increased risk compared to indoor chickens likely because of greater susceptibility to infection from AIV (Aldous et al., 2010; Spackman et al., 2010). Likewise, they are likely at a lower risk than ducks for the same reasons as for indoor birds. As such, we calculated an average between the two.

### *Outdoor ducks*

As currently weighted, this is the most at-risk poultry type. Of note, Gonzales et al., (2012) and Bouwstra et al., (2017) disagree on the ranking of outdoor vs. indoor ducks, with Bouwstra et al. (2017) finding that meat ducks, which are mostly kept indoors are at greater risk. However, these estimates have large confidence intervals and this trend is not significant. As such, we used the values reported in Gonzales et al., (2012) as well as the decision by Hill et al., (2019) because it was the more robust analysis and showed the expected trend.

### *Outdoor geese*

As with indoor geese, direct values are not available. Hill et al., (2019) used the same value as for ducks, which might be an overestimate.

### *Game birds*

There is little information available for game bird species, however they are not explicitly included in our models.

## **Poultry Risk Estimates- Hybrid model categories**

Categories from the European studies do not neatly fall into the population categories for the United States (Table 4). Most notably for the U.S., we lack data on whether birds are housed inside. To account for this, we have matched each hybrid poultry model category to its relative risk for both indoor and outdoor birds from the European categories. Then in the next section we assign percentages of the number of birds of each group that are housed outdoors to calculate a weighted relative risk based on the percentage of birds housed outside. Table 4 includes the hybrid poultry model categories and their relative indoor and outdoor risks. Not all of these categories actually exist (e.g., backyard breeder turkeys) but we have calculated potential risk values to complete the matrix for potential future use. The values in this table come directly from Table 3 above.

Table 4. Poultry categories in the hybrid model.

| Species | Commodity     | Category   | Sector     | Indoor RR | Outdoor RR | Notes                    |
|---------|---------------|------------|------------|-----------|------------|--------------------------|
| Chicken | Broiler       | Commercial | Production | 0.2       | 2.2        |                          |
| Chicken | Broiler       | Commercial | Breeding   | 1         | 11.1       | Treated as layer/breeder |
| Chicken | Layer         | Commercial | Production | 1         | 11.1       |                          |
| Chicken | Layer         | Commercial | Breeding   | 1         | 11.1       |                          |
| Chicken | Layer pullets | Commercial | NA         | 1         | 11.1       |                          |
| Turkey  | All           | Commercial | Production | 7.7       | 18         |                          |
| Turkey  | All           | Commercial | Breeding   | 7.7       | 18         |                          |
| Chicken | Broiler       | Backyard   | Production | 0.2       | 11.1       |                          |
| Chicken | Broiler       | Backyard   | Breeding   | 1         | 11.1       | Treated as layer/breeder |
| Chicken | Layer         | Backyard   | Production | 1         | 11.1       |                          |
| Chicken | Layer         | Backyard   | Breeding   | 1         | 11.1       |                          |
| Chicken | Layer pullets | Backyard   | NA         | 1         | 11.1       |                          |
| Turkey  | All           | Backyard   | Production | 7.7       | 18         |                          |
| Turkey  | All           | Backyard   | Breeding   | 7.7       | 18         |                          |

### Percent of commercial poultry housed outside

There are three categories of commercial poultry that can be housed outside. First, birds labeled as “organic” must be allowed access to the outside for at least half of their lifetime. Second, birds labeled as “free range” must meet the same outdoor access requirements as organic, but simply don’t need to be raised in an organic manner. That is to say, these are not mutually exclusive categories where a bird that is organic is also free range, and a free-range bird can, but does not need to be, organic. Third, some birds are sold as “pasture raised.” This term is not regulated by the USDA and there are no specific housing requirements for a bird to be pasture raised. Due to data availability, we are only able to quantify the number of organic farms. The term “pasture raised” is used for marketing but does not have guidelines or underlying regulation. As such, we are unable to quantify this, and assume that the numbers are negligible.

To get estimates for the percentage of birds that are organic, we have combined the 2019 organic farm survey data available in Table 17 ([organics\\_1\\_017\\_017.pdf \(usda.gov\)](#)) which gives the number of farms that have organic birds with the 2017 USDA, NASS Census of Agriculture (CoA) to get a total number of farms. These are part of the 2017 CoA. Table 5 summarizes these data and contains places to include data on free range or pasture raised birds if the data becomes available. The percentage of farms with organic poultry is the number of



organic farms divided by the total number of farms. Note that this is not actually the percentage of organic farms or percentage of poultry raised organically, but the percentage of farms that have any organic birds raised out of their total flock. Lastly, we have done this for the extent of the United States but can break these data out by state, if desired.

*Table 5. Housing of commercial poultry.*

| Species | Type    | #OrganicFarms | #FreeRangeFarms | #PastureRaised | #TotalFarms | Percentage  |
|---------|---------|---------------|-----------------|----------------|-------------|-------------|
| Chicken | Broiler | 369           | NA              | NA             | 42858       | 0.008609828 |
| Chicken | Layer   | 1057          | NA              | NA             | 232500      | 0.004546237 |
| Turkey  | All     | 129           | NA              | NA             | 23173       | 0.005566823 |

### **Percent of backyard poultry housed outside**

We used an available dataset on backyard poultry included in a 2004 survey from the USDA on backyard poultry practices ([Cover \(usda.gov\)](https://www.ams.usda.gov/cover)). Documentation of the original USDA survey questionnaire is [publicly available](#). This study surveyed people with backyard poultry in 18 major poultry producing states. Within these states, they identified 350 large commercial poultry operations with >10,000 chickens or 5,000 turkeys. Then, animal health officials canvassed the area within a 1-mile radius of these farms for residents with backyard birds (defined as no more than 1,000 birds) on their properties, excluding pets. Residents with birds were then asked to complete the questionnaire. Hence, these are not a random sample of all backyard birds, but instead a sample of backyard birds located next to major commercial poultry operations within major poultry producing states.

The most relevant information at hand is found in section [I.B.3](#). Residents with backyard flocks were asked if they had any poultry on site that fit into any of three categories: Outdoors confined to property, outdoors able to leave property, or inside. Again, this was a “check all that apply” question, and many residents checked multiple options (as these raw totals add up to ~170%). In addition, those that had poultry housed inside (i.e., a barn or coop) were asked if they were allowed to go outside, of which a total of 65% of residents with indoor birds said “yes”. Thus, 65% of the 73% of farms with indoor poultry allow these indoor poultry to go outside.

This type of survey data leads to a problem in trying to estimate either the number of birds housed outside or the number of residents with birds outside as residents could check more than one box. We calculated overall percentages using two methods. The first re-weights the data to calculate the percentage outdoors. If residents are equally likely to check any combination of boxes (an assumption that is likely not true), this would give a reasonable value. This is the sum of percent of birds allowed off property, confined to property, and inside birds times % allowed outside, divided by the sum of the three percentages. This is the value included in the next table. We have also calculated a minimum number that are allowed outside, which assumes that all of the farms with indoor poultry only had indoor poultry. This is calculated as one minus the percentage of residents that had inside poultry times the proportion of inside poultry not allowed outside. This represents the lowest possible percentage of outdoor birds. We have also created a maximum estimate for the number of birds kept outside, which assumes that no residents had birds that were both outside and allowed off property as well as outside and confined to property,

and that their number of inside birds was negligible in comparison to the number of outside birds.

In addition, those that had poultry housed inside (i.e., a barn or coop) were asked if they were allowed to go outside, of which a total of 65% of residents with indoor birds said “yes”.

The following table summarizes this data. We have calculated this for the overall data but could also go back and get separate estimates for the Southwest, Midwest, East, and Southeast regions. This data is not broken down by poultry type.

*Table 6. Housing of backyard birds.*

| Off<br>Property | On<br>Property | Inside | %Inside<br>Allowed<br>Out | Base<br>Percent | Min<br>Outside | Max<br>Outside |
|-----------------|----------------|--------|---------------------------|-----------------|----------------|----------------|
| 0.471           | 0.515          | 0.733  | 0.65                      | 0.851           | 0.74345        | 0.996262       |

## Obtaining relative risk values

The weights from these tables then go into the table of hybrid model poultry types and are used to calculate a weighted risk that takes into account the percentage of birds housed outdoors.

*Table 7. Relative risk by poultry types in the hybrid model.*

| Species | Commodity     | Category   | Sector     | IndoorRR | OutdoorRR | %Outdoor   | WeightedRR  |
|---------|---------------|------------|------------|----------|-----------|------------|-------------|
| Chicken | Broiler       | Commercial | Production | 0.2      | 2.2       | 0.00860983 | 0.217219656 |
| Chicken | Broiler       | Commercial | Breeding   | 1        | 11.1      | 0          | 1           |
| Chicken | Layer         | Commercial | Production | 1        | 11.1      | 0.00454624 | 1.045916989 |
| Chicken | Layer         | Commercial | Breeding   | 1        | 11.1      | 0          | 1           |
| Chicken | Layer pullets | Commercial | NA         | 1        | 11.1      | 0          | 1           |
| Turkey  | All           | Commercial | Production | 7.7      | 18        | 0.00556682 | 7.757338282 |
| Turkey  | All           | Commercial | Breeding   | 7.7      | 18        | 0          | 7.7         |
| Chicken | Broiler       | Backyard   | Production | 0.2      | 11.1      | 0.85075625 | 9.473243165 |
| Chicken | Broiler       | Backyard   | Breeding   | 1        | 11.1      | 0.85075625 | 9.592638162 |
| Chicken | Layer         | Backyard   | Production | 1        | 11.1      | 0.85075625 | 9.592638162 |
| Chicken | Layer         | Backyard   | Breeding   | 1        | 11.1      | 0.85075625 | 9.592638162 |
| Chicken | Layer pullets | Backyard   | NA         | 1        | 11.1      | 0.85075625 | 9.592638162 |
| Turkey  | All           | Backyard   | Production | 7.7      | 18        | 0.85075625 | 16.46278941 |
| Turkey  | All           | Backyard   | Breeding   | 7.7      | 18        | 0.85075625 | 16.46278941 |

There are a few important things to note.

1. We currently lack data on free range and pasture raised poultry that are not certified organic. We are currently assuming that these numbers are negligible.
2. We assume that breeders for all commercial types are only housed indoors, as there is not a cost benefit to the farms for raising these organically/outdoors.

3. We do not have data on layer pullets being kept indoors/outdoors. Currently we are assuming that commercial birds are also always kept indoors while backyard birds are housed outdoors at the same proportions as for other poultry types.
4. All backyard poultry types have the same percentage of birds kept outdoors because we cannot break this data down by poultry type.
5. Breeders of any type are treated as layer/breeder for their relative risk estimates. There may be greater biosecurity at breeder facilities, however we currently have no way to quantify this. That said, the assumption that all breeders are kept indoors does account for this somewhat by lowering the estimate compared to the other species and production types.
6. Currently we are using different values for commercial and backyard broilers, where outdoor commercial broilers are given a lower relative risk because of their short lifespan. However, this is probably less true for backyard broilers, so they are instead assigned the same relative risks as layer/breeders. It is possible that we should also do this for indoor backyard broilers, but we have currently left them with the standard indoor broiler relative risk.

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