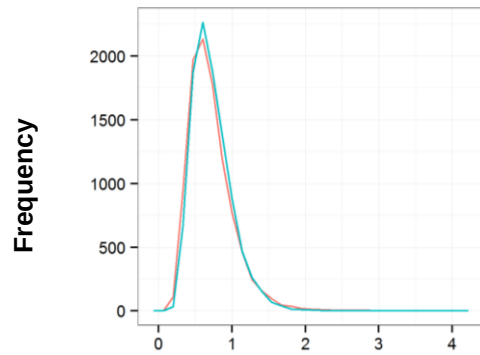


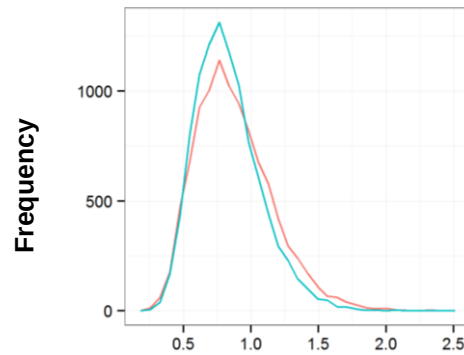
## Supplementary information

### Supplementary Fig 1. Precision of parameter estimates

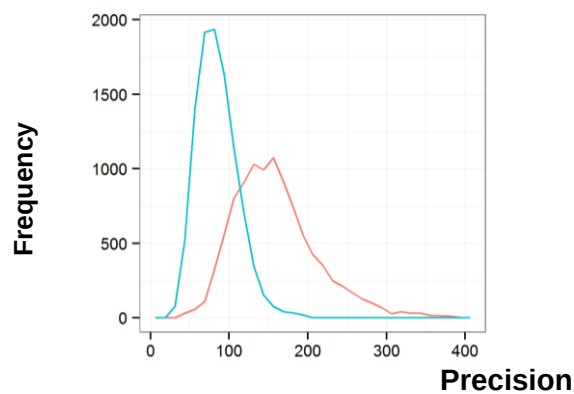
**A) Neonicotinoid exposure**



**B) Oilseed rape cover**



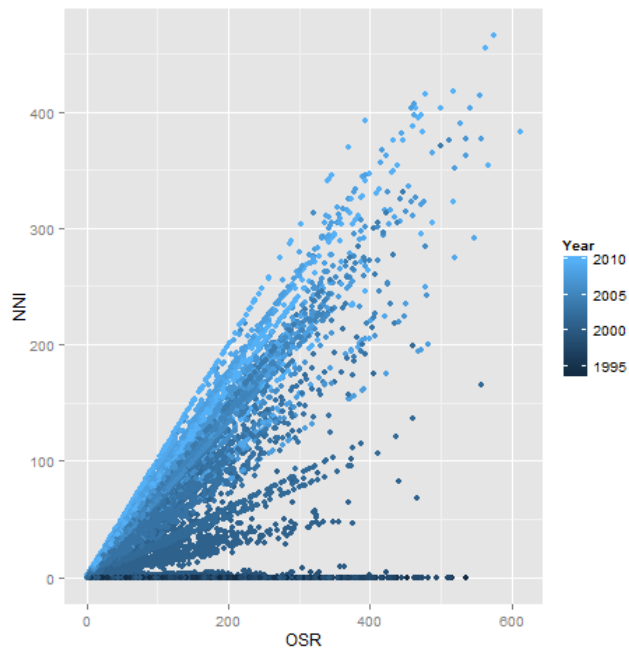
**C) Foliar insecticide index**



**OSR\_forager**  
— FALSE  
— TRUE

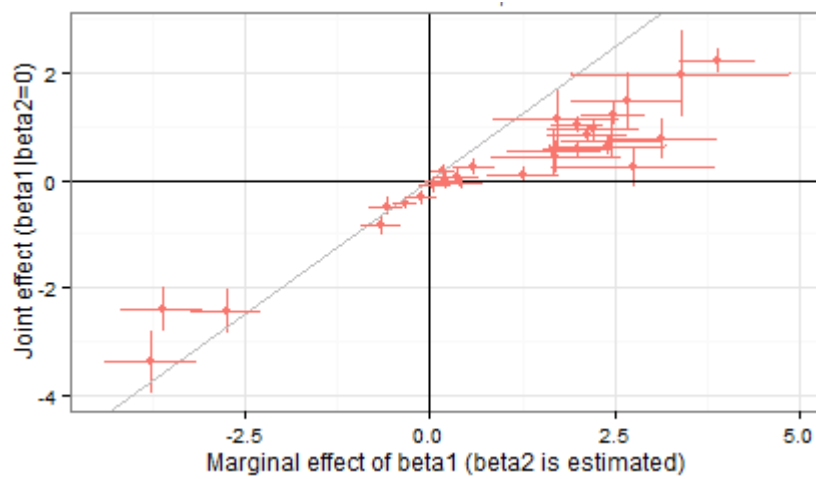
**Supplementary Fig 1.** The precision (1/variance across species) of the parameter estimates derived from the multi-species dynamic Bayesian occupancy-detection model. This shows the precision for oilseed rape foraging (blue) and non-foraging (red) wild bee species to the cover of neonicotinoid seed treated oilseed rape (A), the cover of oilseed rape (B), and the foliar insecticide index (C) from 1993 – 2010.

**Supplementary Fig 2. Colinearity between oilseed rape cover and neonicotinoid exposure.**



**Supplementary Fig 2.** Plot of raw data showing the correlations between oilseed rape cover (OSR, cover in m<sup>2</sup> within 5 km grid squares) and neonicotinoid exposure (NNI, cover in m<sup>2</sup> of treated crop) from 1993 to 2010.

**Supplementary Fig 3. Colinearity between oilseed rape cover and neonicotinoid exposure.**



**Supplementary Fig 3.** Oilseed rape effect ( $\beta_1$ ) in models with and without the neonicotinoid exposure effect ( $\beta_2$ ). Error bars represent one standard deviation of posteriors in each direction. If collinearity was a serious problem there would be poor correlation between the estimates for  $\beta_1$  (the oilseed rape effect) from the simple and complex models.

### Supplementary Table 1.

Table listing species of bee (Apidae) found in association with UK oilseed rape crops. This is derived from published surveys undertaken in 2011 and 2012 <sup>1-3</sup> from 30 English farms and representing 114 hours of observations. It should be noted that while this is based on a robust data set it is possible that wild bee specie not recorded here may utilize the crop. With the exception of the honeybees, all species are assumed to represent un-managed wild populations. While some *Bombus* spp. (e.g. *Bombus terrestris*) may be managed as artificial colonies to promote pollination, particularly in association with glasshouse agriculture, such colonies are not typically placed into UK arable agricultural systems. Species indicated by † were identified by Kleijn et al <sup>4</sup> as being in the top 100 most important wild bee pollinators of world crop.

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#### Apidae (domesticated / managed)

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*Apis mellifera* Linnaeus, 1758

#### Apidae (un-managed wild species)

---

*Anthophora plumipes* (Pallas, 1772)

*Bombus cryptarum* (Fabricius, 1775)

*Bombus hortorum* (Linnaeus, 1761) †

*Bombus hypnorum* (Linnaeus, 1758) †

*Bombus jonellus* (Kirby, 1802)

*Bombus lapidarius* (Linnaeus, 1758) †

*Bombus lucorum* s.l. (Linnaeus, 1761) †

*Bombus magnus* Vogt, 1911

*Bombus pascuorum* (Scopoli, 1763) †

*Bombus pratorum* (Linnaeus, 1761) †

*Bombus terrestris* (Linnaeus, 1758) †

*Bombus vestalis* (Geoffroy, 1785) \*

*Nomada marshamella* (Kirby, 1802)

\* *B. vestalis* is a social parasite of *B. terrestris* and while not directly supporting its offspring by foraging on oilseed rape would though it host have larvae exposed to neonicotinoids expressed in the pollen of the crop.

## Andrenidae

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*Andrena angustior* (Kirby, 1802)  
*Andrena bicolor* Fabricius, 1775  
*Andrena carantonica* Pérez, 1902 †  
*Andrena cineraria* (Linnaeus, 1758) †  
*Andrena chrysosceles* (Kirby, 1802) †  
*Andrena congruens* Schmiedeknecht, 1884  
*Andrena fucata* Smith, F., 1847  
*Andrena dorsata* (Kirby, 1802) †  
*Andrena fulva* Müller, 1766 †  
*Andrena flavipes* Panzer, 1799 †  
*Andrena haemorrhoa* (Fabricius, 1781)  
*Andrena minutula* (Kirby, 1802) †  
*Andrena nigrospina* Thomson, 1872  
*Andrena nigroaenea* (Kirby, 1802)  
*Andrena nitida* (Müller, 1776) †  
*Andrena niveata* Friese, 1887  
*Andrena ovatula* (Kirby, 1802)  
*Andrena subopaca* Nylander, 1848  
*Andrena synadelpha* Perkins, 1914  
*Andrena helvola* (Linnaeus, 1758)

## Halictidae

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*Halictus rubicundus* (Christ, 1791) †  
*Halictus tumulorum* (Linnaeus, 1758)  
*Lasioglossum albipes* (Fabricius, 1781)  
*Lasioglossum calceatum* (Scopoli, 1763) †  
*Lasioglossum cupromicans* (Pérez, 1903)  
*Lasioglossum fulvicorne* (Kirby, 1802)  
*Lasioglossum leucopus* (Kirby, 1802)  
*Lasioglossum leucozonium* (Schrank, 1781)  
*Lasioglossum malachurum* (Kirby, 1802) †  
*Lasioglossum morio* (Fabricius, 1793) †  
*Lasioglossum parvulum* (Schenck, 1853)  
*Lasioglossum pauxillum* (Schenck, 1853)  
*Lasioglossum smeathmanellum* (Kirby, 1802)  
*Lasioglossum zonulum* (Smith, F., 1848).

## Megachilidae

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*Osmia bicolor* (Schrank, 1781)  
*Osmia bicornis* (Linnaeus, 1758) †

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## Supplementary Table 2.

Table listing species of bee (Apidae) which reached the minimum threshold of data quality for inclusion in the multi-species multi-season Bayesian analysis. Species are classified as either foragers or non-foragers on oilseed rape.

| Family     | Species                                        | Oilseed rape preference |
|------------|------------------------------------------------|-------------------------|
| Andrenidae | <i>Andrena barbilabris</i> (Kirby, 1802)       | Non-forager             |
| Andrenidae | <i>Andrena clarkella</i> (Kirby, 1802)         | Non-forager             |
| Andrenidae | <i>Andrena fuscipes</i> (Kirby, 1802)          | Non-forager             |
| Andrenidae | <i>Andrena semilaevis</i> Pérez, 1903          | Non-forager             |
| Andrenidae | <i>Andrena wilkella</i> (Kirby, 1802)          | Non-forager             |
| Andrenidae | <i>Andrena bicolor</i> Fabricius, 1775         | Forager                 |
| Andrenidae | <i>Andrena carantonica</i> Pérez, 1902         | Forager                 |
| Andrenidae | <i>Andrena chrysosceles</i> (Kirby, 1802)      | Forager                 |
| Andrenidae | <i>Andrena cineraria</i> (Linnaeus, 1758)      | Forager                 |
| Andrenidae | <i>Andrena dorsata</i> (Kirby, 1802)           | Forager                 |
| Andrenidae | <i>Andrena flavipes</i> Panzer, 1799           | Forager                 |
| Andrenidae | <i>Andrena fulva</i> Müller, 1766              | Forager                 |
| Andrenidae | <i>Andrena haemorrhoa</i> (Fabricius, 1781)    | Forager                 |
| Andrenidae | <i>Andrena minutula</i> (Kirby, 1802)          | Forager                 |
| Andrenidae | <i>Andrena nigroaenea</i> (Kirby, 1802)        | Forager                 |
| Andrenidae | <i>Andrena nitida</i> (Müller, 1776)           | Forager                 |
| Andrenidae | <i>Andrena subopaca</i> Nylander, 1848         | Forager                 |
| Apidae     | <i>Anthophora bimaculata</i> (Panzer, 1798)    | Non-forager             |
| Apidae     | <i>Bombus sylvestris</i> (Lepeletier, 1832)    | Non-forager             |
| Apidae     | <i>Nomada fabriciana</i> (Linnaeus, 1767)      | Non-forager             |
| Apidae     | <i>Nomada flava</i> Panzer, 1798               | Non-forager             |
| Apidae     | <i>Nomada flavoguttata</i> (Kirby, 1802)       | Non-forager             |
| Apidae     | <i>Nomada fucata</i> Panzer, 1798              | Non-forager             |
| Apidae     | <i>Nomada goodeniana</i> (Kirby, 1802)         | Non-forager             |
| Apidae     | <i>Nomada ruficornis</i> (Linnaeus, 1758)      | Non-forager             |
| Apidae     | <i>Nomada rufipes</i> Fabricius, 1793          | Non-forager             |
| Apidae     | <i>Anthophora plumipes</i> (Pallas, 1772)      | Forager                 |
| Apidae     | <i>Bombus hortorum</i> (Linnaeus, 1761)        | Forager                 |
| Apidae     | <i>Bombus jonellus</i> (Kirby, 1802)           | Forager                 |
| Apidae     | <i>Bombus lapidarius</i> (Linnaeus, 1758)      | Forager                 |
| Apidae     | <i>Bombus pascuorum</i> (Scopoli, 1763)        | Forager                 |
| Apidae     | <i>Bombus pratorum</i> (Linnaeus, 1761)        | Forager                 |
| Apidae     | <i>Bombus terrestris</i> / <i>lucorum</i> agg. | Forager                 |
| Apidae     | <i>Bombus vestalis</i> (Geoffroy, 1785)        | Forager                 |
| Apidae     | <i>Nomada marshamella</i> (Kirby, 1802)        | Forager                 |

|              |                                                  |             |
|--------------|--------------------------------------------------|-------------|
| Colletidae   | <i>Colletes daviesanus</i> Smith, 1846           | Non-forager |
| Colletidae   | <i>Colletes succinctus</i> (Linnaeus,1758)       | Non-forager |
| Colletidae   | <i>Hylaeus communis</i> Nylander,1852            | Non-forager |
| Colletidae   | <i>Hylaeus hyalinatus</i> Smith,1842             | Non-forager |
| Halictidae   | <i>Lasioglossum minutissimum</i> (Kirby,1802)    | Non-forager |
| Halictidae   | <i>Lasioglossum villosulum</i> (Kirby,1802)      | Non-forager |
| Halictidae   | <i>Sphecodes ephippius</i> (Linnaeus,1767)       | Non-forager |
| Halictidae   | <i>Sphecodes geoffrellus</i> (Kirby,1802)        | Non-forager |
| Halictidae   | <i>Sphecodes monilicornis</i> (Kirby,1802)       | Non-forager |
| Halictidae   | <i>Sphecodes pellucidus</i> Smith,1845           | Non-forager |
| Halictidae   | <i>Halictus rubicundus</i> (Christ,1791)         | Forager     |
| Halictidae   | <i>Halictus tumulorum</i> (Linnaeus,1758)        | Forager     |
| Halictidae   | <i>Lasioglossum albipes</i> (Fabricius, 1781)    | Forager     |
| Halictidae   | <i>Lasioglossum calceatum</i> (Scopoli, 1763)    | Forager     |
| Halictidae   | <i>Lasioglossum fulvicorne</i> (Kirby, 1802)     | Forager     |
| Halictidae   | <i>Lasioglossum leucopus</i> (Kirby, 1802)       | Forager     |
| Halictidae   | <i>Lasioglossum leucozonium</i> (Schrank, 1781)  | Forager     |
| Halictidae   | <i>Lasioglossum malachurum</i> (Kirby, 1802)     | Forager     |
| Halictidae   | <i>Lasioglossum morio</i> (Fabricius, 1793)      | Forager     |
| Halictidae   | <i>Lasioglossum parvulum</i> (Schenck, 1853)     | Forager     |
| Halictidae   | <i>Lasioglossum pauxillum</i> (Schenck, 1853)    | Forager     |
| Halictidae   | <i>Lasioglossum smeathmanellum</i> (Kirby, 1802) | Forager     |
| Megachilidae | <i>Megachile versicolor</i> Smith, F.,1844       | Non-forager |
| Megachilidae | <i>Megachile willughbiella</i> (Kirby,1802)      | Non-forager |
| Megachilidae | <i>Osmia caerulea</i> (Linnaeus,1758)            | Non-forager |
| Megachilidae | <i>Osmia spinulosa</i> (Kirby,1802)              | Non-forager |
| Megachilidae | <i>Osmia bicornis</i> (Linnaeus,1758)            | Forager     |

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### **Supplementary Note 1. Collinearity and robustness checks**

Our estimates of neonicotinoid dose incorporate information about oilseed rape cover. As such there is an inherent potential problem that collinearity may exist between two of our core response variables, i.e. oilseed rape cover and neonicotinoid dose. Oilseed rape represents the dominant mass flowering crop to which neonicotinoid seed treatments are applied within the UK (Fig. S2). As such, the correlation between neonicotinoid dose and oilseed rape is a real and unavoidable phenomenon, rather than an artefact of our treatment of the data. However, the statistical point about collinearity deserves investigation. Plotting the raw data shows that, although correlated, there is substantial variation in neonicotinoid dose that is independent of the cover of oilseed rape. In fact, the oilseed rape cover explains less than half the variation in neonicotinoid dose.

This correlation is still high enough to introduce some uncertainty into the estimates for both parameters. In technical terms, correlation in the data leads to a ridge in the likelihood surface where a range of combinations of parameter estimates are an equally good fit to the data <sup>5</sup>. In general, Bayesian statistics are much more robust to collinearity than Frequentist ones, because parameter estimates are expressed as credible intervals of the posterior distribution <sup>6,7</sup>; if serious collinearity existed then the credible intervals would be wider than in a situation where it did not exist. By contrast, frequentist statistics assume that parameter values are fixed points and standard errors on the estimates express uncertainty about the data: if collinearity exists then frequentist models are prone to false precision because the parameters cannot be separately identified <sup>8</sup>.

One way to explore collinearity in more detail is to fit models both with and without the term for neonicotinoids (i.e.  $\beta_2$  is fixed at zero). If collinearity was a serious problem, we would

find a poor correlation between the estimates for  $\beta_1$  (the oilseed rape effect) from the simple and complex models. The plot (Fig. S3) shows three features. First, the correlation is tight overall: the estimate of the oilseed rape parameter ( $\beta_1$ ) is generally similar in both sets of models. Second, the oilseed rape estimate is generally shallower when the neonicotinoid effect is absent. This is entirely expected: by omitting  $\beta_2$ , the estimate of  $\beta_1$  is forced to explain both the positive effect of oilseed rape in addition to the negative effect of neonicotinoids. The third feature of this plot is that uncertainty (the width of the posterior) is larger in the model where  $\beta_2$  is estimated than in the model where it is excluded. This additional uncertainty is due to collinearity. In other words, the simple model is able to estimate with the same precision the joint effects of oilseed rape and neonicotinoids: the complex model is able to estimate the marginal effects, but with lower precision.

In summary, we believe that potential collinearity has probably reduced the precision with which we can estimate the oilseed rape and neonicotinoid effects, but has not introduced directional bias into the parameter estimates. Therefore, the conclusions that neonicotinoid dose has a negative impact on many species, and that species foraging on oilseed rape are more negatively affected are both robust to any collinearity issue that exist.

## Supplementary Note 2: Dynamic occupancy model to assess the role of neonicotinoid pesticides (and other covariates) on bees

#####

# Dynamic occupancy model to assess the role of neonicotinoid pesticides (and other covariates) on bees

# State model: Occupancy is a function of previous state, modified by colonization and persistence

# Persistence model: of individual grid cells, as a function of pesticide load

# Observation model: one line per visit, and DATATYPE (a measure of sampling intensity per visit)

#####

# Nick Isaac, 2015

# the state model structure comes from Royle and Dorazio <sup>9</sup>.

# the observation part of the model is derived from van Strien et al. <sup>10</sup>.

# the multispecies component follows Ruiz-Gutiérrez, et al. <sup>11</sup>.

#####

model {

##### State Priors

# for species terms where all species are drawn from a common distribution

for(i in 1:nspecies){

  # FIXED EFFECTS

  init.occ[i] ~ dunif(0, 1) # vague prior on occupancy in year 1.

```

# RANDOM EFFECTS
alpha.phi[i] ~ dnorm(mu.alpha.phi, tau.alpha.phi)
logitgamma[i] ~ dnorm(mu.gamma, tau.gamma) # Colonisation probabilities
logit(gamma[i]) <- logitgamma[i]

# EFFECTS THAT ARE RANDOM BUT DEPENDENT ON TRAIT (OSR forager)
beta1[i] ~ dnorm(mu.beta1[OSRf[i]], tau.beta1[OSRf[i]])
beta2[i] ~ dnorm(mu.beta2[OSRf[i]], tau.beta2[OSRf[i]])
beta3[i] ~ dnorm(mu.beta3[OSRf[i]], tau.beta3[OSRf[i]])
}

# State model hyperpriors
mu.alpha.phi ~ dnorm(0, 0.01) #persistence intercept (expected value=0, so persistence=0.5)
mu.gamma ~ dnorm(0, 0.01)

tau.alpha.phi ~ dt(0,1,1)T(0,)
tau.gamma ~ dt(0,1,1)T(0,)

for(f in 1:2){
  #Response to OSR cover differs between forager and non-foragers
  beta1.mean[f] ~ dunif(0,1) # parameter on the measurement scale
  mu.beta1[f] <- logit(beta1.mean[f])
  tau.beta1[f] ~ dt(0,1,1)T(0,)

  #Response to NNI differs between forager and non-foragers
  beta2.mean[f] ~ dunif(0,1) # parameter on the measurement scale
  mu.beta2[f] <- logit(beta2.mean[f])
  tau.beta2[f] ~ dt(0,1,1)T(0,)

  #Response to neonics differs between forager and non-foragers
  beta3.mean[f] ~ dunif(0,1) # parameter on the measurement scale
  mu.beta3[f] <- logit(beta3.mean[f])
  tau.beta3[f] ~ dt(0,1,1)T(0,)
}

##### Observation model priors
for(i in 1:nspecies){
  dtype1.p[i] ~ dnorm(mu.d1.p, tau.lp1)
  dtype2.p[i] ~ dnorm(mu.d2.p, tau.lp2)
  dtype3.p[i] ~ dnorm(mu.d3.p, tau.lp3)
}

for (t in 1:nyear) {
  alpha.t.p[t] ~ dnorm(0, tau.lp4)
}

# observation model hyperpriors

```

```

mu.d1.p ~ dnorm(-2, 0.01) # mean species effect ilt(-2) = 0.12 (probability of being recorded
on a list of length 1) #
mu.d2.p ~ dnorm(0, 0.01)
mu.d3.p ~ dnorm(0, 0.01)

tau.lp1 ~ dt(0,1,1)T(0,)
tau.lp2 ~ dt(0,1,1)T(0,)
tau.lp3 ~ dt(0,1,1)T(0,)
tau.lp4 ~ dt(0,1,1)T(0,)

#####
# State model
for (i in 1:nspecies){
  for (j in 1:nQ){ # j loop indexes the quadrant (5km grid cell), not monad
    z[i,j,1] ~ dbern(init.occ[i])
    for (t in 2:nyear){
      # Persistence at site i in year t is a function of covariates in year t-1
      logit(phi[i,j,t]) <- alpha.phi[i] + beta1[i] * OSR[j,t-1] + beta2[i] * NNI[j,t-1] + beta3[i] *
FBI[j,t-1]

      # Dynamic Occupancy = previous occupancy, modified by persistence + colonization
      muZ[i,j,t] <- z[i,j,t-1] * phi[i,j,t] + (1 - z[i,j,t-1]) * gamma[i]

      # True occupancy z at site i in year t
      z[i,j,t] ~ dbern(muZ[i,j,t])
    }}
}

# Observation model: go through the visits and find the matching year and site identity
for (i in 1:nspecies){
  for(k in 1:nvisit) {
    #for each visit, find the matching site, quadrant and year identities
    logit(p[i,k]) <- alpha.t.p[Year[k]] + dtype1.p[i] + dtype2.p[i]*DATATYPE2[k] +
dtype3.p[i]*DATATYPE3[k]

    Py[i,k]<- z[i,q[Site[k]],Year[k]] * p[i,k] # Site refers to the monad in q[Site[k]]

    y[k,i] ~ dbern(Py[i,k])
  }}

##### DERIVED PARAMETERS

# difference between OSR and non foragers
beta1.diff <- mu.beta1[1] - mu.beta1[2]
beta2.diff <- mu.beta2[1] - mu.beta2[2]
beta3.diff <- mu.beta3[1] - mu.beta3[2]

# end of model formulation
}

```

## Supplementary References

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