Appendix

Code for the transmission model (see chapter 8, equations 8.1-8.11).

The model was encoded in Visual Basic (Microsoft Inc.). Each function that is called on refers to separate code, which undertakes that particular task. Thus, for example, “DeadEggs” refers to a function that calculates egg loss at each time step, according to rates of development and mortality that are themselves drawn from functions that generate these rates for each area according to rules governing climatic stochasticity. The code structure is therefore not linear. Only the ‘core code’ is reproduced here, i.e. that which deals with equations 8.1-8.11. Abbreviations are not given, but comments in italics explain each segment of code.

```
'Enter loop
‘dT is the time step for Euler approximation, which can be set to any duration (default= 1 day)

For sngDay = 361 To intTerm Step dT

'work out locations of saigas (Loc1) and transhumant sheep (Loc2) from rules laid out elsewhere
‘Present location (Loc) determines the pasture that is contaminated with eggs, and previous location
‘(Pickup) determines the geographical origin of  nematodes maturing now.

intLoc1 = Loc1((sngDay))
intLoc2 = Loc2((sngDay))
intPickup1 = Loc1((sngDay - sngPPP))
intPickup2 = Loc2((sngDay - sngPPP))

'compute seasonally-varying parameters
‘Refers to a separate module that simulates all seasonally-varying rates for each location, according to
‘rules laid out in the text of Chapter 8

Seasonality (sngDay)

'host population dynamics
‘Number of juveniles in each sub-population depends on rates of birth, mortality and maturation.
‘That of adults depends on rates of maturation and mortality.

'H1=saigas <1 year old, H2=saigas >1 year old
H1(sngDay) = H1(sngDay - dT) + dT * (-deadH((H1(sngDay - dT)), 1) + bornH(H2(sngDay - dT), 1) -
bornH(H1(sngDay - dT), 2))
H2(sngDay) = H2(sngDay - dT) + dT * (-deadH((H2(sngDay - dT)), 2) + bornH(H1(sngDay - dT), 2))
'H3, H4=transhumant lambs and sheep
H3(sngDay) = H3(sngDay - dT) + dT * (-deadH((H3(sngDay - dT)), 3) + bornH(H4(sngDay - dT), 3) -
bornH(H3(sngDay - dT), 4))
H4(sngDay) = H4(sngDay - dT) + dT * (-deadH((H4(sngDay - dT)), 4) + bornH(H3(sngDay - dT), 4))
'H5,H6=lambs and sheep in Centre
H5(sngDay) = H5(sngDay - dT) + dT * (-deadH((H5(sngDay - dT)), 3) + bornH(H6(sngDay - dT), 3) -
bornH(H5(sngDay - dT), 4))
H6(sngDay) = H6(sngDay - dT) + dT * (-deadH((H6(sngDay - dT)), 4) + bornH(H5(sngDay - dT), 4))
'H7,H8=lambs and sheep in North
H7(sngDay) = H7(sngDay - dT) + dT * (-deadH((H7(sngDay - dT)), 3) + bornH(H8(sngDay - dT), 3) -
bornH(H7(sngDay - dT), 4))
H8(sngDay) = H8(sngDay - dT) + dT * (-deadH((H8(sngDay - dT)), 4) + bornH(H7(sngDay - dT), 4))
'H9,H10=lambs and sheep in South
H9(sngDay) = H9(sngDay - dT) + dT * (-deadH((H9(sngDay - dT)), 3) + bornH(H10(sngDay - dT), 3) -
bornH(H9(sngDay - dT), 4))
H10(sngDay) = H10(sngDay - dT) + dT * (-deadH((H10(sngDay - dT)), 4) + bornH(H9(sngDay - dT),
4))
```

'adjust mean burdens to allow for recruitment of uninfected hosts

sngP1(sngDay) = AdjJuv((sngP1(sngDay - dT)), (H1(sngDay - dT)), (H2(sngDay - dT)), 1)
sngP3(sngDay) = AdjJuv((sngP3(sngDay - dT)), (H3(sngDay - dT)), (H4(sngDay - dT)), 3)
sngP5(sngDay) = AdjJuv((sngP5(sngDay - dT)), (H5(sngDay - dT)), (H6(sngDay - dT)), 3)
sngP7(sngDay) = AdjJuv((sngP7(sngDay - dT)), (H7(sngDay - dT)), (H8(sngDay - dT)), 3)
sngP9(sngDay) = AdjJuv((sngP9(sngDay - dT)), (H9(sngDay - dT)), (H10(sngDay - dT)), 3)

sngP2(sngDay) = AdjAd((sngP2(sngDay - dT)), (H2(sngDay - dT)), (sngP1(sngDay - dT)), (H1(sngDay - dT)), 2)
sngP4(sngDay) = AdjAd((sngP4(sngDay - dT)), (H4(sngDay - dT)), (sngP3(sngDay - dT)), (H3(sngDay - dT)), 4)
sngP6(sngDay) = AdjAd((sngP6(sngDay - dT)), (H6(sngDay - dT)), (sngP5(sngDay - dT)), (H5(sngDay - dT)), 4)
sngP8(sngDay) = AdjAd((sngP8(sngDay - dT)), (H8(sngDay - dT)), (sngP7(sngDay - dT)), (H7(sngDay - dT)), 4)
sngP10(sngDay) = AdjAd((sngP10(sngDay - dT)), (H10(sngDay - dT)), (sngP9(sngDay - dT)), (H9(sngDay - dT)), 4)

'free-living stages in each location (1=North, 2=Centre, 3= South of Betpak-Dala).

'Egg mortality and loss through onward development

dblE(sngDay, 1) = dblE(sngDay - dT, 1) - dT * (DeadEggs((dblE(sngDay - dT, 1)), 1))
dblE(sngDay, 2) = dblE(sngDay - dT, 2) - dT * (DeadEggs((dblE(sngDay - dT, 2)), 2))
dblE(sngDay, 3) = dblE(sngDay - dT, 3) - dT * (DeadEggs((dblE(sngDay - dT, 3)), 3))

'Eggs added from migrating saigas and transhumant stock

dblE(sngDay, intLoc1) = (dblE(sngDay, intLoc1)) _
+ dT * ((NewEggs((sngP1(sngDay - dT)), (intLoc1), (H1(sngDay)), 1)) + ((NewEggs((sngP2(sngDay - dT)), (intLoc1), (H2(sngDay)), 2))))
dblE(sngDay, intLoc2) = (dblE(sngDay, intLoc2)) _
+ dT * ((NewEggs((sngP3(sngDay - dT)), (intLoc2), (H3(sngDay)), 3)) + ((NewEggs((sngP4(sngDay - dT)), (intLoc2), (H4(sngDay)), 4))))

'Eggs added fom sedentary stock populations

dblE(sngDay, 2) = dblE(sngDay, 2) _
+ dT * ((NewEggs((sngP5(sngDay - dT)), 2, (H5(sngDay)), 5)) + (NewEggs((sngP6(sngDay - dT)), 2, (H6(sngDay)), 6)))
dblE(sngDay, 1) = dblE(sngDay, 1) _
+ dT * ((NewEggs((sngP7(sngDay - dT)), 1, (H7(sngDay)), 7)) + (NewEggs((sngP8(sngDay - dT)), 1, (H8(sngDay)), 8)))
dblE(sngDay, 3) = dblE(sngDay, 3) _
+ dT * ((NewEggs((sngP9(sngDay - dT)), 3, (H9(sngDay)), 9)) + (NewEggs((sngP10(sngDay - dT)), 3, (H10(sngDay)), 10)))

'Larval development within the egg

dblEL(sngDay, 1) = dblEL(sngDay - dT, 1) + dT * (-DeadEL((dblEL(sngDay - dT, 1)), 1) _
+ NewEL((dblE(sngDay - dT, 1)), 1))
dblEL(sngDay, 2) = dblEL(sngDay - dT, 2) + dT * (-DeadEL((dblEL(sngDay - dT, 2)), 2) _
+ NewEL((dblE(sngDay - dT, 2)), 2))
dblEL(sngDay, 3) = dblEL(sngDay - dT, 3) + dT * (-DeadEL((dblEL(sngDay - dT, 3)), 3) _
+ NewEL((dblE(sngDay - dT, 3)), 3))

'Larvae emerging from eggs

```
dblL(sngDay, 1) = dblL(sngDay - dT, 1) + dT * (-DeadL((dblL(sngDay - dT, 1)), 1) _
+ NewL((dblEL(sngDay - dT, 1)), 1))
dblL(sngDay, 2) = dblL(sngDay - dT, 2) + dT * (-DeadL((dblL(sngDay - dT, 2)), 2) _
+ NewL((dblEL(sngDay - dT, 2)), 2))
dblL(sngDay, 3) = dblL(sngDay - dT, 3) + dT * (-DeadL((dblL(sngDay - dT, 3)), 3) _
+ NewL((dblEL(sngDay - dT, 3)), 3))
```

'Onward development to the infective L3 stage

```
dblL3(sngDay, 1) = dblL3(sngDay - dT, 1) + dT * (-DeadL3((dblL3(sngDay - dT, 1)), 1) _
+ NewL3((dblL(sngDay - dT, 1)), 1) - LostL3((dblL3(sngDay - dT, 1)), 1))
dblL3(sngDay, 2) = dblL3(sngDay - dT, 2) + dT * (-DeadL3((dblL3(sngDay - dT, 2)), 2) _
+ NewL3((dblL(sngDay - dT, 2)), 2) - LostL3((dblL3(sngDay - dT, 2)), 2))
dblL3(sngDay, 3) = dblL3(sngDay - dT, 3) + dT * (-DeadL3((dblL3(sngDay - dT, 3)), 3) _
+ NewL3((dblL(sngDay - dT, 3)), 3) - LostL3((dblL3(sngDay - dT, 3)), 3))
```

'Migration of L3 onto herbage

```
dblLh(sngDay, 1) = dblLh(sngDay - dT, 1) + dT * (-DeadLh((dblLh(sngDay - dT, 1)), 1) _
+ NewLh((dblL3(sngDay - dT, 1)), 1))
dblLh(sngDay, 2) = dblLh(sngDay - dT, 2) + dT * (-DeadLh((dblLh(sngDay - dT, 2)), 2) _
+ NewLh((dblL3(sngDay - dT, 2)), 2))
dblLh(sngDay, 3) = dblLh(sngDay - dT, 3) + dT * (-DeadLh((dblLh(sngDay - dT, 3)), 3) _
+ NewLh((dblL3(sngDay - dT, 3)), 3))
```

'Removal of L3 from herbage - ingested by migrating animals

```
dblLh(sngDay, intLoc1) = dblLh(sngDay, intLoc1) - _
dT * ((LostLh((dblLh(sngDay, intLoc1)), (intLoc1), (H1(sngDay)), 1)) + (LostLh((dblLh(sngDay,
intLoc1)), (intLoc1), (H2(sngDay)), 2)))
dblLh(sngDay, intLoc2) = dblLh(sngDay, intLoc2) - _
dT * ((LostLh((dblLh(sngDay, intLoc2)), (intLoc2), (H3(sngDay)), 3)) + (LostLh((dblLh(sngDay,
intLoc2)), (intLoc2), (H4(sngDay)), 4)))
```

'Removal of L3 from herbage by sedentary stock

```
dblLh(sngDay, 1) = dblLh(sngDay, 1) - _
dT * ((LostLh((dblLh(sngDay, 1)), (1), (H7(sngDay)), 7)) + (LostLh((dblLh(sngDay, 1)), (1),
(H8(sngDay)), 8)))
dblLh(sngDay, 2) = dblLh(sngDay, 2) - _
dT * ((LostLh((dblLh(sngDay, 2)), (2), (H5(sngDay)), 5)) + (LostLh((dblLh(sngDay, 2)), (2),
(H6(sngDay)), 6)))
dblLh(sngDay, 3) = dblLh(sngDay, 3) - _
dT * ((LostLh((dblLh(sngDay, 3)), (3), (H9(sngDay)), 9)) + (LostLh((dblLh(sngDay, 3)), (3),
(H10(sngDay)), 10)))
```

'larvae ingested are either inhibited...

```
sngLi1(sngDay) = sngLi1(sngDay - dT) + _
dT * ((NewLi((dblLh(sngDay - sngPPP, intPickup1)), 1)) - LostLi((sngLi1(sngDay - dT))))
sngLi2(sngDay) = sngLi2(sngDay - dT) + _
dT * ((NewLi((dblLh(sngDay - sngPPP, intPickup1)), 2)) - LostLi((sngLi2(sngDay - dT))))
sngLi3(sngDay) = sngLi3(sngDay - dT) + _
dT * ((NewLi((dblLh(sngDay - sngPPP, intPickup2)), 3)) - LostLi((sngLi3(sngDay - dT))))
sngLi4(sngDay) = sngLi4(sngDay - dT) + _
dT * ((NewLi((dblLh(sngDay - sngPPP, intPickup2)), 4)) - LostLi((sngLi4(sngDay - dT))))
```

```
sngLi5(sngDay) = sngLi5(sngDay - dT) + _
dT * ((NewLi((dblLh(sngDay - sngPPP, 2)), 5)) - LostLi((sngLi5(sngDay - dT))))
sngLi6(sngDay) = sngLi6(sngDay - dT) + _
dT * ((NewLi((dblLh(sngDay - sngPPP, 2)), 6)) - LostLi((sngLi6(sngDay - dT))))
sngLi7(sngDay) = sngLi7(sngDay - dT) + _
dT * ((NewLi((dblLh(sngDay - sngPPP, 1)), 7)) - LostLi((sngLi7(sngDay - dT))))
sngLi8(sngDay) = sngLi8(sngDay - dT) + _
dT * ((NewLi((dblLh(sngDay - sngPPP, 1)), 8)) - LostLi((sngLi8(sngDay - dT))))
sngLi9(sngDay) = sngLi9(sngDay - dT) + _
dT * ((NewLi((dblLh(sngDay - sngPPP, 3)), 9)) - LostLi((sngLi9(sngDay - dT))))
sngLi10(sngDay) = sngLi10(sngDay - dT) + _
dT * ((NewLi((dblLh(sngDay - sngPPP, 3)), 10)) - LostLi((sngLi10(sngDay - dT))))

'...or develop straight to adult worms

sngP1(sngDay) = sngP1(sngDay) + dT * ((-DeadP((sngP1(sngDay - dT))) _
+ NewPtype1((dblLh(sngDay - sngPPP, intPickup1)), 1)) + NewPtype2((sngLi1(sngDay - dT))))
sngP2(sngDay) = sngP2(sngDay) + dT * ((-DeadP((sngP2(sngDay - dT))) _
+ NewPtype1((dblLh(sngDay - sngPPP, intPickup1)), 2)) + NewPtype2((sngLi2(sngDay - dT))))
sngP3(sngDay) = sngP3(sngDay) + dT * ((-DeadP((sngP3(sngDay - dT))) _
+ NewPtype1((dblLh(sngDay - sngPPP, intPickup2)), 3)) + NewPtype2((sngLi3(sngDay - dT))))
sngP4(sngDay) = sngP4(sngDay) + dT * ((-DeadP((sngP4(sngDay - dT))) _
+ NewPtype1((dblLh(sngDay - sngPPP, intPickup2)), 4)) + NewPtype2((sngLi4(sngDay - dT))))

sngP5(sngDay) = sngP5(sngDay) + dT * ((-DeadP((sngP5(sngDay - dT))) _
+ NewPtype1((dblLh((sngDay - sngPPP), 2)), 5)) + NewPtype2((sngLi5(sngDay - dT))))
sngP6(sngDay) = sngP6(sngDay) + dT * ((-DeadP((sngP6(sngDay - dT))) _
+ NewPtype1((dblLh((sngDay - sngPPP), 2)), 6)) + NewPtype2((sngLi6(sngDay - dT))))
sngP7(sngDay) = sngP7(sngDay) + dT * ((-DeadP((sngP7(sngDay - dT))) _
+ NewPtype1((dblLh((sngDay - sngPPP), 1)), 7)) + NewPtype2((sngLi7(sngDay - dT))))
sngP8(sngDay) = sngP8(sngDay) + dT * ((-DeadP((sngP8(sngDay - dT))) _
+ NewPtype1((dblLh((sngDay - sngPPP), 1)), 8)) + NewPtype2((sngLi8(sngDay - dT))))
sngP9(sngDay) = sngP9(sngDay) + dT * ((-DeadP((sngP9(sngDay - dT))) _
+ NewPtype1((dblLh((sngDay - sngPPP), 3)), 9)) + NewPtype2((sngLi9(sngDay - dT))))
sngP10(sngDay) = sngP10(sngDay) + dT * ((-DeadP((sngP10(sngDay - dT))) _
+ NewPtype1((dblLh((sngDay - sngPPP), 3)), 10)) + NewPtype2((sngLi10(sngDay - dT))))

'calculate "R0" surrogates:
'First, "Rate of increase", i.e. rate of increase (+) or decrease (-)in mean parasite burden, per time ‘step, for each host sub- population
Ri12(sngDay) = Ri((sngP1(sngDay)), (sngP1(sngDay - dT)), (sngP2(sngDay)), (sngP2(sngDay - dT)), (H1(sngDay)), (H1(sngDay - dT)), (H2(sngDay)), (H2(sngDay - dT)))
Ri34(sngDay) = Ri((sngP3(sngDay)), (sngP3(sngDay - dT)), (sngP4(sngDay)), (sngP4(sngDay - dT)), (H3(sngDay)), (H3(sngDay - dT)), (H4(sngDay)), (H4(sngDay - dT)))
Ri56(sngDay) = Ri((sngP5(sngDay)), (sngP5(sngDay - dT)), (sngP6(sngDay)), (sngP6(sngDay - dT)), (H5(sngDay)), (H5(sngDay - dT)), (H6(sngDay)), (H6(sngDay - dT)))
Ri78(sngDay) = Ri((sngP7(sngDay)), (sngP7(sngDay - dT)), (sngP8(sngDay)), (sngP8(sngDay - dT)), (H7(sngDay)), (H7(sngDay - dT)), (H8(sngDay)), (H8(sngDay - dT)))
Ri910(sngDay) = Ri((sngP9(sngDay)), (sngP9(sngDay - dT)), (sngP10(sngDay)), (sngP10(sngDay - dT)), (H9(sngDay)), (H9(sngDay - dT)), (H10(sngDay)), (H10(sngDay - dT)))

'Second, “Qi” (pseudo-Ro), i.e. number of adult female worms produced by each in the present ‘generation, within each host pop (juv and adult), assuming constant environmental conditions ‘(snapshot). Per area - varies with host presence.
Qi1(sngDay) = Qi(1)
Qi2(sngDay) = Qi(2)
Qi3(sngDay) = Qi(3)

Next sngDay
```