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Parasites, climate, and fuzzy logic models.

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Parasites, climate, and fuzzy logic models

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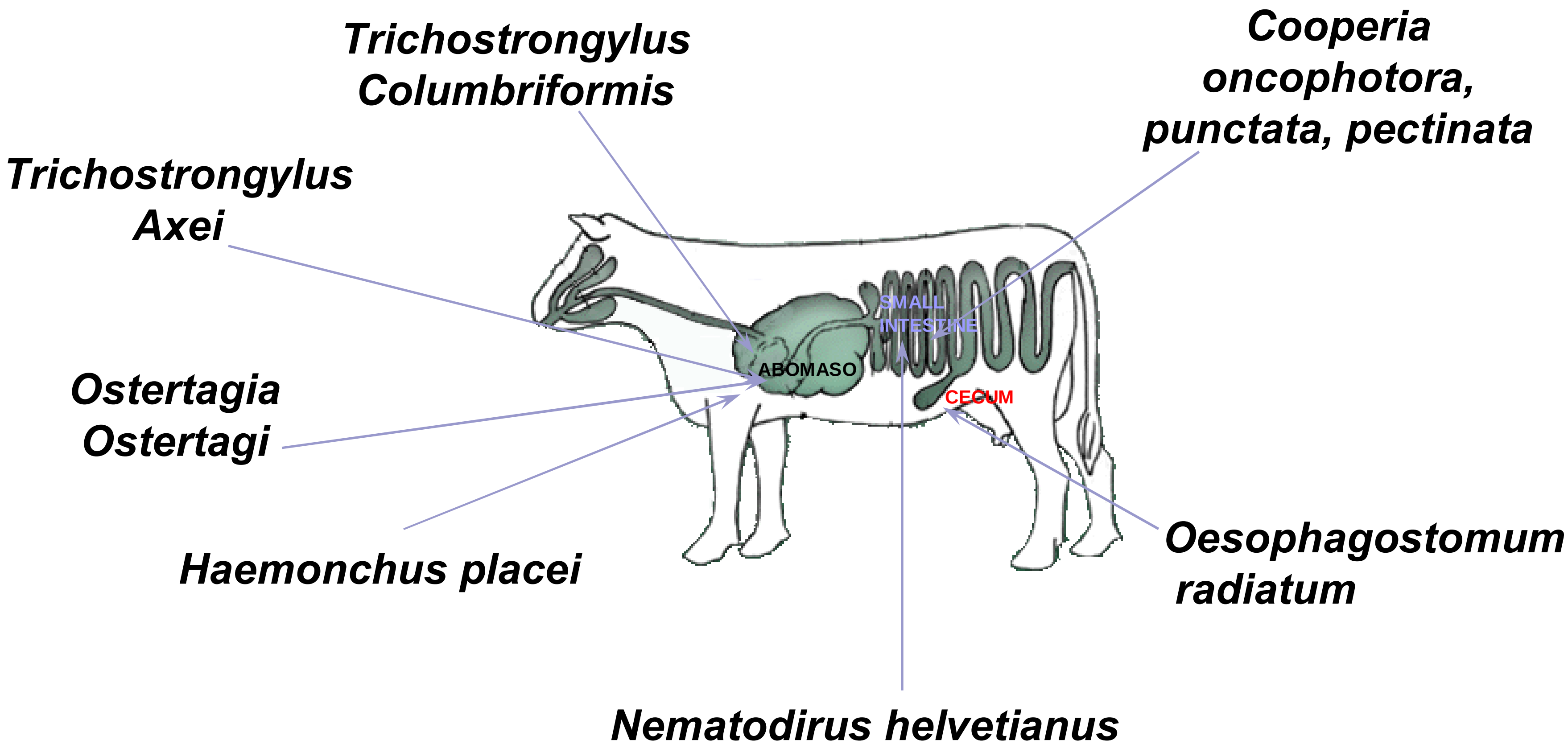
Dime cuanto llueve y te diré cuantos bichos tienes en el pasto

Nematodes in the Pampean region



Life Cycle

- *Stages*

Deposition of eggs in the cow dung

Non parasitic phase:

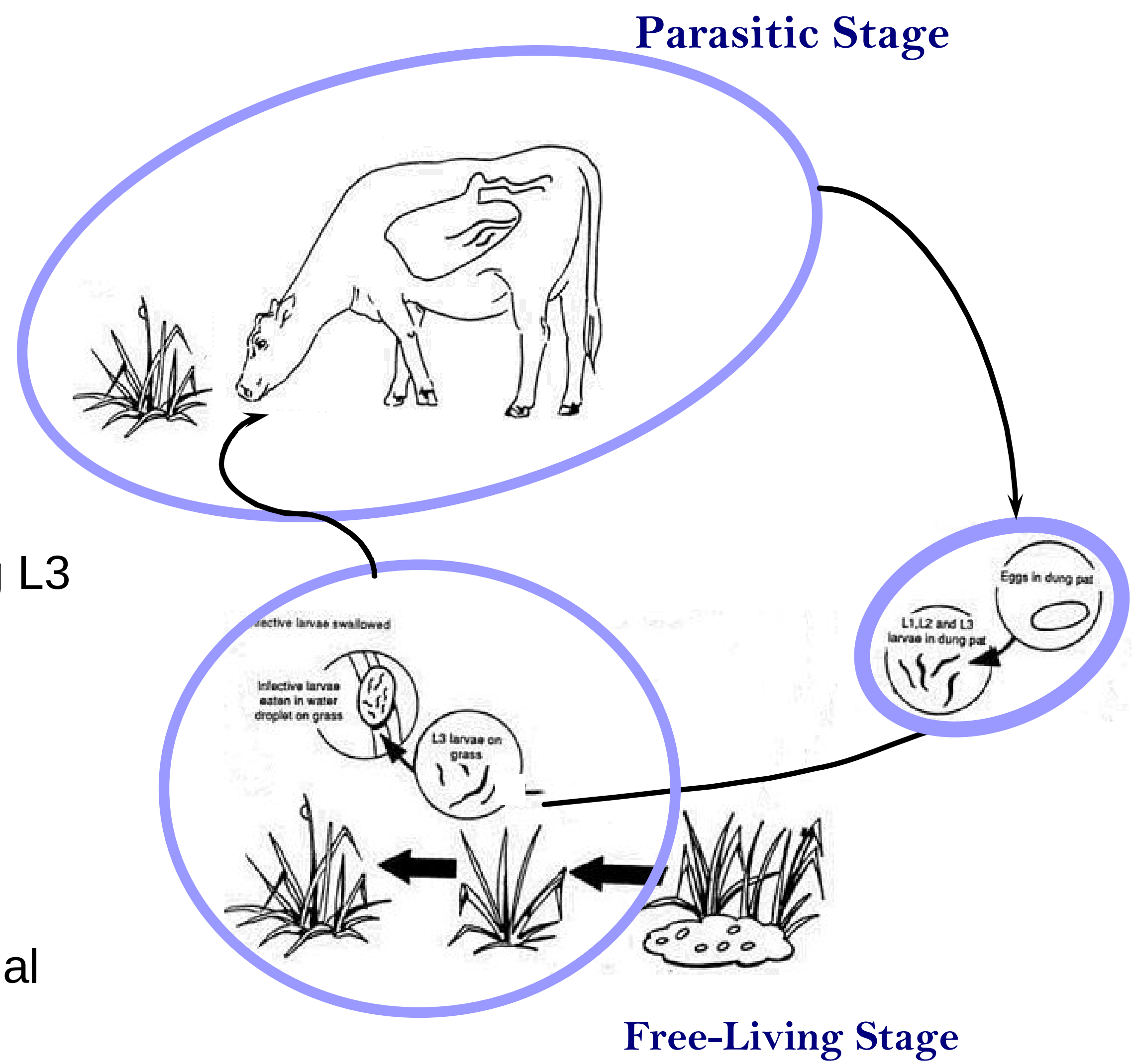
Growth from eggs to infecting L3

Migration to pastures

Auto-infection

Parasitic phase:

Growth of L3 to adult individual



Effects

- Diseases with high economic impact on meat production systems.

- Losses include high mortality in young individuals, antihelmintic drugs costs, and a considerable decrease in weight gain (*Entrocasso & Steffan, 1981; Steffan; et.al. 1982*)

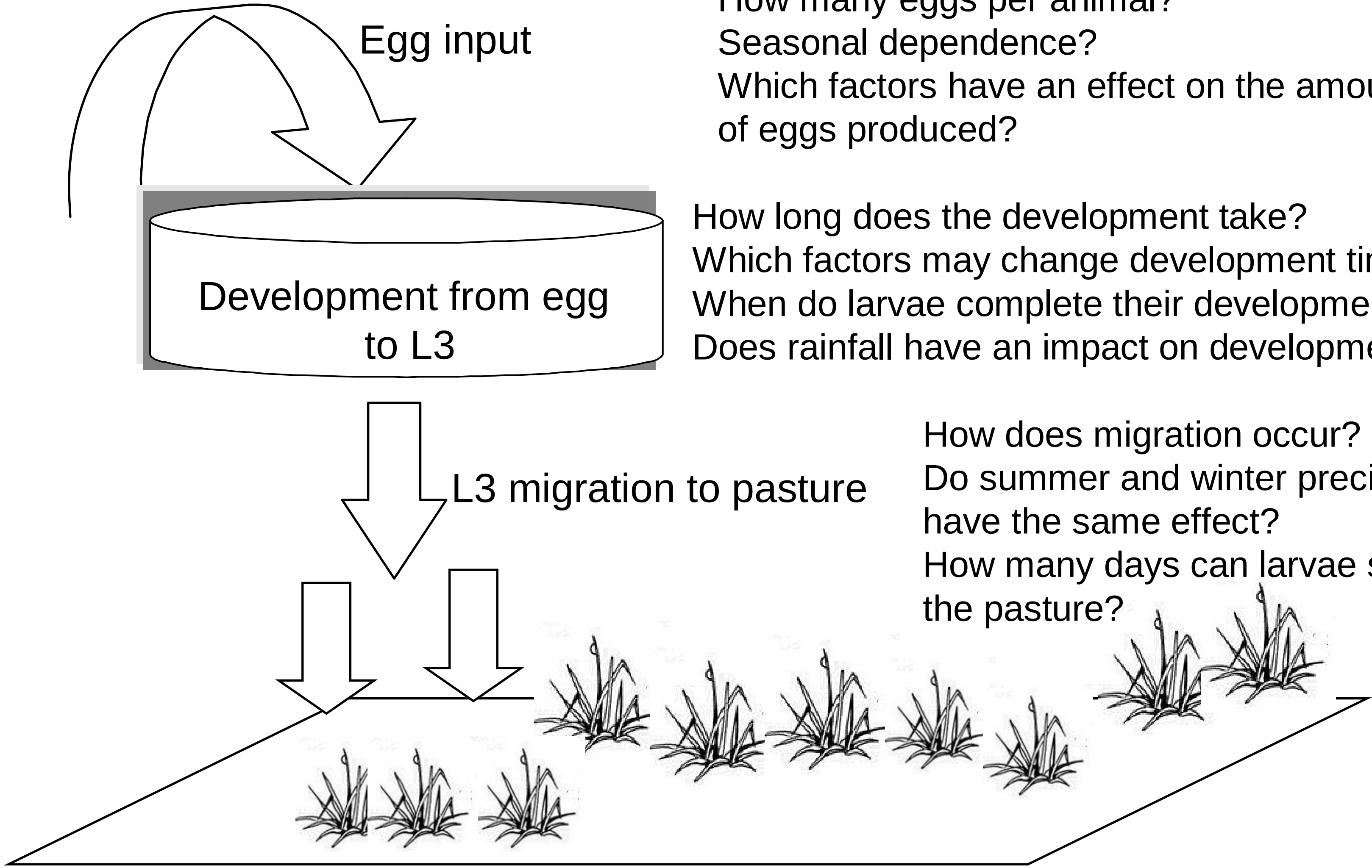
- Lately, resistance to antihelmintic drugs has been detected.

First step

- Estimation of development time from egg to infecting larva L3 taking into account climate conditions.

- Estimation of availability of infecting larva L3 ready to migrate to pastures at any given time.

Conceptual Model



How many eggs per animal?
Seasonal dependence?
Which factors have an effect on the amount of eggs produced?

How long does the development take?
Which factors may change development time?
When do larvae complete their development?
Does rainfall have an impact on development time?

How does migration occur?
Do summer and winter precipitations have the same effect?
How many days can larvae survive in the pasture?

Weather conditions

Temperature

$$T(t) = \frac{(T\max + T\min)}{2} + \frac{(T\max - T\min)}{2}\cos\left(\frac{2\pi t}{365}\right)$$

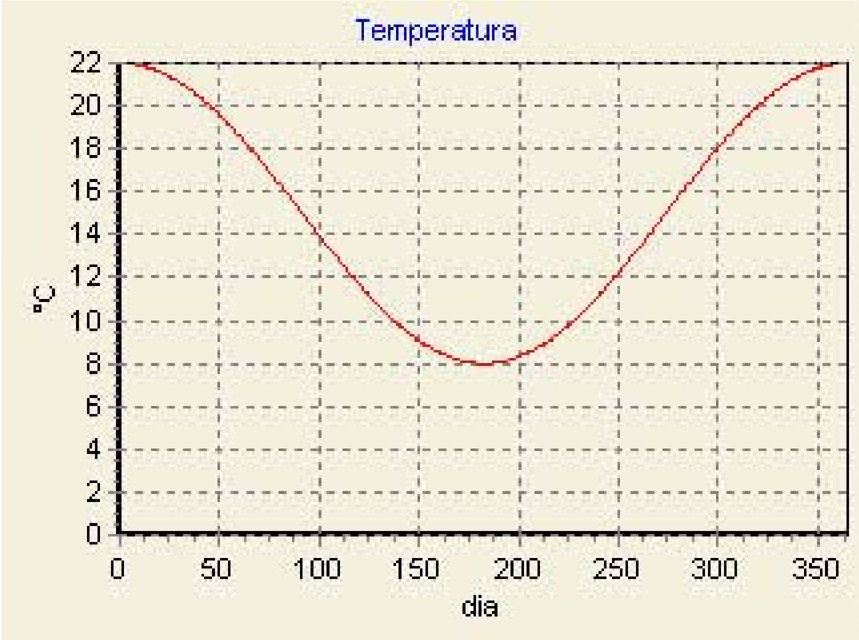
For Tandil (Argentina), we use:

Annual maximum average = 22°C

Annual minimum average = 8°C

$$T(t) = 15 + 7\,Cos\left(\frac{2\pi t}{365}\right)$$

where t is Julian day



Climatic conditions

Rainfall

Two effects:

- Regulates migration of L3 larvae to pasture.
- Affects pre-infective mortality of L3 larvae.

A random function was used to generate rainfall, probabilistically generated from precipitation data between 1951 and 2004, in Tandil.

Population Model

Let $f(L,t)$ be the function that describes the density of individuals of size L at time t.

Population's processes are described by:

$$PDE \qquad \frac{\partial f}{\partial t} + \frac{\partial}{\partial L}(f g) = -\mu(L,t) f$$

$$IC \qquad f(L,0) = \phi(L)$$

$$BC \qquad f(l_0(t), t) = A(t)$$

where:

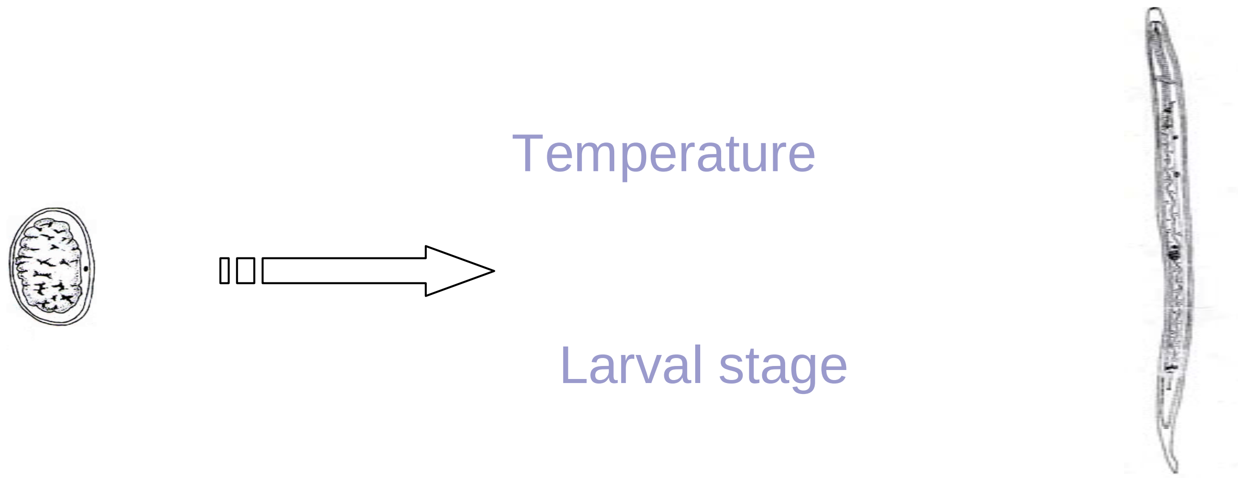
$g(L,t)$ Growth rate of an individual of size *L* at time *t*

$l_0(t)$ Length at eclosion at time *t*

$\mu(L,t)$ Mortality rate of an individual of size *L* at time *t*

$A(t)$ Input rate of eggs

What factors have an influence on the time it takes to grow from egg to L3?



- Growth time is strongly controlled by temperature: at higher temperatures, shorter development times are observed.
- At each stage, larval mobility increases in relation with its previous stage, therefore, it becomes easier to each larva to feed itself.
- **Consequently, the growth rate increases when temperature does, and when the larva is closer to reach the L3 stage**

Larva's growth from its eclosion to L3 stage

There is a difference in length for larvae when they undergo an eclosion and complete their growth at various temperatures.

Using data from lab experiments:

Eclosion's length

$$l_0(T) = y_0 + \frac{A}{\sqrt{2\pi wT}} e^{\left(\frac{-Ln^2\left(\frac{T}{xc}\right)}{2w^2}\right)}$$

L3 final length

$$l_F(T) = a + bT + cT^2$$

Larva's growth from its eclosion to L3 stage

Growth of an individual larva is modulated by a function ***r(t)*** that depends on the day of the year and also on the larva's size. This can be expressed as:

$$\frac{\partial L}{\partial a}(a,t) = r(t)\,L(a,t)$$

$$CI \qquad L(0,t) = l_0(t)$$

The seasonal effect is introduced considering

Summer if $1 \leq t \leq 89$
Autumn if $90 \leq t \leq 181$
Winter if $182 \leq t \leq 273$
Spring if $274 \leq t \leq 365$

Larva's growth from its eclosion to L3 stage

For simplicity, we assume constant lengths:

$$l_0(T) = 350\mu m \qquad l_F(T) = 850\mu m$$

So, our expression for individual growth can be written as:

$$\frac{\partial L}{\partial a}(a,t) = r(t)\,L(a,t)$$

$$CI \qquad L(0,t) = 350$$

where *r(t)* can be fitted to growth data in Tandil:

$$r(t) = 0.00509T(t) - 0.00922$$

Development time

From the length function, it is possible to estimate a minimum development time a that a larva takes to reach its L3 stage. Thus, we obtain:

$$\tau(i) = a$$

where i is the day of eclosion of the egg and a is the minimum age value for which

$$L(a, \underbrace{i + a}_{t}) \geq 850$$

Mortality Rate

According to *Smith et al. (1985)*, the relationship between temperature and mortality of pre-infective larvae is given by:

$$\mu(t) = \exp(a_1 + a_2 \frac{T(t) + 273}{100})$$

Constants a_1 and a_2 depend on different conditions (*Smith et al*., 1985)

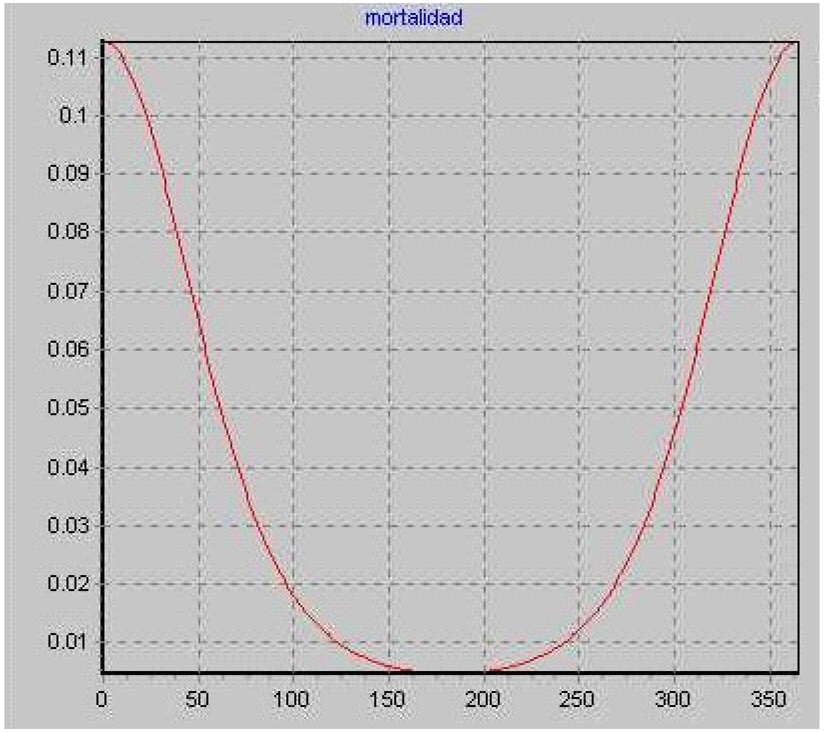
Fitting this function to field data:

$$\mu(t) = \exp(-69.09 + 22.68 \frac{T(t) + 273}{100})$$

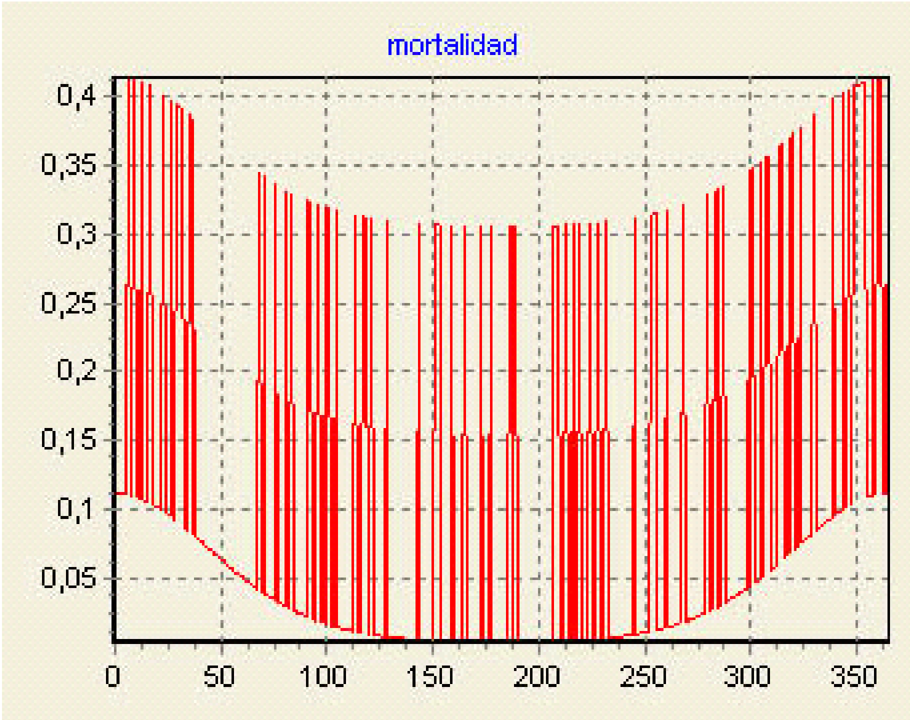
Mortality Rate

In order to include a rainfall effect into the mortality function, a random function was added.

Mortality without rainfall



Mortality with rainfall

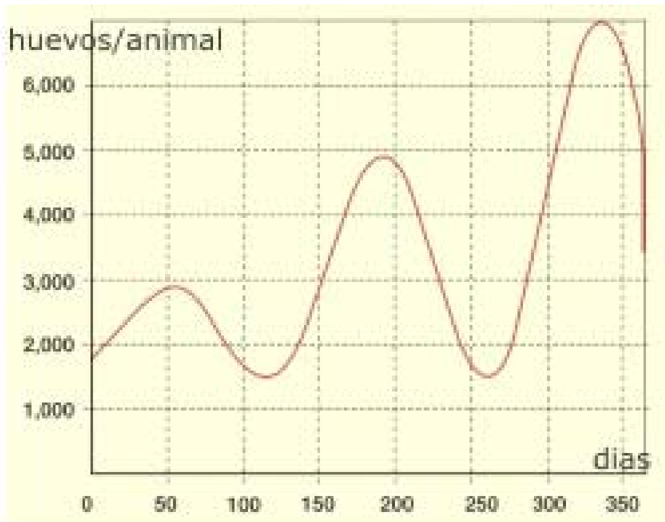


Boundary condition

According to *González et al (1998)* and *Pedonese et al (2000),* the **rate of egg input** related to the quantity of eggs per gram of dung was estimated using the following functions:

$$A(t) = 0.04\, Weight\,[t]\, Ta[t]$$

$$Ta(t) = 100 + \frac{t+50}{2}\left(1 + sen\left(\frac{5\pi(t-5)}{365}\right)\right)$$



Looking for solutions of our model

Once parameters and functions were estimated for the Tandil area, we solve the PDE.

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial L}(f\ g) = -\mu(L,t)f$$

$$IC \qquad f(L,0) = \phi(L)$$

$$BC \qquad f(l_0(t),t) = A(t)$$

Method of characteristics

Characteristic curves

$$\frac{dt}{ds} = 1$$

$$\frac{dL}{ds} = g(L,s) = r(s)\,L$$

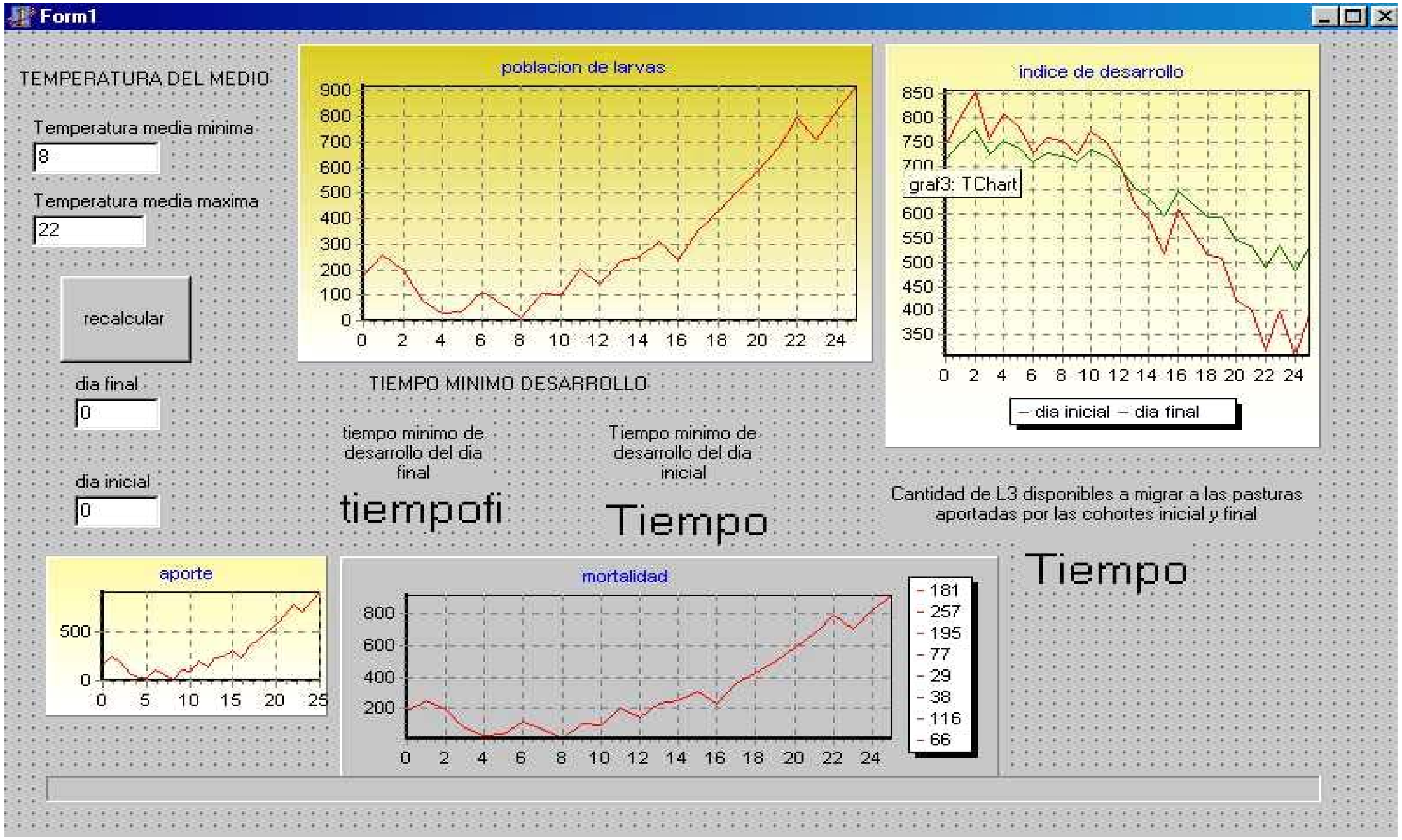
Differential equation to solve

$$\frac{df}{ds} + \left(r(s) + \mu(s)\right)f(s) = 0$$

IC $f(0)=A(t)$

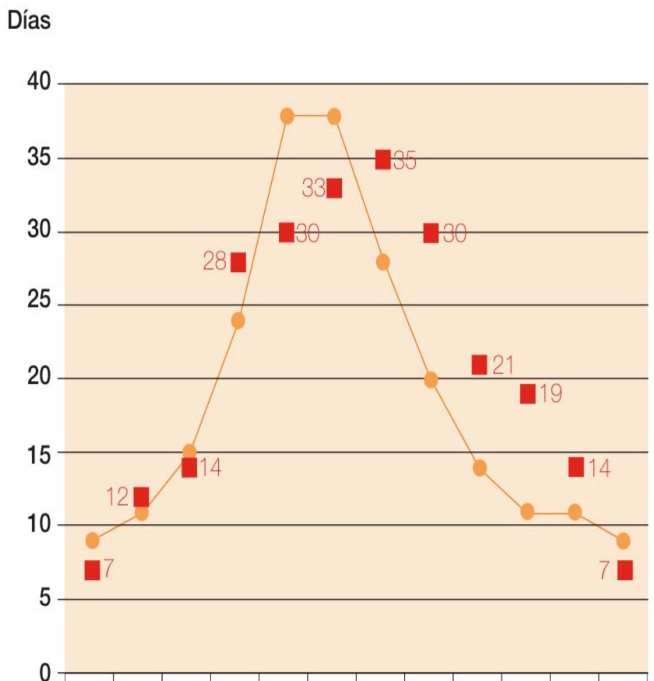
Numerical solution of ODE

Construction of a new software in *Delphi* language.

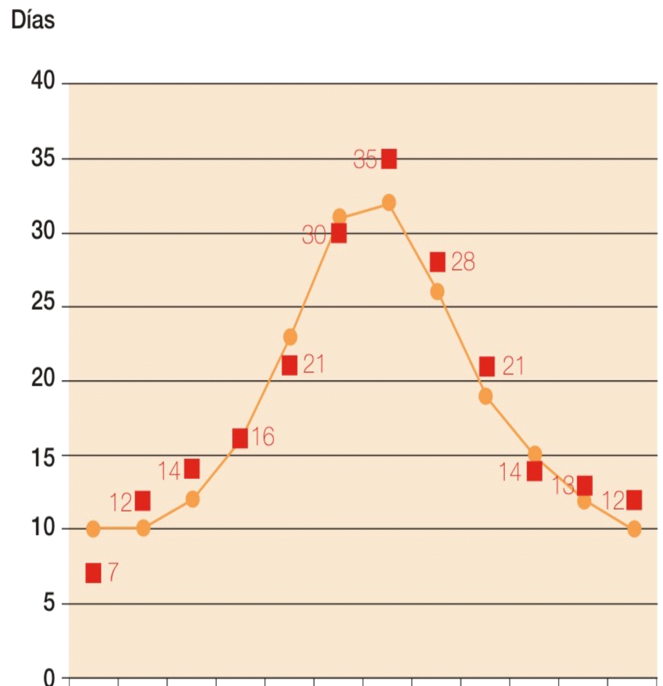


Development time

Model output vs. field data (Tandil)

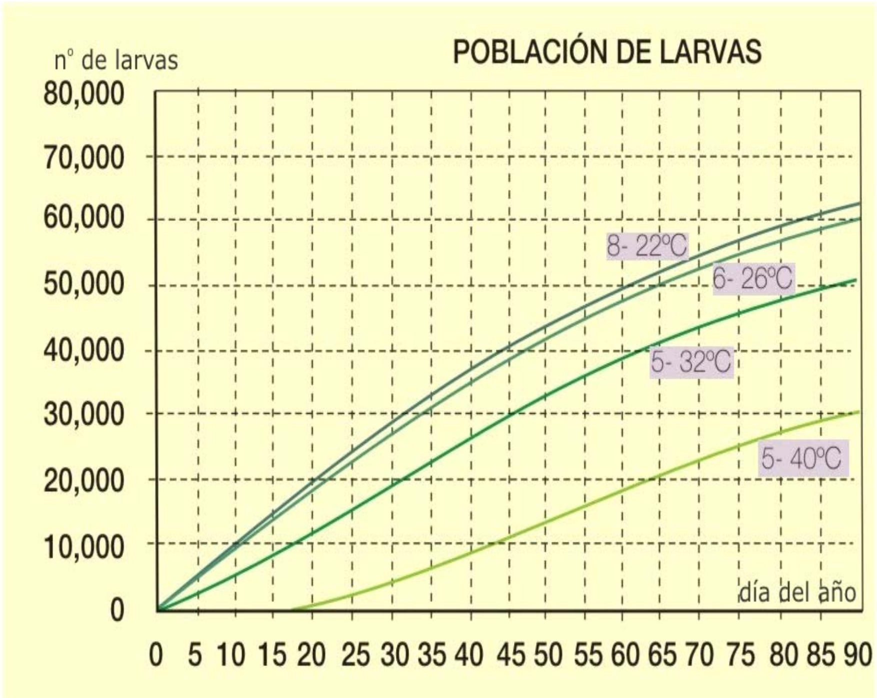


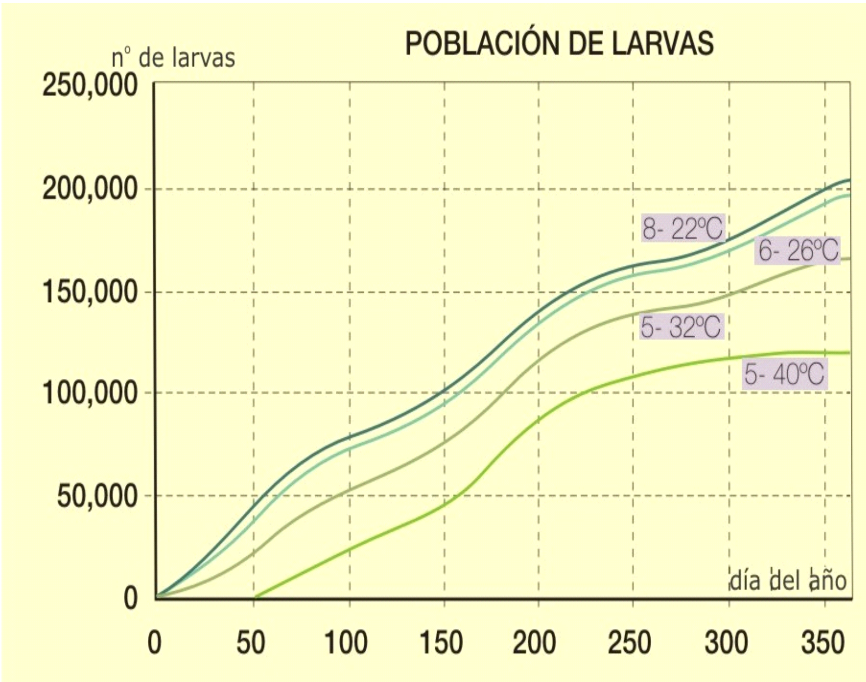
	E	F	M	A	My	J	Jl	Ag	S	O	N	D
Tiempo estimado por el modelo	9	11	15	24	38	38	28	20	14	11	11	9
González et. al. rango de temperaturas 5- 22º C	7	12	14	28	30	33	35	30	21	19	14	7



	E	F	M	A	My	J	Jl	Ag	S	O	N	D
Tiempo estimado por el modelo	10	10	12	16	23	31	32	26	19	15	12	10
Pedones et. al. rango de temperaturas 7- 20º C	7	12	14	16	21	30	35	28	21	14	13	12

Cumulative population density





Conclusions

• The model shows a strong sensitivity to temperature: it is noticeable in the population dynamics.

• There is higher sensitivity to changes in minimum average temperatures than maximum average temperatures.

• It is possible to modify and fit the model to several climate conditions: temperature and rainfall.

•This model permits to include more realistic functions.

• The model gives good estimations of development times in the field.

Some pending questions

- Is the time of appearence of L3 larvae in the pasture related to the precipitation pattern?

- How long is the delay before the first L3 larvae are found in the pasture?

- Is it possible to determine the population dynamics of the L3 larvae in the pasture from EPG, monthly precipitation, and the time cattle enter the paddock?

Fuzzy Logic Model

Why Fuzzy Logic?

- It makes possible to represent linguistic expressions and allows to include non quantitative information gathered during field work.
- Allows to enrich the model without replacing crisp logic.
- Permits a flexible design.
- Improves the model's performance.
- It is easy to implement.

Basic Definitions

Definition: A fuzzy set *A* defined in an *X* universe is a set of pairs $(x, \mu_A(x))$ where *x* belongs to *X* and $\mu_A(x)$ is a number in the interval *[0, 1]* representing the degree of membership of *x* in *A*.

$$\mu_A : X \to [0,1]$$

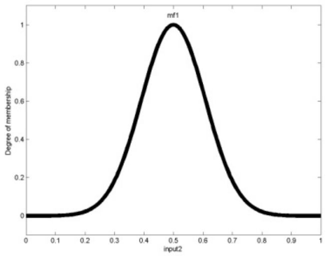
This suggests that membership in a fuzzy subset should not be on a 0 or 1 basis, but rather on a 0 to 1 scale. That is, the membership should be an element of the interval *[0, 1].*

Membership functions

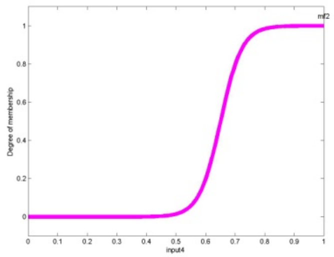
Membership functions are used to quantify the degree of membership of an element of the universe X to the associated fuzzy set A.

The choice of such function depends on the context of the variable. Most common functions are:

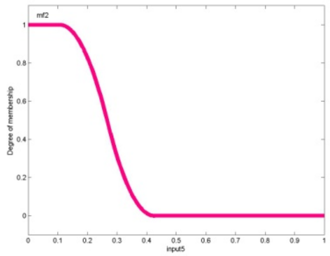
Gaussian



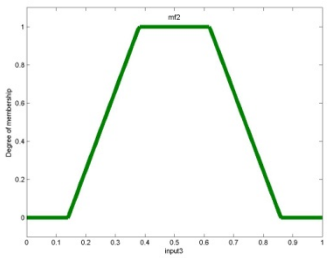
S-sigmoids



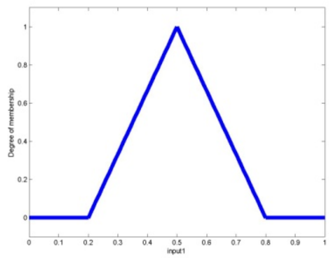
Z-sigmoids



Trapezoidal



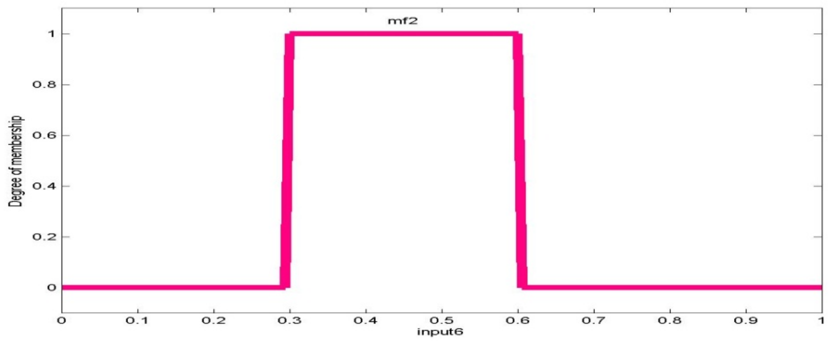
Triangular



Membership functions

Example: “fuzzified” classic sets

It is possible to look at a classic or crisp set as a fuzzy set by taking the characteristic function as the membership function.



Fuzzy rules

Usually, the degree of membership is assigned through the application of a certain number of rules.

A fuzzy rule is a set of *IF-THEN* propositions that model the problem to be solved.

The simpler rules have the format:

"If x is A then y is B"

A rule expresses a relationship between two fuzzy sets $\mathbf{A}$ *and* $\mathbf{B}$*, whose membership function is represented by*

$$\mu_{A \rightarrow B}(x, y)$$

a logical implication.

Fuzzy rule-based systems (FRBS)

Fuzzy rule-based systems (FRBS) have four components: an input processor, a collection of fuzzy rules called rule base, a fuzzy inference machine, and an output processor.

- **Input processor (Fuzzification):** Here, non quantifiable input is translated into fuzzy sets of their respective universes.
- **Rule base:** This is a key knowledge-encoding component of fuzzy rule-based systems. Essentially, fuzzy rules are fuzzy relations of the Cartesian product of the universes of the variables of interest. The base is composed by a collection of fuzzy conditional propositions in the form of *IF-THEN* rules.

Fuzzy rule-based systems (FRBS)

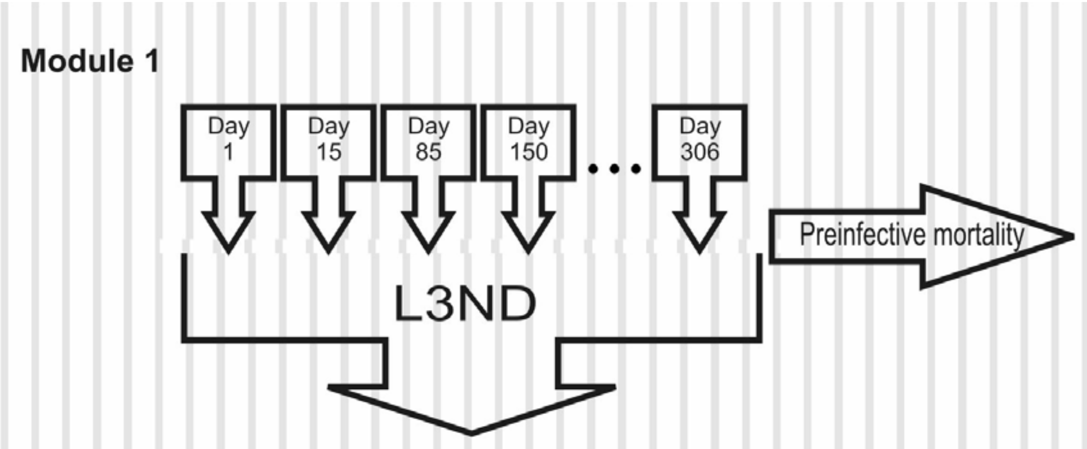
Fuzzy rule-based systems (FRBS) have four components: an input processor, a collection of fuzzy rules called rule base, a fuzzy inference machine, and an output processor.

- **Fuzzy inference:** The fuzzy inference machine performs approximate reasoning using the compositional rule of inference. In this work, the Mamdani method is used (Barros L. C., 2006).

- **Defuzzification:** In fuzzy rule-based systems, the output is usually a fuzzy set. Often, especially in system modelling, a real number is required as output. The output processor provides real-valued output through defuzzification, a process used to choose a real number that is representative of the corresponding fuzzy set.

The complete model

Module 1: Pre-infective stages in dung (waiting to migrate to pasture)



Module 1+1/2: Migration to pasture

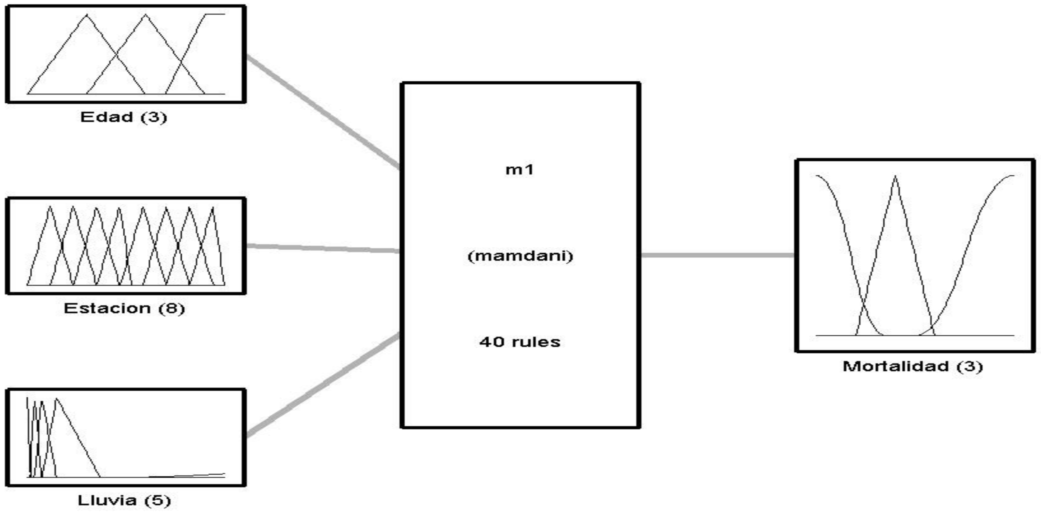
$$H\left(t+a,a+1\right)=(1-\mu_P)H\left((t-1)+(a-1),a\right)$$
$$si\ a+1\leq\tau\left(t\right)$$

Module 2: Larval dynamics in pasture

$$L3D\left(t+1\right)=\left(1-\delta_D\right)\left(1-\mu_{ID}\right)L3D(t)+L3ND(t+1)$$

$$L3P\left(t\right)=\left(1-\mu_P\right)L3P\left(t-1\right)+\delta_{DP}\left(1-\mu_{ID}\right)L3D\left(t\right)$$

Module 1 Pre-infective mortality



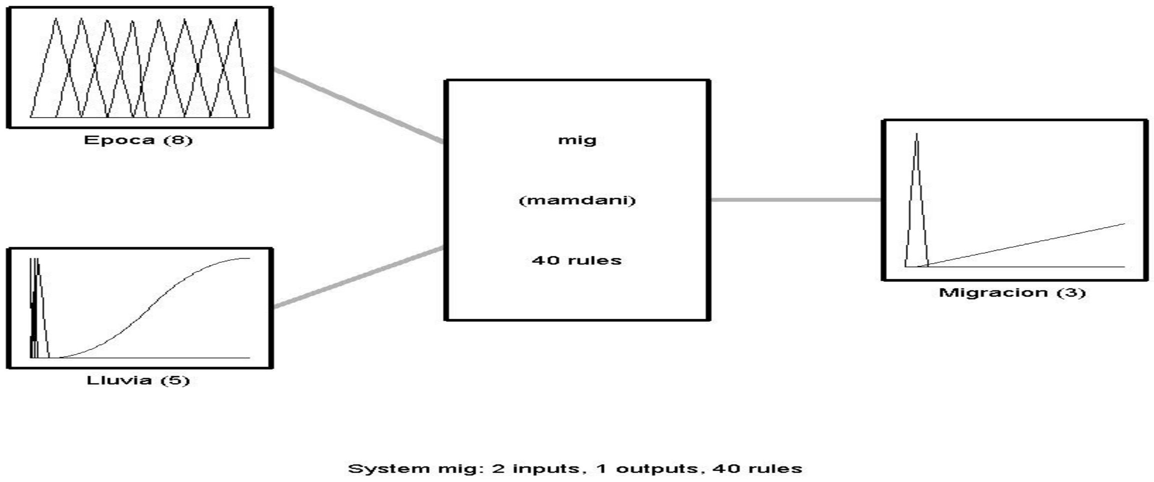
	Age ([%])	Season ([d])	Rainfall ([mm])	Mortality ([%])
1	L1(0-0.6)	Summer (-45-136)	Drizzle1 (0-2)	Low (0-0.35)
2	L2 (0.3-0.9)	Winter (136-319)	Drizzle2 (2-10)	Moderate (0.2-0.6)
3	L3 (0.7-1)	Spring (228-365)	Rain (5-20)	High (0.5-1)
4		Autumn (45-228)	Downpour1 (10-50)	
5			Downpour2 (50-600)	

Module 1 Pre-infective mortality

IF NOT YET L3					
Season/Precip.	Drizzle1	Drizzle2	Rain	Downpour1	Downpour2
Summer	Moderate	Moderate	Moderate	High*0,8	High
Autumn	Low*0,1	Low*0,5	Low	Moderate*0,5	Moderate
Winter	Low*0,5	Low	Moderate*0,5	Moderate	High*0,5
Spring	Low*0,5	Low	Moderate*0,5	Moderate	High*0,5

IF ALREADY L3					
Season/Precip.	Drizzle1	Drizzle2	Rain	Downpour1	Downpour2
Summer	Low	Low	Moderate*0,5	Moderate	Moderate
Autumn	Low	Moderate	Moderate	High*0,5	High
Winter	Low	Low	Low	Low	Low
Spring	Low	Low	Low	Low	Low

Module 1+1/2 Fuzzy Migration



	Season ([d])	Precipitation ([mm])	Migration ([%])
1	Summer (-45-136)	Drizzle1 (0-2)	Low (0-0.1)
2	Winter (136-319)	Drizzle2 (2-10)	Moderate (0.05-0.5)
3	Spring (228-365)	Rain (5-20)	High (0.35-0.6)
4	Autumn (45--228)	Downpour1 (10-50)	
5		Downpour2 (50-600)	

Module 1+1/2 Fuzzy Migration

Season/Precip	Drizzle1	Drizzle2	Rain	Downpour1	Downpour2
Summer	Low*0,05	Low*0,5	Low	Moderate	High
Autumn	Low	Moderate	High*0,7	High*0,9	High
Winter	Low*0,5	Low	Moderate	High*0,7	High
Spring	Low*0	Low	Moderate	High*0,7	High

Module 2 Mortality in pasture

	Season ([d])	Temperature ([ºC])	Mortality ([%])
1	Summer (-45-136)	Low (0-14)	Low ()
2	Winter (136-319)	Moderate (12-26)	Moderate ()
3	Spring (228-365)	High (23-35)	High ()
4	Autumn (45--228)		

Season/Temperature	Low (0-14ºC)	Moderate (12-26ºC)	High (23-35ºC)
Summer	Low	Moderate	High
Autumn	Low	Moderate*0,5	High*0,5
Winter	Low	Low	High*0,5
Spring	Low	Moderate*0,5	High*0,5

The Fuzzy Model

$$H(t+a, a)=(1- \mu_P)\, H((t+a-1,a-1) \quad \text{if } a \leq \tau(t)$$

where:

H(t+a, a) = amount of preinfective larvae (eggs, L1 and L2) aged a, which "started" on julian day t.

μ_P = rate of preinfective mortality;

$\tau(t)$= minimum development time for cohort initiated on julian day t.

$$L3D(t+1)=(1-\delta_{DP})(1-\mu_{ID})L3D(t)+L3ND(t+1)$$

where:

L3D(t) = amount of L3 larvae in the dung pool on day *t*

L3ND(t) = amount of L3 larvae in dung that have completed their development precisely on julian day *t*

μ_{ID} = rate of mortality inside dung;

δ_{DP} = rate of migration from dung to pasture.

$$L3P(t) = (1-\mu_P)\, L3P(t-1)+ \delta_{DP}\, (1-\mu_{ID})\, L3ND(t)$$

where:

L3P(t) = amount of larvae in pasture on day *t*

μ_P = rate of mortality in pasture;

μ_{ID} = rate of mortality inside dung;

δ_{DP} = rate of migration from dung to pasture.

Implementation

The model was implemented using GNU Scilab 5.0.

INPUT:

- Weather data: the model includes data on temperature and precipitation.
  - Temperature is measured in Celsius degrees (ºC). Maximum (*Tmaxn*) and minimum (*Tminn*) annual average temperature for year *"n"* (1994-1998) are taken for constructing a temperature function . The temperature on julian day *t* of year n is represented as before.
  - Precipitation is measured in *[mm]* and is given daily (SMN data)
- Initial and final day [day, month, year] of the period in which the animals are in the pen "scattering" eggs over the pasture. These days are called “the period of study”.
- Egg per grams of dung (*HPG)* in the period of study.
- Average weight of the animals in the pen.

OUTPUT:

- the dynamics of L3 larval population available for migrating to pasture *(module 1)*
- the infection of pastures on a daily basis *(module 3)*

Field work

A 0.96 hectare paddock located on the University Campus (UNCPBA) in Tandil was used for the field work. The paddock was divided into 16 sub-paddocks.
Two naturally infected calves contaminated the sub-paddocks with eggs of gastrointestinal parasites.
Faecal samples for egg counts and coprocultures were taken weekly from the "contaminating" calves during the grazing period. Faecal egg counts were used to plot the contamination of the paddock. Coprocultures allowed the identification of which nematode species were present in the contamination.
On the 15th day of each month, faecal matter was collected from the paddock. Then weekly samples were taken in the lab from collected faecal matter in order to analyse the development from egg to *L3*. Simultaneously, grass samples were regularly taken from the paddock over the 16-month period to assess the infection of pastures as well as the survival of *L3* larvae in pasture. (Fiel, C.A., et al., 2008)

Data

- HPG (eggs per gram): from field data. Value is kept constant from the day of the sampling till next day of sampling (aprox. 15 days)

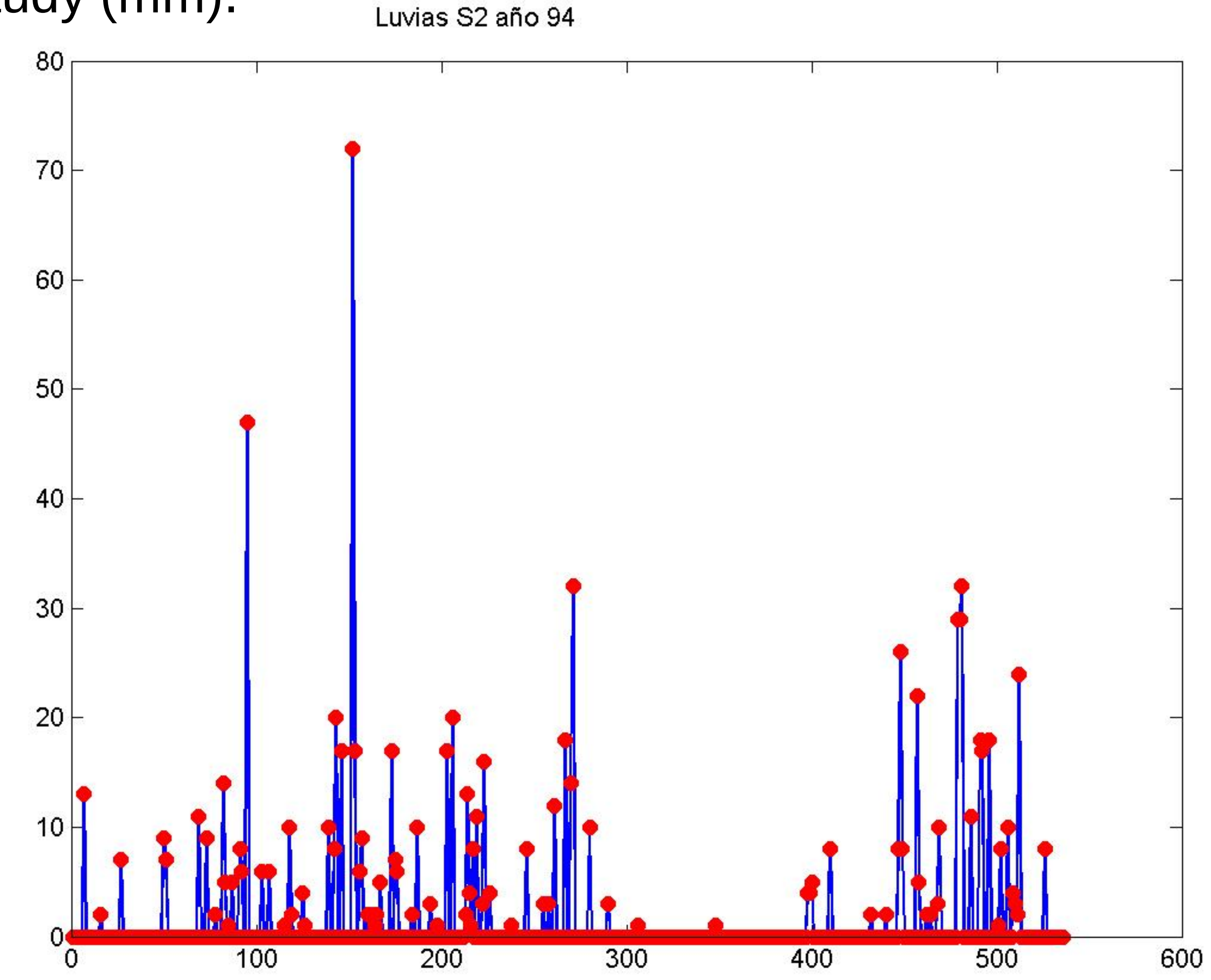
Example Year 1994, 2º semester

Sampling day

S2 year 94																															
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
July	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785	1785
August	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930	930
September	930	930	930	930	195	195	195	195	195	195	195	365	365	365	365	365	365	365	365	365	365	365	365	365	365	365	365	365	365	365	
October	365	365	365	365	30	30	30	30	30	30	30	30	30	30	30	30	30	30	55	55	55	55	55	55	55	40	40	40	40	40	40
November	40	70	70	70	70	70	70	70	50	50	50	50	50	50	50	110	110	110	110	110	110	110	95	95	95	95	95	95	95	200	
December	200	200	200	200	200	200	200	200	200	200	200	200	130	130	130	130	130	130	130	130	25	25	25	25	25	25	25	20	20	20	20

Data

- **Precipitation**: Daily precipitation from SMN data base for the area under study (mm).



Year 1994 2º semester

Simulations

Tandil, Province of Buenos Aires

Initial Conditions

A paddock with 2 animals weighting 250 kg. each.

Temperature Tmax=25°C; Tmin=7°C

Grazing period of 6 months (181 days aprox.).

Eggs per gram values (HPG) are those determined by field work along 1994-1998 (Fiel *et. al., 2008)*

Three complete semesters of precipitation data (550 days aprox.).

Egg to L3 development time

As before, the development is described by the differential equation:

$$\frac{\partial L}{\partial a}(a,t) = r(t)\,L(a,t)$$

$$IC \qquad L(0,t) = l_0(t)$$

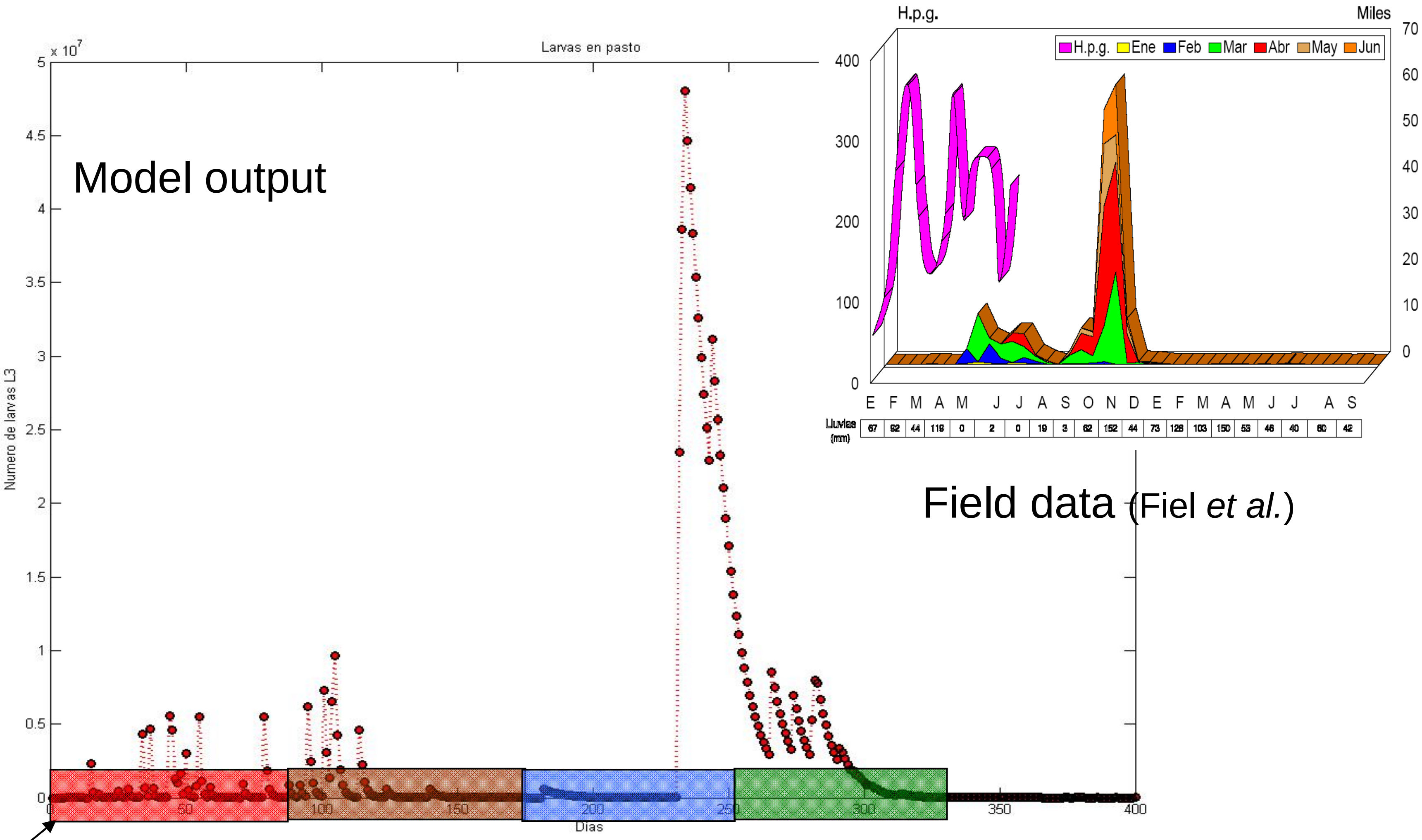
where:
r(t)=AT(t)+B
is the function that regulates the development rate depending on the temperature *T(t);*

A and *B* obtained by fitting laboratory data from Pandey (1972).

	Median	Mínimum	Máximum
Summer	5	4	7
Autumn	18	7	31
Winter	33	25	35
Spring	14	6	14

Tandil, Province of Buenos Aires

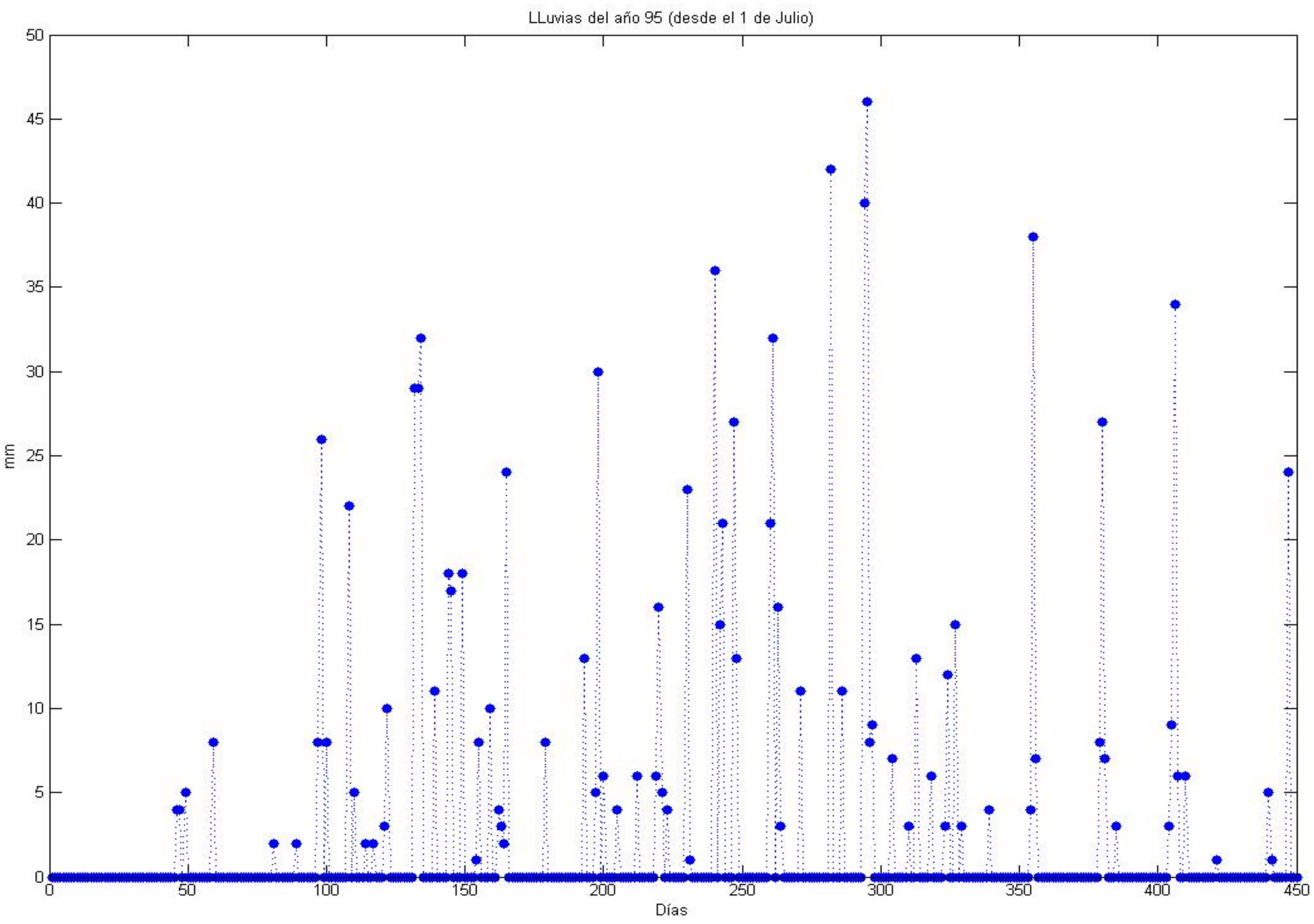
Semestre 1, Year 1996



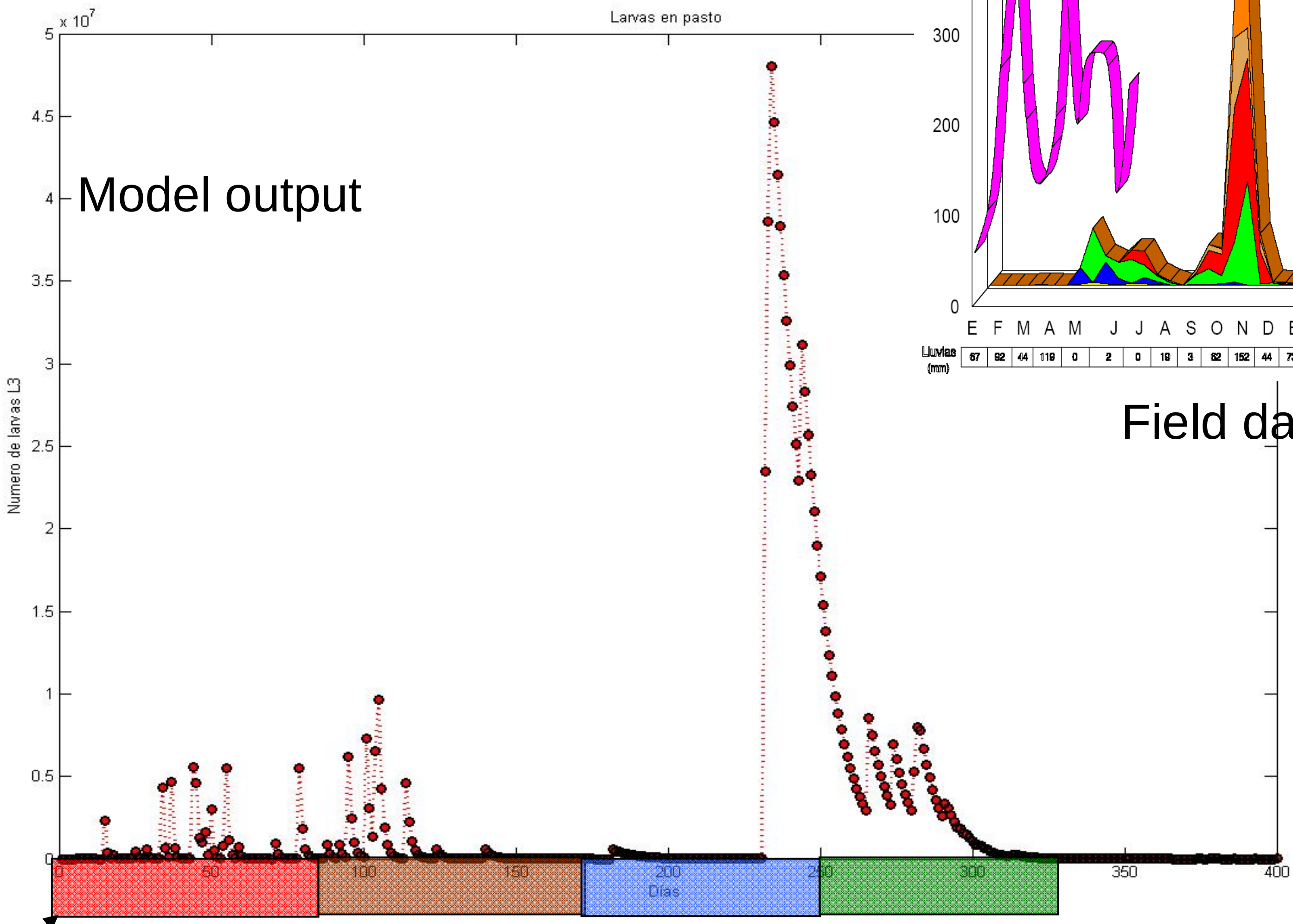
01 January

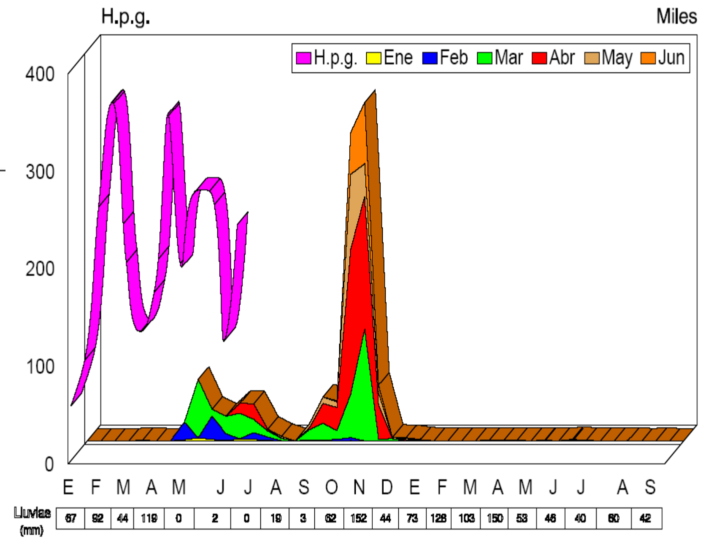
Tandil, Province of Buenos Aires

Semestre 2 Year 1996



Tandil, Province of Buenos Aires





01 January

Beginning of infection

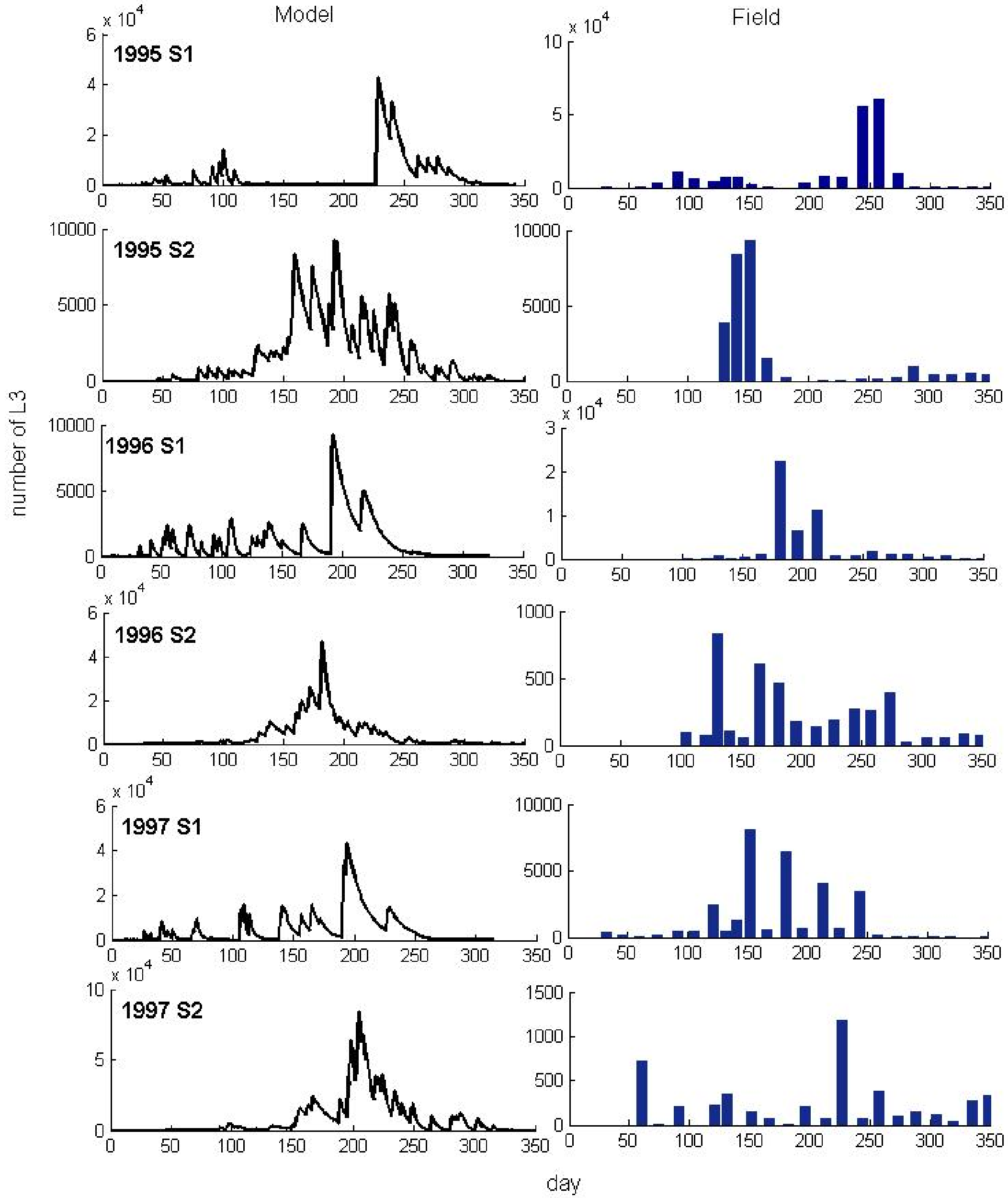
Semester: (Year)	Field data	Simulation
1:(1995)	April	January
2:(1995)	October	October
1:(1996)	April	January
2:(1996)	October	October
1:(1997)	March	January
2:(1997)	October	October

Peak of infection

Semester: (Year)	Field data	Simulation
1:(1995)	November 1995	September 1995
2:(1995)	November-December 1995	November-December 1995
1:(1996)	July 1996	July 1996
2:(1996)	August 1997	November 1997
1:(1997)	July 1997	July 1997
2:(1997)	April 1998	December 1997 - January 1998

End of infection

Semester: (Year)	Field data	Simulation
1:(1995)	End of December 1995	End of December 1995
2:(1995)	End of June 1996	End of June 1996
1:(1996)	End of November 1996	End of October 1996
2:(1996)	End of June 1997	End of June 1997
1:(1997)	End of September 1997	End of September 1997
2:(1997)	End of October 1998	End of October 1998


Model
Field
1995 S1
1995 S2
1996 S1
1996 S2
1997 S1
1997 S2
number of L3
day

Simulations

Mercedes, Province of Corrientes

Initial Conditions

A paddock with 2 animals weighting 250 kg. each.

Temperature Tmax=27°C; Tmin=12°C

Grazing period of 12 months (365 days).

Eggs per gram values (HPG) are those determined by field work in Tandil over the same period (Fiel *et. al., 2008)*

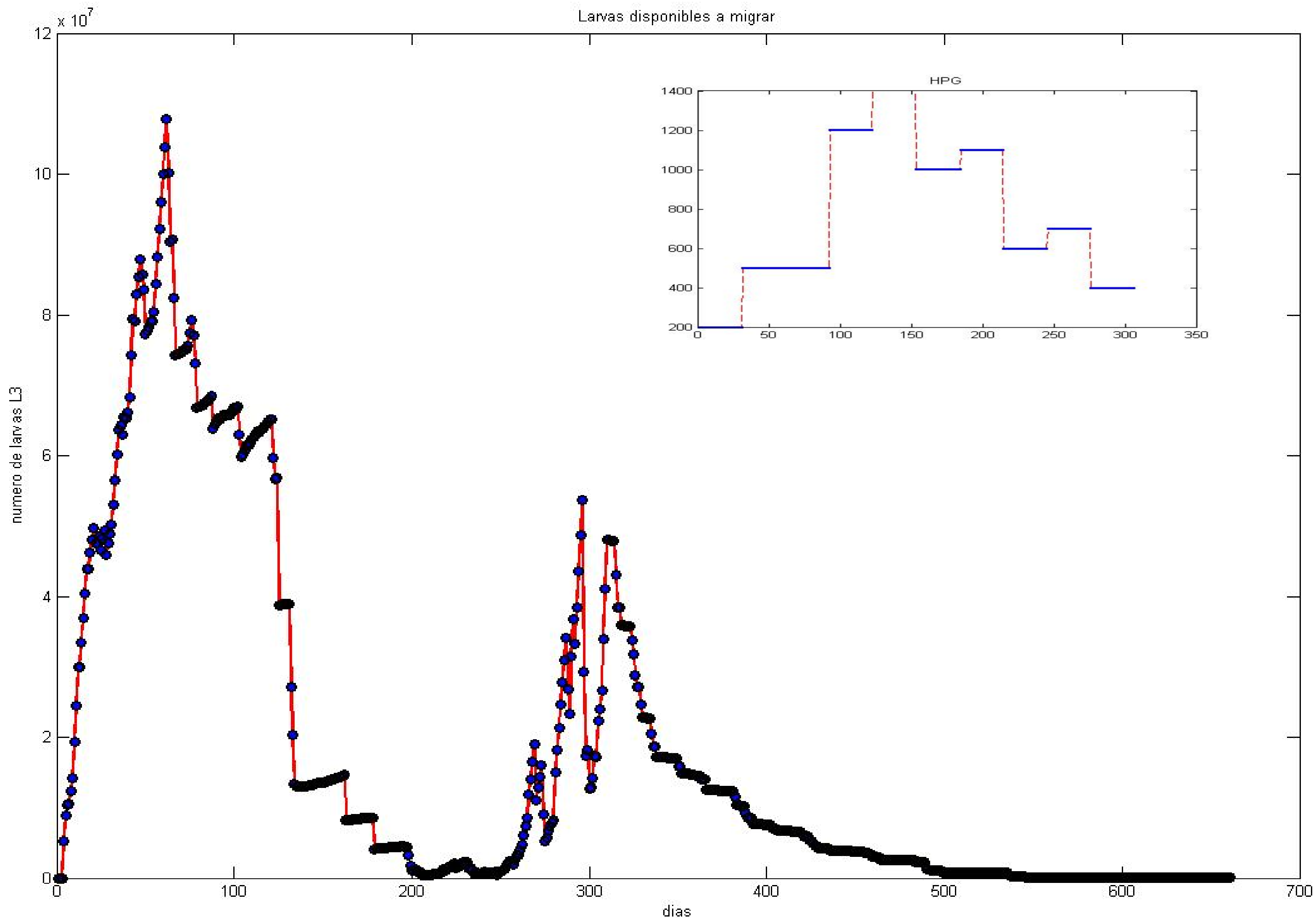
350 days of precipitation data.

Mercedes, Province of Corrientes

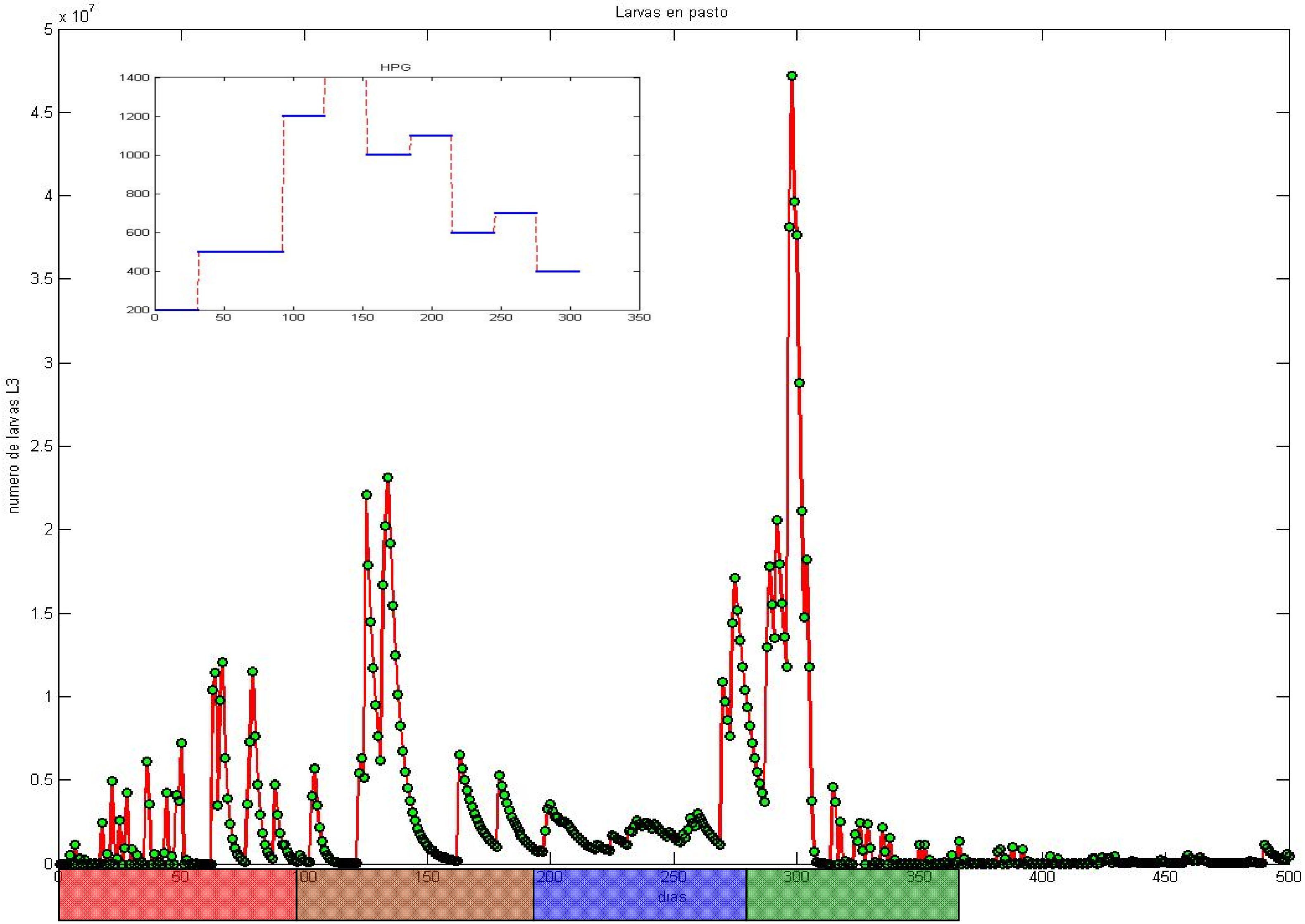
Egg to L3 development time

	Median	Mínimum	Máximum
Summer	3	3	4
Autumn	9	4	17
Winter	18	15	19
Spring	8	4	15

Mercedes, Province of Corrientes



Mercedes, Province of Corrientes



Reconquista, Province of Santa Fe

Initial Conditions

A paddock with 2 animals weighting 250 kg. each.

Temperature Tmax=28°C; Tmin=15°C

Grazing period of 6 months (181 days aprox.).

Eggs per gram values (HPG) are those determined in *"Epidemiology of Bovine Nematode Parasites in the Americas".*

Three complete semesters of precipitation data (550 days. INTA Reconquista).

Conclusions

•The model is a good approximation to field data.

•The knowledge of egg-to-*L3* development time inside the fecal paths permits to determine the minimum delays for the pasture to become infected.

• There is a clear dependency on precipitations for pasture infection.

• The determination of infectivity levels is a very useful tool in the diagnosis of the disease because it allows assessing the exposure risk of animals in the paddock. It also allows inferring infectivity patterns and relating them to climate variations and cattle management

•The fact that the survival of L3 depends on climate permits to estimate how long the delay will be before cattle can be reintroduced in the paddock with a minimal risk of infection.

Conclusions

The model based on fuzzy logic produces very satisfactory results. The simulations adequately mimic the dynamics of the infection of pastures.

This accurate representation obtained from the model is reflected in the similarity of the output with field experiment data in several key aspects:

•Estimation of egg-to-L3 development time under different climatic conditions and in different seasons.

•Estimation of time of the first L3 larvae appearing in pasture under different climatic conditions and in different seasons.

•Estimation of the Julian day in which the peak infection is expected.

•Estimation of the duration of the infection.

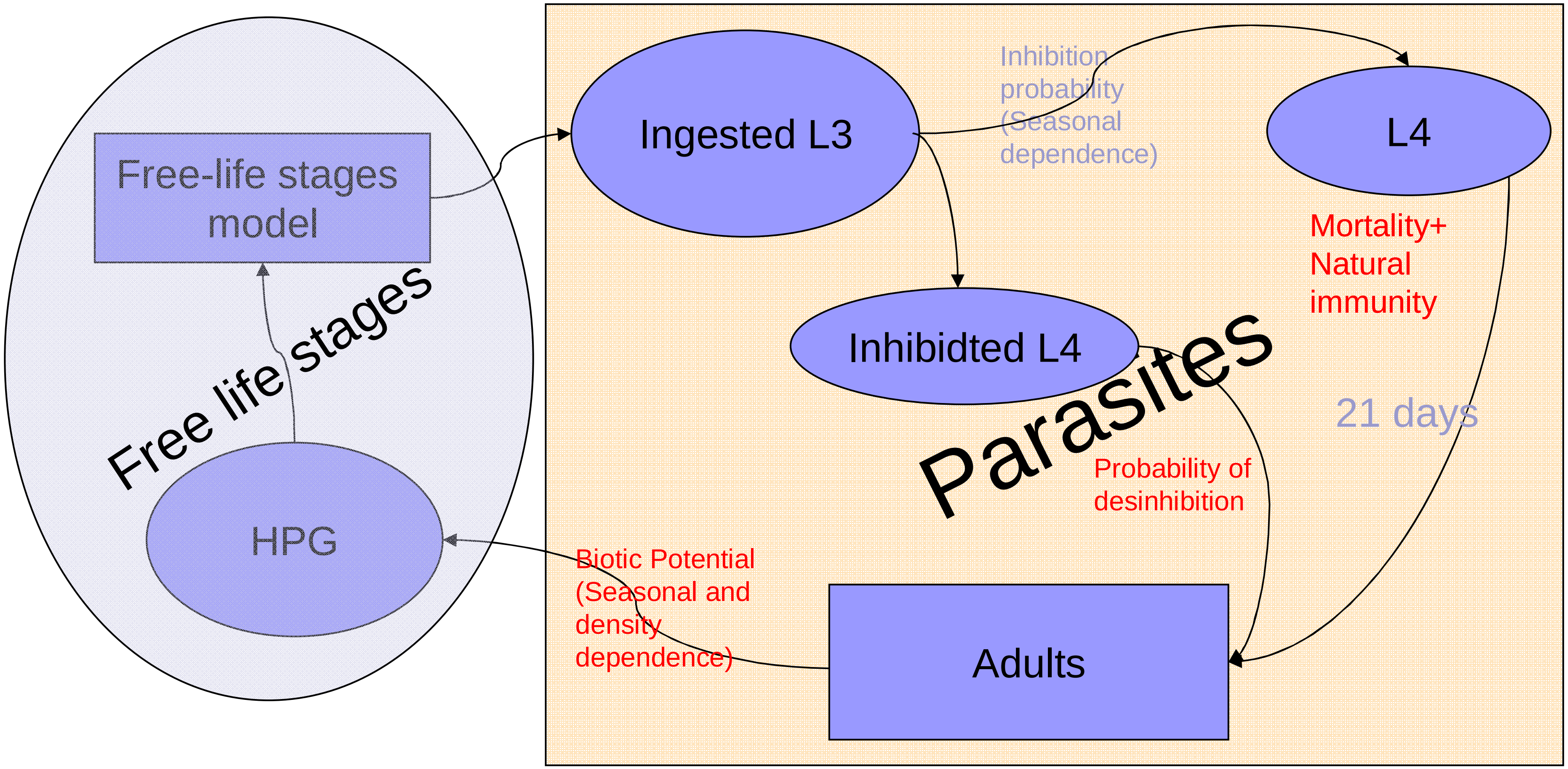
Conclusions

One important feature of this model is its simplicity. It is expressed in terms of three difference equations and their fuzzy parameters.

This permitted to handle a large number of variables and information that is not straightforwardly quantifiable and that could not have been possible to include if using classic mathematical tools. The inclusion of knowledge gained through experience along many years of research is a very valuable aspect of this modelling approach.

Work in progress

- Completing the life cycle



Dime cuanto llueve y te diré cuantos bichos tienes en el pasto

Tell me how it rains and I’ll tell you how many bugs you have in the grass.

Thank you!