Introduction à la génétique quantitative des interactions sociales

Timothée Flutre

Introduction à la génétique quantitative des interactions sociales

Timothée Flutre

Unité "Génétique Quantitative et Evolution"
Université Paris-Saclay — INRAE — CNRS — AgroParisTech

28/11/2022

Journée MoBiDiv & APIMET-SEPMET (Agro Montpellier)

Préambule

Lush (1943)

> *No effort of mine could keep the book entirely free from statistical terms. After all, a breed is a population, and any attempt at precision in discussing methods of changing its characteristics must necessarily be phrased in terms of the measurements of populations ; that is, in terms of averages and variability.*

Plan

Rappels de génétique quantitative

Interactions entre organismes

Extension de la formalisation

Applications

Plan

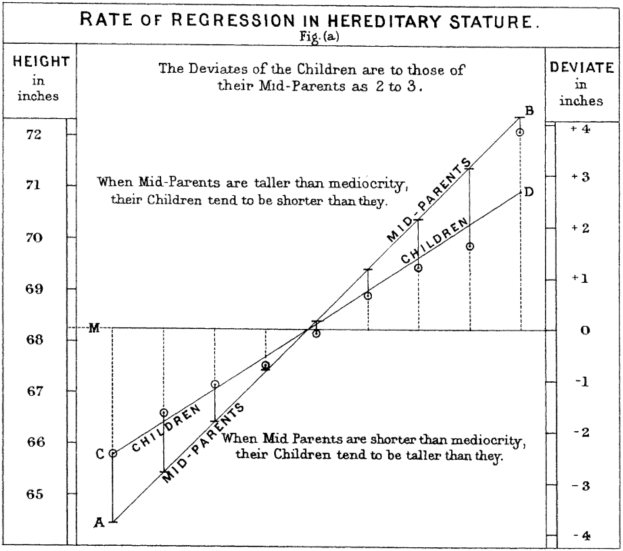
Rappels de génétique quantitative

Interactions entre organismes

Extension de la formalisation

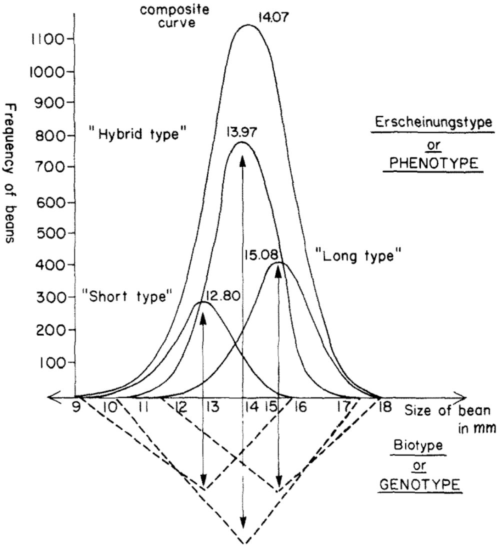
Applications

Galton (1886)



RATE OF REGRESSION IN HEREDITARY STATURE.
Fig. (a)
HEIGHT in inches
The Deviates of the Children are to those of their Mid-Parents as 2 to 3.
DEVIATE in inches
72
71
70
69
68
67
66
65
+4
+3
+2
+1
0
-1
-2
-3
-4
B
D
M
C
A
MID-PARENTS
CHILDREN
When Mid-Parents are taller than mediocrity, their Children tend to be shorter than they.
When Mid Parents are shorter than mediocrity, their Children tend to be taller than they.

Johanssen (1909)



Fisher (1918)

The contributions of imperfectly additive genetic factors divide themselves for statistical purposes into two parts: an additive part which reflects the genetic nature without distortion, and gives rise to the correlations which one obtains; and a residue which acts in much the same way as an arbitrary error introduced into the measurements.

[...]

In general

$$\alpha^2 = \beta^2 + \delta^2,$$

and if

$$\sigma^2 = \Sigma\alpha^2 \quad \text{(VIII)}$$

$$\tau^2 = \Sigma\beta^2 \quad \text{(IX)}$$

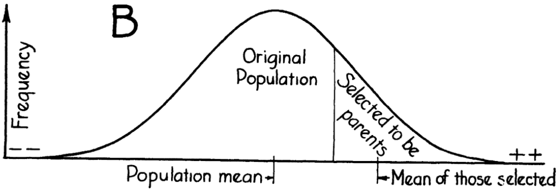
and

$$\epsilon^2 = \Sigma\delta^2 \quad \text{(X)}$$

then

$$\sigma^2 = \tau^2 + \epsilon^2.$$

Lush (1943)



[...]

Mass selection is expected to cause the average of each generation to exceed the average of the preceding generation by an amount (M) which is equal to the heritability fraction $\frac{\sigma_G^2}{\sigma_O^2}$ of the selection differential (S), the latter being the average merit of those selected to be parents minus the average of the whole generation from which they were taken.

Résumé

$$P_i = G_i + \text{termes non-héritables} \tag{1}$$
$$G_i = G_{A,i} + \text{termes non-héritables} \tag{2}$$

Résumé

$$P_i = G_i + \text{termes non-héritables} \quad (1)$$

$$G_i = G_{A,i} + \text{termes non-héritables} \quad (2)$$

$$\sigma_P^2 = \sigma_A^2 + \text{termes non-héritables} \quad (3)$$

$$h^2 = \sigma_A^2 \;/\; \sigma_P^2 \quad (4)$$

$$cov(G_{A,i}, G_{A,j}) = \sigma_A^2 \times r_A = \sigma_A^2 \times 2\phi_{A,ij} \quad (5)$$

Résumé

$$P_i = G_i + \text{termes non-héritables} \quad (1)$$

$$G_i = G_{A,i} + \text{termes non-héritables} \quad (2)$$

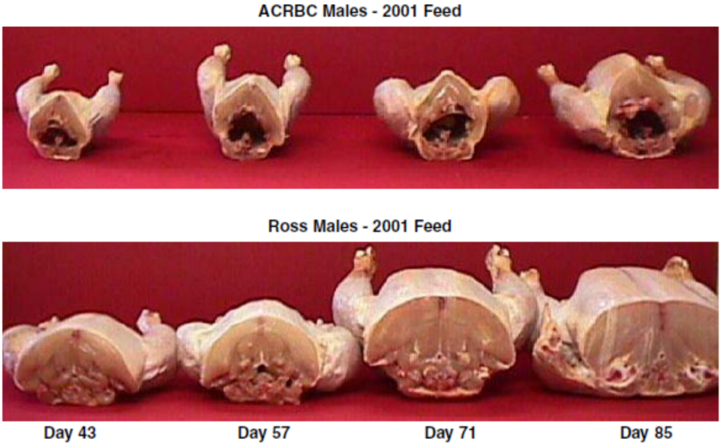
$$\sigma_P^2 = \sigma_A^2 + \text{termes non-héritables} \quad (3)$$

$$h^2 = \sigma_A^2 \; / \; \sigma_P^2 \quad (4)$$

$$cov(G_{A,i}, G_{A,j}) = \sigma_A^2 \; \times \; r_A = \sigma_A^2 \; \times 2\phi_{A,ij} \quad (5)$$

$$R = h^2 \, S = i \, \rho \, \sigma_A \;\; \text{avec} \;\; \rho = cor(G_A, \bar{P}) \quad (6)$$

Exemple de sélection artificielle directionnelle



http://www.dcam.upv.es/dcia/ablasco/Unpublished/U9.%20Animal%20breeding.pdf

Plan

Rappels de génétique quantitative

Interactions entre organismes

Extension de la formalisation

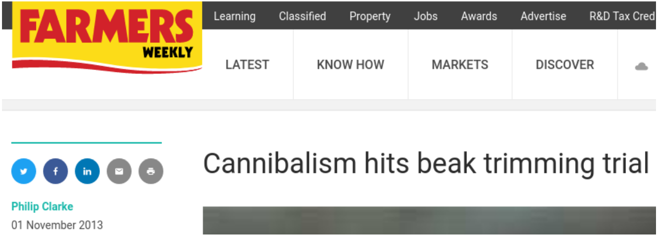
Applications

Objectif :

décrypter les bases *génétiques*...

... des interactions *écologiques* entre organismes

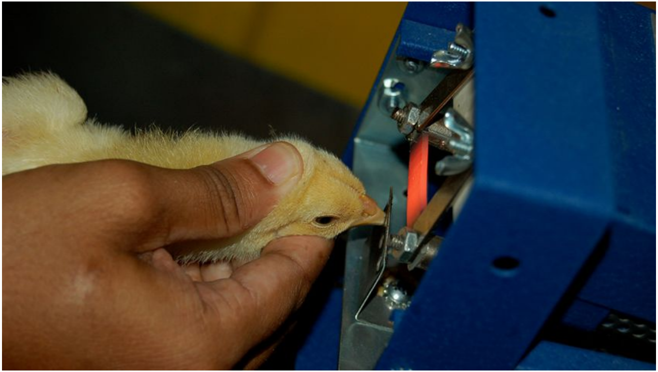
https://www.dailymail.co.uk/news/article-8086869/Shoppers-urged-buy-white-eggs-come-aggressive-hens.html



https://www.fwi.co.uk/livestock/poultry/cannibalism-hits-beak-trimming-trial

https://www.britannica.com/topic/poultry-farming

https://www.dailymail.co.uk/news/article-8086869/Shoppers-urged-buy-white-eggs-come-aggressive-hens.html



https://www.hightoppoultry.com/debeak-chickens-debeaking-beak-trimming-tips/

Compétition intra-spécifique

https://commons.wikimedia.org/wiki/File:Fighting_Hartebeest.jpg

Compétition intra-spécifique

https://doi.org/10.1016/B978-0-12-374855-3.00022-4

Coopération intra-spécifique

https://fr.123rf.com/photo_16443377_l-unit%C3%A9-et-la-coop%C3%A9ration-des-fourmis.html

Coopération intra-spécifique

https://www.shutterstock.com/fr/image-photo/trust-teamwork-bees-linking-two-bee-262155599

Coopération intra-spécifique

https://doi.org/10.1007/978-3-319-19650-3_1367

Effect maternel comme interaction inter-générationnelle

https://www.slu.se/en/departments/animal-nutrition-management/education/undergraduate-and-master-studies/c

Coopération et compétition intra-spécifique

https://www.lemonde.fr/sport/article/2022/11/20/rugby-les-bleus-l-emportent-face-au-japon-et-terminent-l-a

Conceptualisation en biologie évolutive

Notion de *phénotype étendu* de Dawkins (1982) :

> *Genes affect proteins, and protein affect X which affects Y which affects Z which... affects the phenotypic character of interest. But the conventionnal geneticist defines 'phenotypic effect' in such a way that X, Y and Z must all be confined inside one individual body wall. The extended geneticist recognizes that this cut-off is arbitrary, and he is quite happy to allow his X, Y and Z to leap the gap between one individual body and another.*
>
> [...]
>
> *I gave my intention of using extended phenotype language only when the character concerned might conceivably influence, positively or negatively, the replication success of the gene or genes concerned.*

Conceptualisation en biologie évolutive

Notion de *valeur sélective inclusive* de Hamilton (1964) : valeur sélective d'un génotype, à laquelle sont retirées toutes les composantes dues à l'environnement social de celui-ci, mais sont ajoutés les effets de celui-ci sur la valeur sélective des autres, pondérés par leur apparentement

Notions de sélection de *groupe* et de *parentèle* (Hamilton, 1975).

Gardner (2020) :

> *Price's equation has been identified as largely resolving this debate, by showing that the kin selection and group selection approaches to social evolution are actually just different ways of describing the very same thing.*

Interactions inter-spécifiques

https://www.flickr.com/photos/epiney/51376578799

Interactions inter-spécifiques

https://commons.wikimedia.org/wiki/File:Image-Pollination_Bee_Dandelion_Zoom2.JPG

Interactions inter-spécifiques

nature > news & views > article

NEWS AND VIEWS | 24 October 2018

Gut microbes alter the walking activity of fruit flies

A gut bacterium has been found to modulate locomotor activity in the fruit fly *Drosophila melanogaster*. This effect is mediated by the level of a sugar and the activity of neurons that produce the molecule octopamine.

nature > news & views > article

NEWS AND VIEWS | 23 October 2019

Gut microbes regulate neurons to help mice forget their fear

Microorganisms in the gut influence fear-related learning. The results of a study that reveals some of the mechanistic underpinnings of this phenomenon promise to boost our understanding of gut–brain communication.

Compétition pour la lumière chez les plantes

https://blogs.princeton.edu/research/2016/01/08/in-rainforests-battle-for-sunlight-shapes-forest-structure

Compétition pour la lumière chez les plantes

Pépinière de blé tendre, projet MoBiDiv, Saclay, 14/06/2021

Coopétition inter-spécifique

Mélange de blé (céréale) et pois (légumineuse), projet intercropRNAseq, Saclay, 20/05/2022

Caractères définis à l'échelle du groupe

https://doi.org/10.1016/j.beproc.2011.09.006

Caractères définis à l'échelle du groupe

Essai non-traité de génotypes de blé tendre en monoculture et en mélange, projet Wheatamix, Versailles

Plan

Effets additifs directs et sociaux/indirects/associés

Dans un groupe de taille n, $\bar{r}_A$ étant la moyenne des relations génétiques additives :

$$P_i = P_{D,i} + \sum_{j \neq i}^{n} P_{S,j} \tag{7}$$

$$= G_{A_D,i} + \sum_{j \neq i}^{n} G_{A_S,j} + \text{termes non-héritables} \tag{8}$$

Effets additifs directs et sociaux/indirects/associés

Dans un groupe de taille n, $\bar{r}_A$ étant la moyenne des relations génétiques additives :

$$
\begin{aligned}
P_i &= P_{D,i} + \sum_{j \neq i}^{n} P_{S,j} && (7) \\
&= G_{A_D,i} + \sum_{j \neq i}^{n} G_{A_S,j} + \text{termes non-héritables} && (8)
\end{aligned}
$$

$$
\begin{aligned}
\sigma_P^2 = \sigma_{A_D}^2 &+ (n-1)\sigma_{A_S}^2 && (9) \\
&+ (n-1)\ \bar{r}_A\ [2\sigma_{A_{DS}} + (n-2)\sigma_{A_S}^2] && (10) \\
&+ \text{termes non-héritables} && (11)
\end{aligned}
$$

Valeur génétique additive *totale*

$$G_{A_T,i} = G_{A_D,i} + (n-1) G_{A_S,i} \tag{12}$$

Valeur génétique additive *totale*

$$G_{A_T,i} = G_{A_D,i} + (n-1)G_{A_S,i} \tag{12}$$

$$\sigma^2_{A_T} = \sigma^2_{A_D} + (n-1)^2\sigma^2_{A_S} + 2(n-1)\sigma_{A_{DS}} \tag{13}$$

Valeur génétique additive *totale*

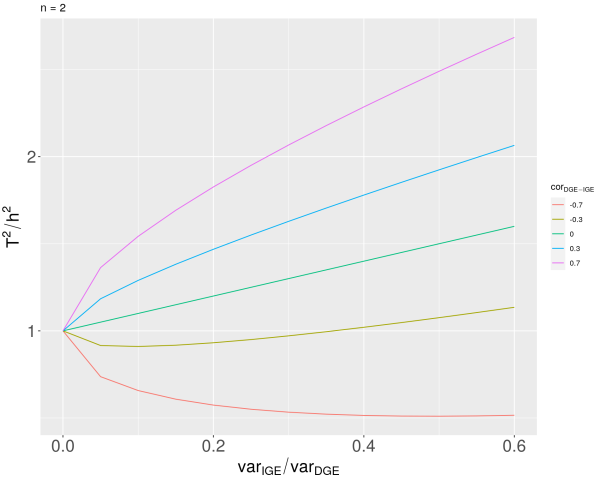
$$G_{A_T,i} = G_{A_D,i} + (n-1) G_{A_S,i} \tag{12}$$

$$\sigma^2_{A_T} = \sigma^2_{A_D} + (n-1)^2 \sigma^2_{A_S} + 2(n-1)\sigma_{A_{DS}} \tag{13}$$

$$\sigma^2_P \neq \sigma^2_{A_T} + \text{termes non-héritables}$$

- Les effets sociaux créent de la variance génétique cachée, hors de la variance phénotypique.

$$h^2 = \sigma^2_{A_D}/\sigma^2_P \text{ et } T^2 = \sigma^2_{A_T}/\sigma^2_P \Rightarrow T^2/h^2 = \sigma^2_{A_T}/\sigma^2_{A_D}$$



Réponse à la sélection

Puisque $\sigma^2_{A_T}$ est la variance héritable totale :

$$R = i \, \rho \, \sigma_{A_T} \tag{14}$$

- Les effets sociaux peuvent augmenter le potentiel de réponse...
- ... ou au contraire le diminuer, voire l'annuler.

Influence de la taille du groupe

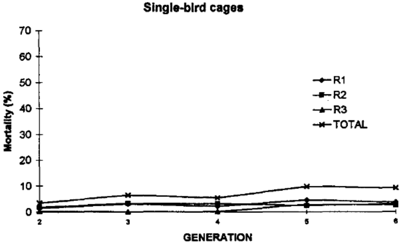
$$P_{S,j,n} = \frac{1}{(n-1)^d} \; P_{S,j,2} \tag{15}$$

- $d = 0$: pas d'influence
  - ex. signal d'alerte de prédateurs
- $d = 1$: dilution complète
  - ex. compétition pour les ressources

Besoin de groupes de différentes tailles pour estimer d.

Plan

Evolution expérimentale avec sélection de groupe



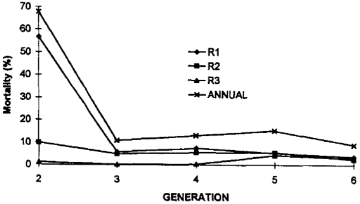
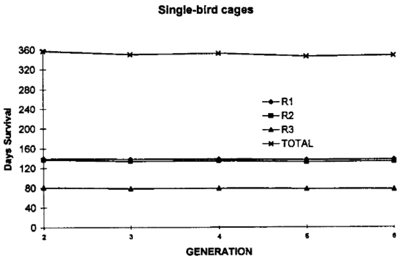


FIGURE 2. a) Percentage mortality (MORT) for the unselected control in one-bird cages for the total record, from 20 to 40 (R1), 41 to 60 (R2), and 61 to 72 wk of age (R3) for Generations 2 through 6. b) MORT for the selected line in multiple-bird cages for the total record, from 20 to 40 (R1), 41 to 60 (R2), and 61 to 72 wk of age (R3) for Generations 2 through 6.

Muir (1996)

Evolution expérimentale avec sélection de groupe



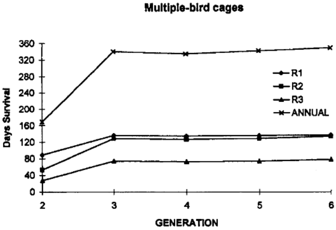
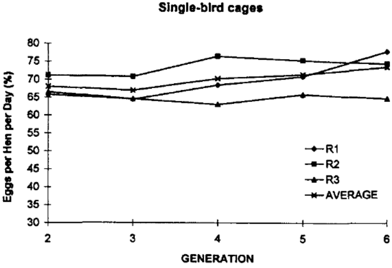


FIGURE 3. a) Days survival (DS) for the unselected control in 1-bird cages for the total record, from 20 to 40 (R1), 41 to 60 (R2), and 61 to 72 wk of age (R3) for Generations 2 through 6. b) DS for the selected line in multiple-bird cages for the total record, from 20 to 40 (R1), 41 to 60 (R2), and 61 to 72 wk of age (R3) for Generations 2 through 6.

Muir (1996)

Evolution expérimentale avec sélection de groupe



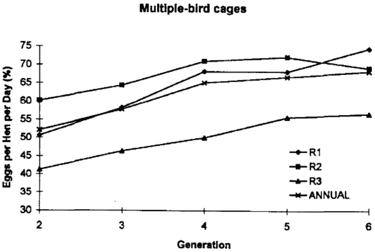
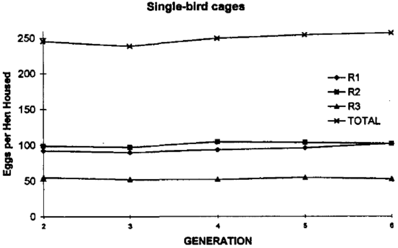


FIGURE 4. a) Eggs per hen per day (EHD) for the unselected control in 1-bird cages for the total record, from 20 to 40 (R1), 41 to 60 (R2), and 61 to 72 wk of age (R3) for Generations 2 through 6. b) EHD for the selected line in multiple-bird cages for the total record, from 20 to 40 (R1), 41 to 60 (R2), and 61 to 72 wk of age (R3) for Generations 2 through 6.

Muir (1996)

Evolution expérimentale avec sélection de groupe



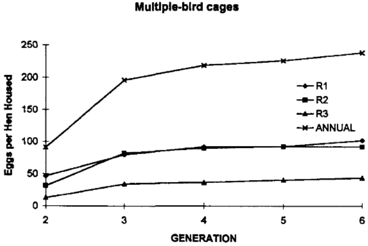
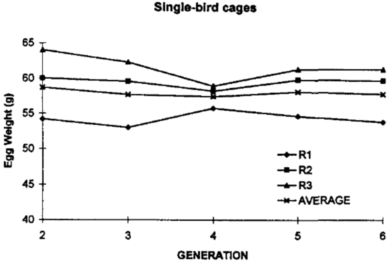


FIGURE 5. a) Eggs per hen housed (EHH) for the unselected control in 1-bird cages for the total record, from 20 to 40 (R1), 41 to 60 (R2), and 61 to 72 wk of age (R3) for Generations 2 through 6. b) EHH for the selected line in multiple-bird cages for the total record, from 20 to 40 (R1), 41 to 60 (R2), and 61 to 72 wk of age (R3) for Generations 2 through 6.

Muir (1996)

Evolution expérimentale avec sélection de groupe



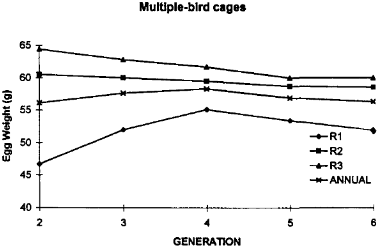
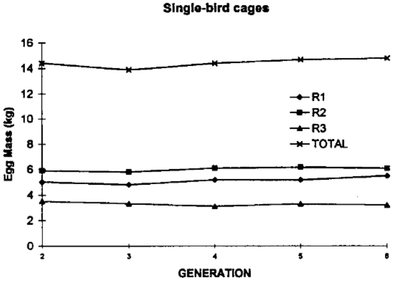


FIGURE 6. a) Egg weight (EWT) for the unselected control in 1-bird cages for the total record, from 20 to 40 (R1), 41 to 60 (R2), and 61 to 72 wk of age (R3) for Generations 2 through 6. b) EWT for the selected line in multiple-bird cages for the total record, from 20 to 40 (R1), 41 to 60 (R2), and 61 to 72 wk of age (R3) for Generations 2 through 6.

Muir (1996)

Evolution expérimentale avec sélection de groupe



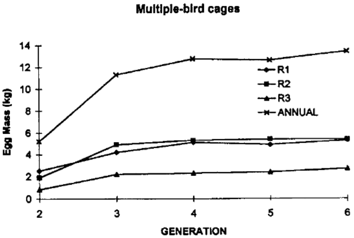


FIGURE 7. a) Egg mass (EM) for the unselected control in 1-bird cages for the total record, from 20 to 40 (R1), 41 to 60 (R2), and 61 to 72 wk of age (R3) for Generations 2 through 6. b) EM for the selected line in multiple-bird cages for the total record, from 20 to 40 (R1), 41 to 60 (R2), and 61 to 72 wk of age (R3) for Generations 2 through 6.

Muir (1996)

Evolution expérimentale avec sélection de groupe

The fact that DS and MORT had improved over the generations in the selected line, housed in multiple-bird cages [although with intact beaks], to the point that livability was similar to that of the unselected control line, housed in single-bird cages, is dramatic evidence that group selection is effective in improving animal well-being in competitive environments.

[...]

[This] suggests that the practice of beak trimming can be discontinued with proper genetic selection.

Muir (1996)

Evolution expérimentale avec indice de sélection

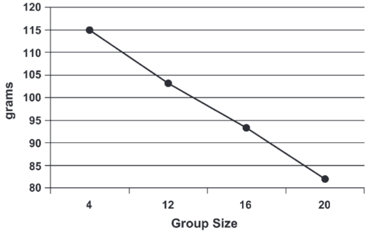


FIGURE 6.—Mean body weight at 42 days by group (pen) size.

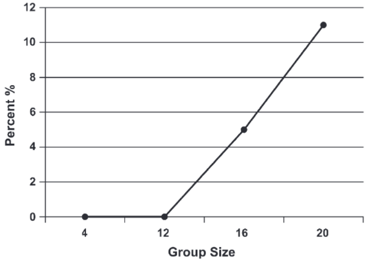


FIGURE 7.—Mean percentage of mortality by group size.

Muir (2005)

Evolution expérimentale avec indice de sélection

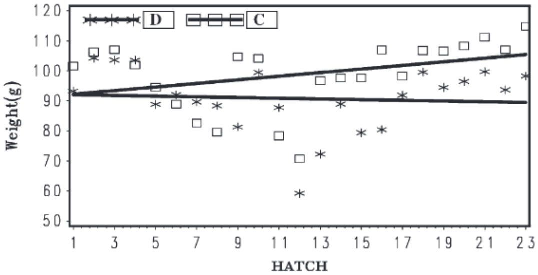


FIGURE 8.—Mean body weight at 6 weeks for each hatch by method of selection (D-BLUP, selection on direct effects only; C-BLUP, index selection on direct and associative effects).

Muir (2005)

Evolution expérimentale avec indice de sélection

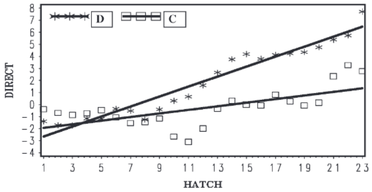


FIGURE 9.—Mean of estimated direct genetic effects for body weight at 6 weeks for each hatch by method of selection (D-BLUP, selection on direct effects only; C-BLUP, index selection on direct and associative effects).

Muir (2005)

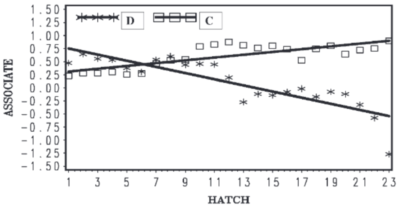


FIGURE 10.—Mean of estimated associative genetic effects for body weight at 6 weeks for each hatch by method of selection (D-BLUP, selection on direct effects only; C-BLUP, index selection on direct and associative effects).

Evolution expérimentale avec indice de sélection

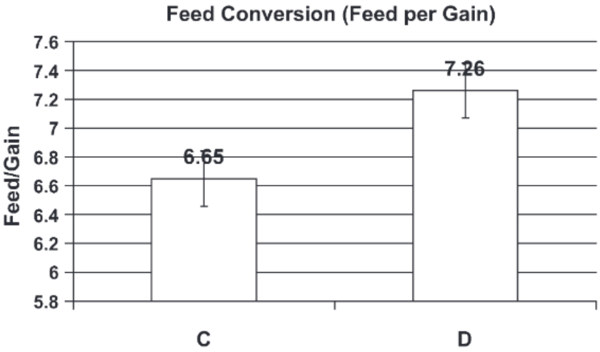


FIGURE 11.—Efficiency of feed conversion of quail after 23 cycles of selection with either C-BLUP (index selection on direct and associative effects) or D-BLUP selection on direct effects only.

Muir (2005)

Evolution expérimentale avec indice de sélection

> *with D-BLUP, the responses in direct and associative effects were in opposite directions, with associative effects negating the positive change in the direct effects*
>
> [...]
>
> *with C-BLUP, improvement in associative effects more than compensated for the slower rate of improvement in direct effects*

Muir (2005)

Quelques perspectives chez les plantes cultivées

Analyse de l'architecture génétique de l'aptitude au mélange, décomposée en effets directs et sociaux/indirects :

- mélanges intra-spécifiques : blé tendre avec le projet Wheatamix (J. Enjalbert à GQE) et blé dur avec le projet SCOOP (H. Fréville à AGAP)
  - analyses qui se continuent dans le groupe de travail `gwasvarmix` du projet MoBiDiv
- mélanges inter-spécifiques : blé-pois dans MoBiDiv (J. Enjalbert et T. Flutre à GQE avec A. Baranger et N. Moutier à l'IGEPP)

Quelques références additionnelles

Griffing (1967, 1976) ; Gallais (1976) ; Wright (1977, 1985, 1986) ; Wolf et coll. (1998) ; Frank (1998, 2007) ; Lehmann et coll. (2007) ; Mutic and Wolf (2007) ; Bijma et coll. (2007) ; Bergsma et coll. (2008) ; Bijma (2010, 2014) ; Heidaritabar et coll. (2019)

Remerciements

Jérôme Enjalbert et Jacques David pour les nombreuses discussions autour des mélanges et de la génétique quantitative.

Les membres de l'équipe DEAP de l'unité GQE, dont Maxence Remérand, ainsi que du groupe de travail `gwasvarmix` du projet MoBiDiv, notamment Germain Montazeaud.