Two ABM approaches to the spread of the Neolithic in the western Mediterranean

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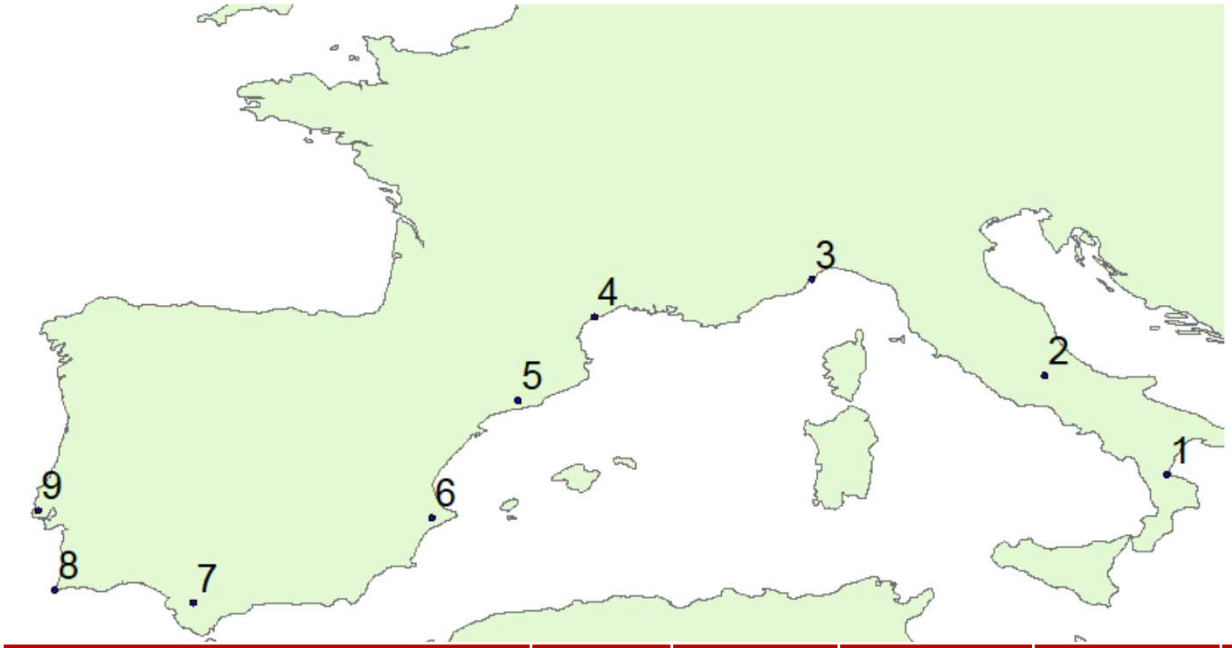
Background

· 20 years ago Zilhao (*PNAS* 2001) noted that **'the dates for the first appearance of the Neolithic package are indistinguishable statistically from central Italy to Portugal'**. He reached this conclusion after rejecting almost all dates, e.g., all long-lived samples (due to the old-wood effect).

· 15 years ago it was still not possible to estimate the spread rate in km/yr due to the paucity of reliable dates (Zilhao, personal communication, 10/3/2006).

· 5 years ago we estimated the spread rate as **8.7 km/yr** (Isern, Zilhao, Fort & Ammeran, *PNAS* 2017).

· This year: analysis on dispersal distances and the cultural effect (Fort, AAS 2022). It is the topic of this talk.

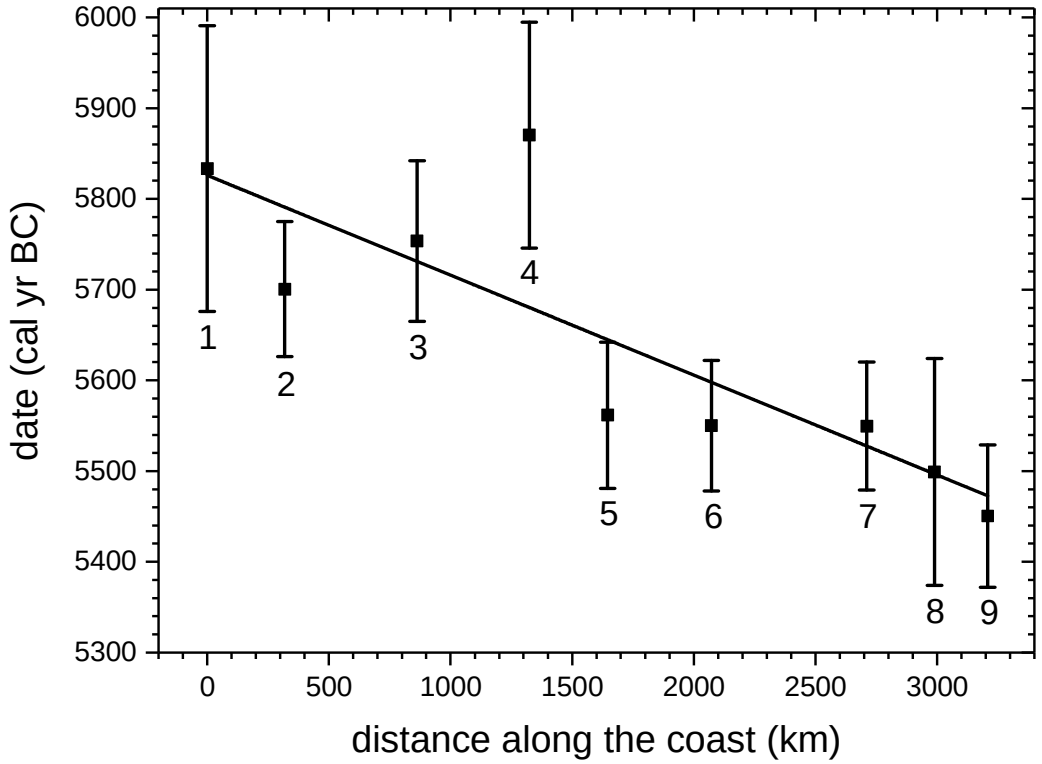


· New database.
· 215 early Neolithic sites.
· 3 new regions: 1, 2, and 4 (not included in our *PNAS* 2017).

· Oldest date per region on a domesticated, short-lived species.

Region	uncal BP	error	cal. BC max	cal. BC min	site
1 Southwestern Italy	**6956**	75	5991	5676	**Favella della Corte**
2 Central western Italy	6809	45	5774	5626	Colle Santo Stefano
3 NW Italy/SE France	6870	40	5842	5665	Arene Candide
4 Languedoc/Roussillon	**7010**	60	5995	5746	**Pont de Roque-Haute**
5 Catalonia	6655	45	5642	5481	Guixeres (de Vilobí)
6 Valencia	6600	50	5622	5478	Mas d'Is
7 Andalusia	6609	35	5620	5479	Dehesilla
8 southern Portugal	6550	70	5624	5374	Cabranosa
9 central Portugal	6497	34	5529	5372	Lameiras

Spread rate



<u>9.1 km/yr</u>, $r = 0.84$.

It is encouraging that this spread rate is similar to our previous estimation of 8.7 km/yr (Isern et al., *PNAS* 2017).

Bootstrap resampling using the calibrated probability distribution for each site: **<u>7.5-10.6 km/yr</u>** (80% CL). We will use this range in other slides. The mean is 9.1 km/yr, nicely consistent with the value above.

Technical note: The usual approach (based Student's *t*) yields 5.9-12.3 km/yr (80% CL) but is invalid because the data (squares) have not been found by sampling from normal distributions <u>with a single variance</u> and <u>centered about the regression</u>.

Agent-based model (ABM)

· Rectangular grid of square cells. **This allows us to obtain analytical equations for the spread rate.**

A real map would yield similar results (Isern et al., *PNAS* 2017).

· Initially farmers only at the lower row.

· All other grid cells are initially empty of farmers and with HGs at their saturation density.

· At each node in the grid and time step (of 1 generation =32 yr), we compute 3 processes:

(1) Reproduction: logistic, with net fecundities $Ro=e^{aT} = 2.45$ for farmers and $R'o=e^{a'T} = 1.81$ for HGs (from ethnographic data), where a and a' are the growth rates.

Technical note: Carrying capacities: 1.28 farmers/km^2, 0.064 HGs/km^2 (from ethnography). They do not have any effect on the spread rates, neither does R'o.

Agent-based model (ABM)

(2) Cultural transmission (e.g., interbreeding):

P_N = farmers

P_{HG} = hunter-gatherers

Cultural transmission theory [1-3] (children of mixed matings are farmers):

$$P_N(t+1,x,y) = P_N(t,x,y) + \eta\frac{P_{HG}P_N}{P_{HG}+P_N}$$

$$P_{HG}(t+1,x,y) = P_{HG}(t,x,y) - \eta\frac{P_{HG}P_N}{P_{HG}+P_N}$$

η = intensity of interbreeding $0 \leq \eta \leq 1$ (random mating $\rightarrow \eta = 1$)

[1] Cavalli-Sforza & Feldman, *Cultural transmission & evo*l., Princeton 1981

[2] Fort, *Phys. Rev. E* 2011

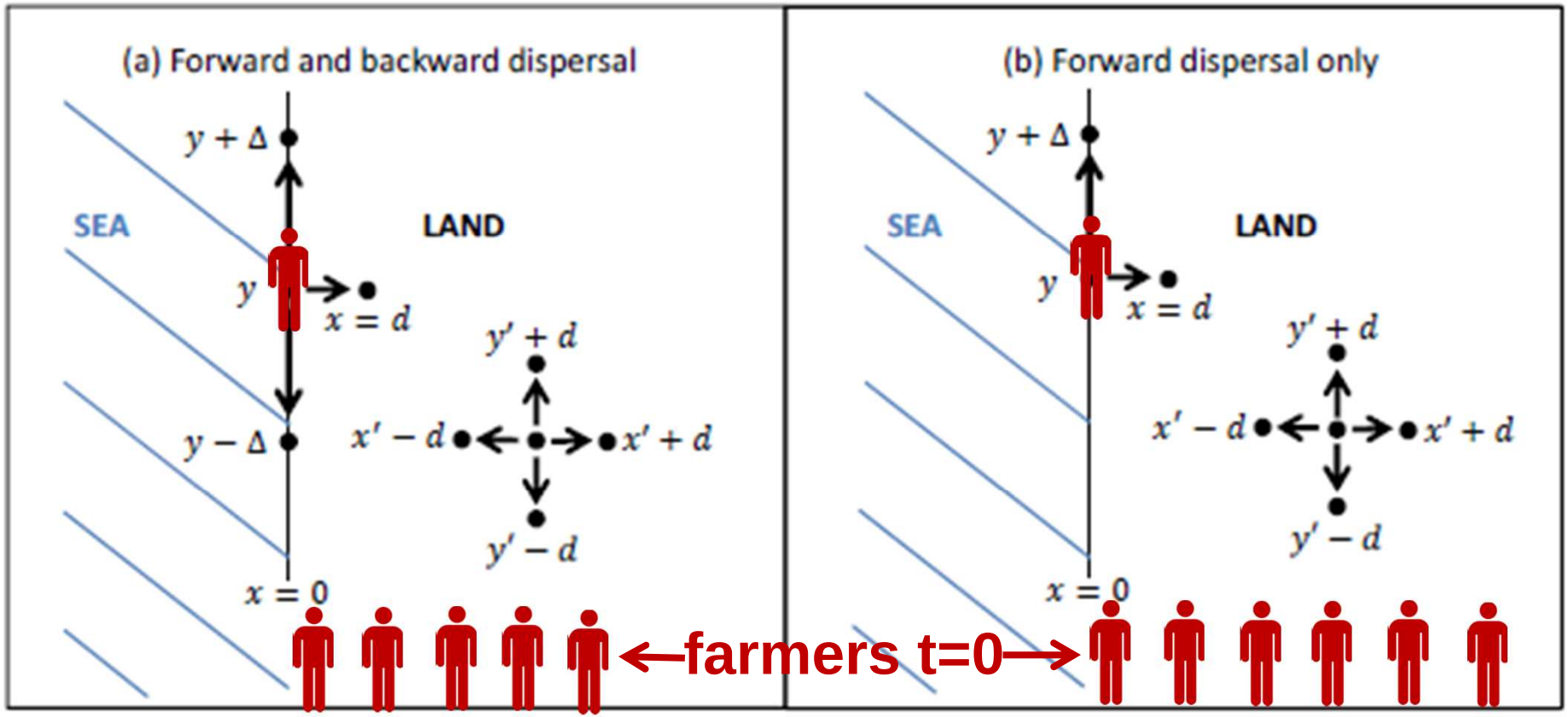
[3] Fort, *PNAS* 2012

(3) Dispersal: 38% do not migrate *(p_e=0.38),* from ethnography.

Two dispersal ABMs: next slide

Two agent-based models (ABMs)

First model **Second model**



Inland: $d = 50$ km from ethnography, and to obtain1 km/yr as observed. We want to find what values of the sea-travel distance Δ are consistent with the observed spread rate along the coast (7.5-10.6 km/yr, slide #4).

Theory

First equations for the **spread rate s** **along a coast** [4]

- First model (forward and backward dispersal):

$$s = \min_{\lambda > 0} \frac{ln\left[R_0^F(1+\eta)\left(\frac{2p_e+1}{3}+\frac{2}{3}(1-p_e)\cosh(\lambda\Delta)\right)\right]}{\lambda T}$$

- Second model (forward dispersal only):

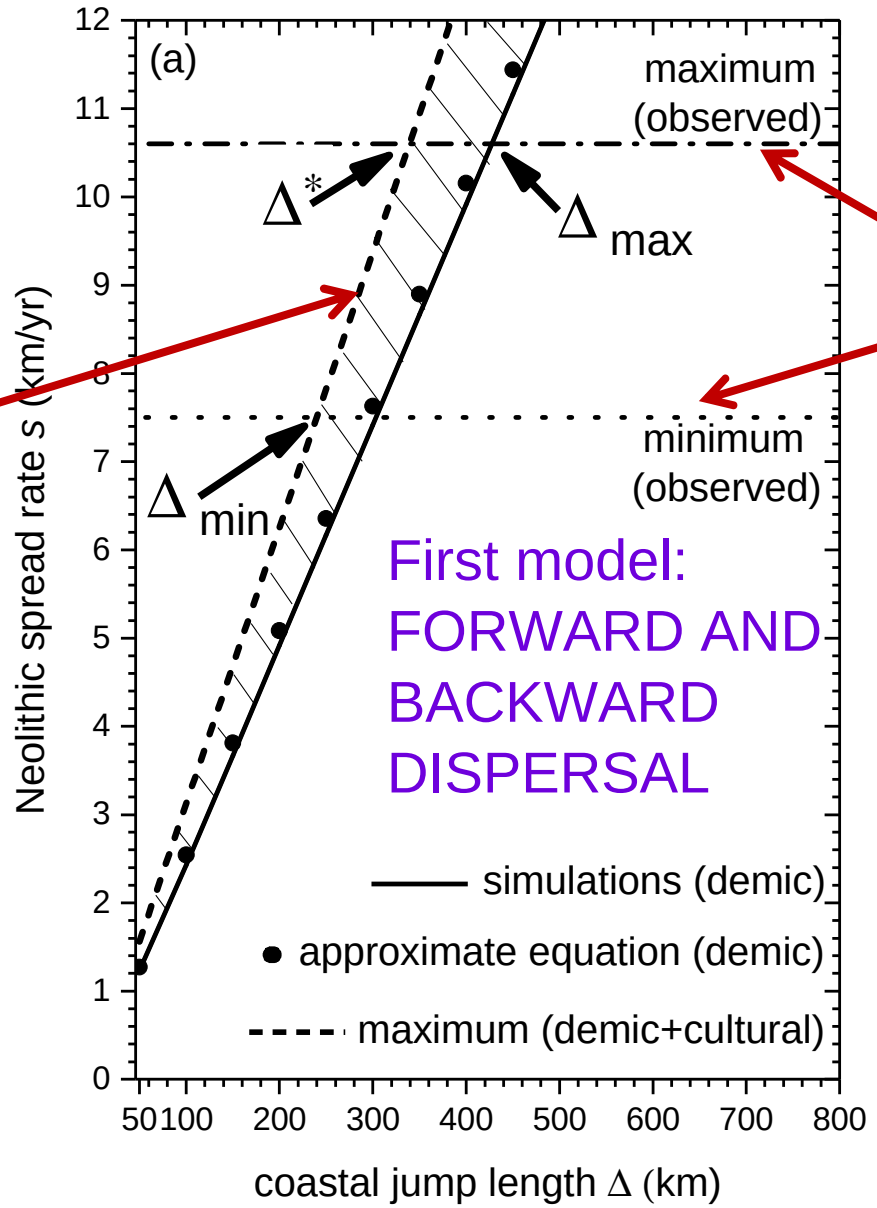
$$s = \min_{\lambda > 0} \frac{ln\left[R_0^F(1+\eta)\left(\frac{p_e+1}{2}+\frac{1-p_e}{2}e^{\lambda\Delta}\right)\right]}{\lambda T}$$

[4] Fort, *Arch. & Anthropol. Sci.* (2022)

Results

maximum possible spread rate:

$s_{max} = \Delta / T$



archaeological data: **7.5-10.6 km/yr** (slide #4)

Results from this figure:

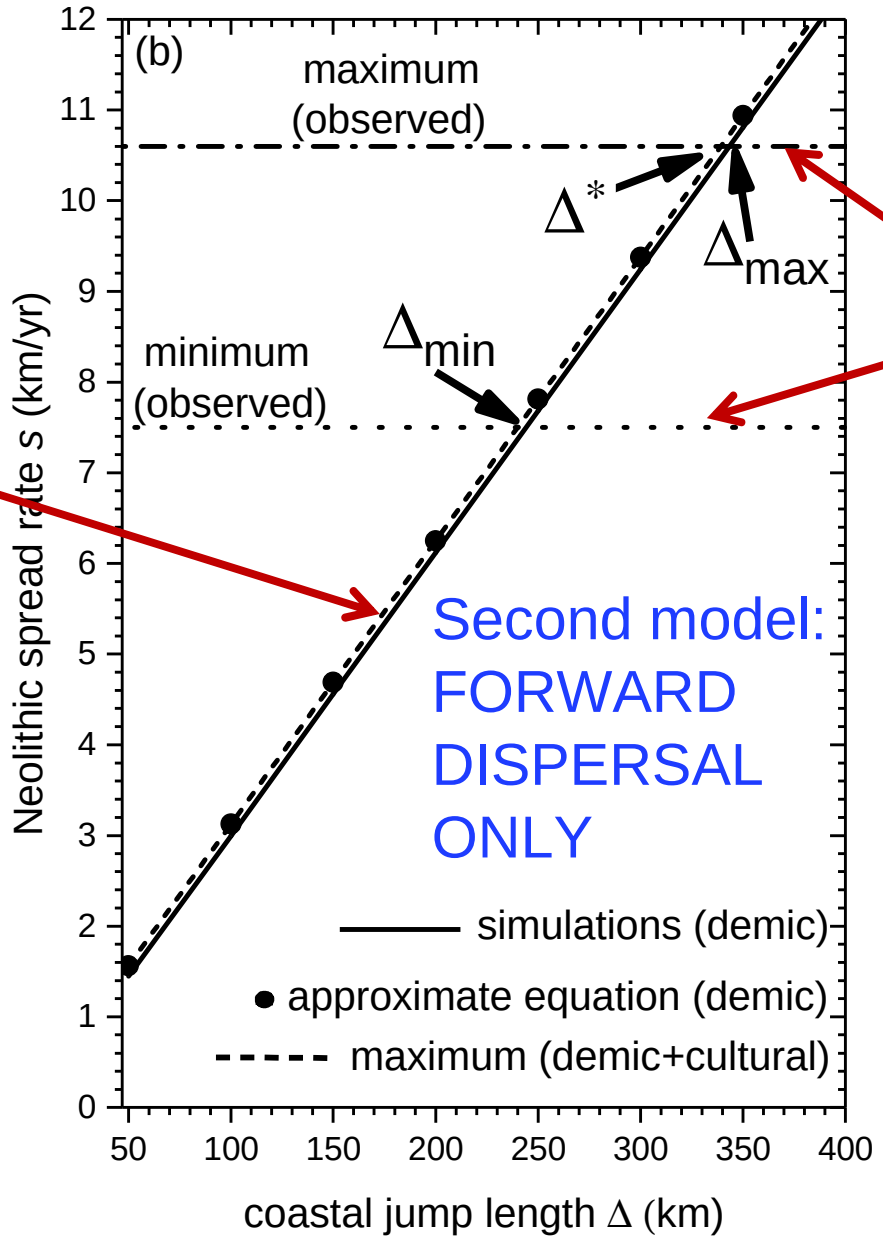
$\Delta_{min} = 240$ km

$\Delta_{max} = 427$ km

Results

maximum possible spread rate:

$s_{max} = \Delta / T$



archaeological data: **7.5-10.6 km/yr** (slide #4)

Results from this figure:

$\Delta_{min} = 240$ km

$\Delta_{max} = 343$ km

Results

1st model (forward and backward dispersal): Δ_{min} = 240 km, Δ_{max} = 427 km
2nd model (forward dispersal only): Δ_{min} = 240 km, Δ_{max} = 343 km
Overall range: 240 km ≤ Δ ≤ 427 km per generation

Technical notes:

1. Why are they much longer than inland (about 50 km)?
Perhaps because by foot: 5km/hour·10 hours= 50km
but ancient boats (reconstructions): 19 km/h·13h=250km.

2. Not surprising because ethnographic records of pre-industrial peoples used to sea travel display such long distances. Examples:

-Fiji to Samoa (>700 km) to get married since >300 years ago.

-XIX-century migrations from Nukuria to Mimigo (1,100 km), the Gilberts to the Solomons (1,900 km) and to Buka (2,200 km), etc.

-routine travels of 650-975 km by pre-Columbian Caribbeans.

-Kula ring travels, near Papua New Guinea, early XXth century,150 km.

-Obsidian trade in near Oceania: 240 km 20,000 yr BP, 400 km by Lapita populations 3,000 yr ago.

Cultural effect

Cultural effect= Percentage C of cultural diffusion [3]:

$$C = \frac{s - s_{\eta=0}}{s} \cdot 100 \quad (1)$$

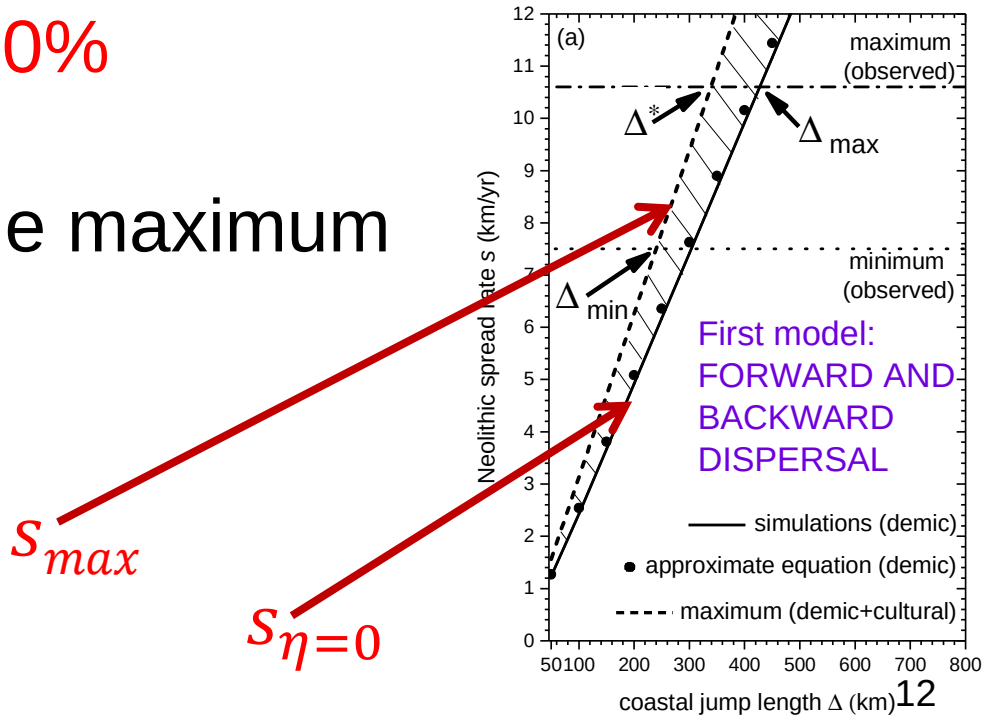
Percentage D of demic diffusion:

$$D = \frac{s_{\eta=0}}{s} \cdot 100$$

Therefore: $C + D = 100\%$

From Eq. (1) we find the maximum cultural effect:

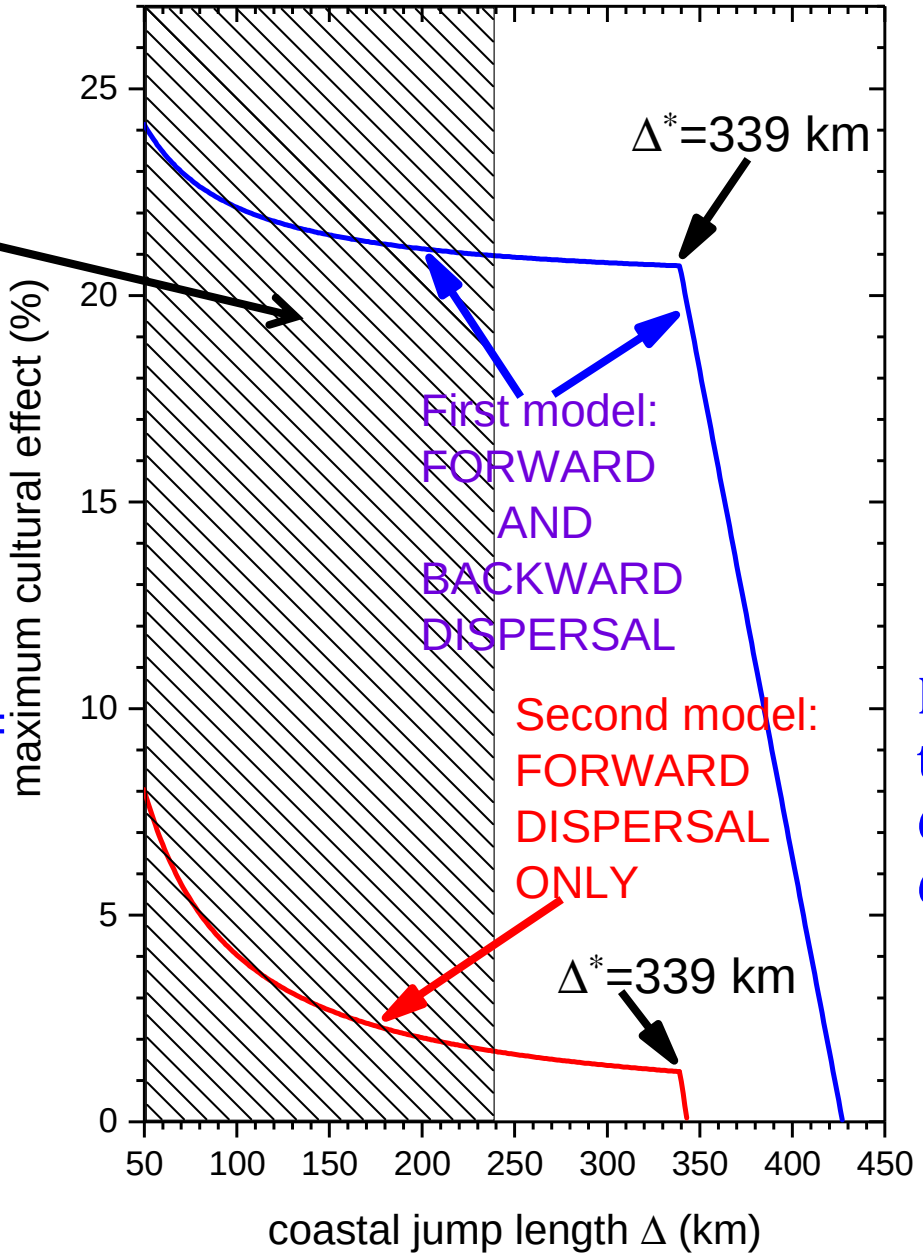
$$C_{max} = \frac{s_{max} - s_{\eta=0}}{s_{max}} \cdot 100$$



[3] Fort, *PNAS* 2012

Results

shaded area: inconsistent with the archaeological data because $\Delta_{min} = 240$ km for both models

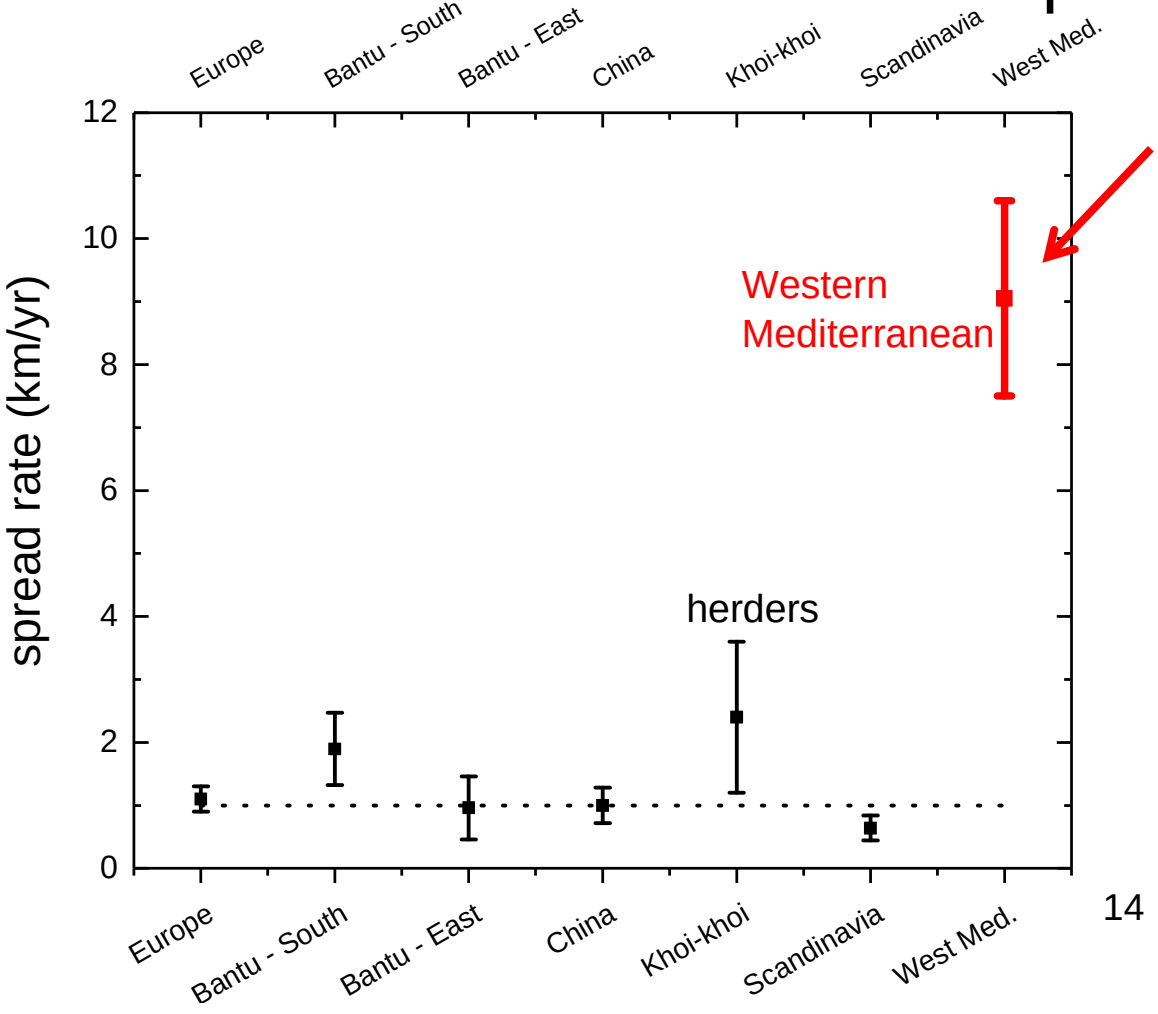


Results from this figure:
C_{max}=0-21% 1st model
C_{max}=0-2% 2nd model

Conclusions

· Neolithic spread rate in the western Mediterranean: **7.5-10.6 km/yr.**

· Much faster that the Neolithic across inland Europe (~1 km/yr) and all other Neolithic rates that have been measured so far (all of them **inland**):



Conclusions

· Dispersal distances Δ along the coast: **240-427 km** per generation.

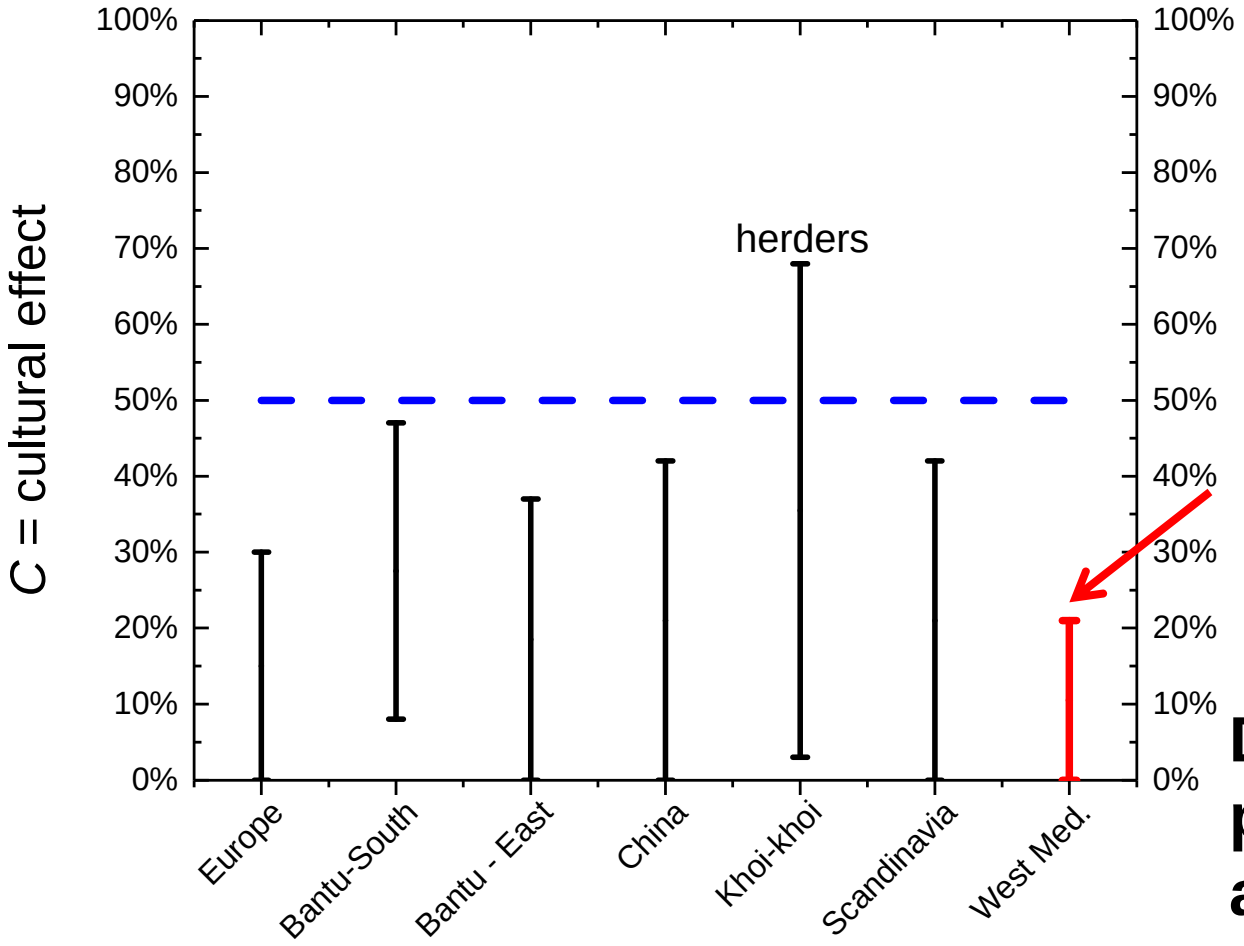
· Much longer than **inland (d~50 km).**

Technical note: The inland value (*d*~50 km) is well-established in 2 ways: 1. by ethnographic data of pre-industrial farmers [4,5].
2. to obtain the observed spread rate (~1 km/yr) using ABM simulations or analytical equations [4,6].

[4] Ammeman & Cavalli-Sforza, *The Neolithic...,* Princeton (1984)
[5] Fort, *Sci. Rep.* (2020), Supp. Info.
[6] Fort, *PNAS* (2012)

Conclusions

- Cultural effect **0-21%**.
- Previously only ***inland*** results for the Neolithic cultural effect. They all yield upper bounds >21%:



Technical note:
Consistent with this range (0%-21%), Genetics suggests a cultural effect of 1%-2% [7].

[7] Fort, *Human Popul. Genet. Genom*. (2022)

Differences with previous results are substantial