The impacts of environmental variability on within-host parasite diversity

CSB1021: Introduction to Python, Final Project

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Introduction

Conceptual Background

In 2019, SARS-CoV-2 spilled into the human population, sparking a global pandemic from which we've yet to emerge. Worryingly, SARS-CoV-2 is not the first zoonotic disease we've encountered, nor is it predicted to be the last (Jones et al. 2008; Brulliard, 2020). At the between-host level, we know that climate and land-use change can facilitate novel species interactions and increase contact rates between wild populations and humans, enabling zoonotic spillover events and disease emergence (Daszak et al. 2000; Daszak et al. 2001; Patz et al. 2004; Plowright et al. 2017; Plowright et al. 2020). Less studied are the mechanisms that promote parasite diversity and allow parasites to circulate within hosts, creating kindling for the spillover events we observe among hosts. Separately, community ecologists have theorized that an intermediate level of disturbance may promote species coexistence by precluding the competitive advantages allowed by low levels of disturbance, and the extinction risks brought on by high levels of disturbance (Connell 1978).

If we think about environmental variability as a sustained, or "press", disturbance, there arise two separate but related ways to consider the effects of environmental variability on parasite diversity within hosts. First, we may consider rising environmental variability as an consequence of climate change. While much attention has been paid to the effects of rising temperatures on disease systems, we've invested far less in exploring the effects of rising temperature variability, despite evidence of its outsized impacts on species outcomes (Dobson and Carpenter 1992; Lafferty 2009; Vasseur et al. 2014). In ectothermic hosts, increasingly erratic external conditions will affect the internal conditions of the host, thereby also affecting any parasites the host may harbour. Second, we may consider environmental variability as a physiological trait. Bats (order Chiroptera) have long been acknowledged as prolific reservoirs for disease and implicated in zoonotic spillover events (Calisher et al. 2006; Brook and Dobson 2015; Irving et al. 2021). Bats are also somewhat unique in their ability to vary their internal temperature according to their activity level (Fumagalli et al. 2021). It has been theorized that these variations in internal temperatures may aid in bats' immune responses, allowing them to carry microparasites without suffering outsized morbidity (Fumagalli et al. 2021; Luo et al. 2021). Extending on that idea, we became interested in how variation in internal temperature may contribute to bats' propensity to support diverse communities of parasites.

Here, we aim to investigate the impacts of environmental variability on the viability and maintenance of parasite diversity within hosts. We began by modifying Antia et al.'s (1994) model of within-host population dynamics to include a secondary parasite (see below). We wrote a demographically stochastic version of the model, an environmentally stochastic version of the model wherein each parasite's growth rate was defined along a thermal performance curve, and a demographically and environmentally stochastic version of the model (Melbourne and Hastings 2008). We simulated each of these models forward in time, beginning simulations with the primary parasite in the system, and introducing the secondary parasite at different points along the timeseries. We simulated several permutations of the environmentally stochastic versions of the model, altering the frequency and magnitude of thermal disturbance within the system. All our simulations were performed in R.

For This Project

Between and among the deterministic and stochastic simulations of the model, we will compare the ability of the secondary parasite to invade a system containing the primary parasite and the host's immune system, and the number of time steps for which the primary and secondary parasites co-occurred.

To accomplish these goals, we will:

1. Import our data from .rds files, to pandas data frames.
    a. Please note that all my data can be found in a Github repo, here.
2. Explore the data.
3. Wrangle the data.
4. Analyse the data.
5. Visualize the data.

Methods

Model Description

Antia et al.'s (1994) Model of Within-Host Population Dynamics:

Antia et al.’s (1994) model of within host population dynamics uses a system of ordinary differential equations to represent the interaction between an infecting parasite and its host’s immune system as analogous to the interaction between a prey item and its predator. The model assumes that the growth rate of the host’s immune system is proportional to parasite density at low parasite densities, and saturates at high parasite densities, allowing the host’s immune system to either extirpate or succumb to the infection (Eqns. 1-2) (Antia et al. 1994).

$$\frac{dP}{dt} = rP - kPI, \text{ if P} < \text{D and P} \rightarrow 0 \text{ if P} > \text{D} \tag{1}$$

$$\frac{dI}{dt} = \rho I \frac{P}{P + \phi} \tag{2}$$

Where:

In [185…

```
%%html
<style>
table {float:left}
</style>
```

Parameters	Values
P, Parasite abundance	NA
I, Host immune cell abundance	NA
r, Intrinsic growth rate of parasite	0.1 - 10.0
k, Rate of destruction of parasite by host immune system	10^{-3}
ρ, Maximum growth rate of the immune system	1
ϕ, Parasite density at which growth rate of host immune system is half its maximum	10^3
D, Lethal within-host parasite density	10^9

In the above model, $\frac{dP}{dt}$ and $\frac{dI}{dt}$ represent the changes in parasite and immune cell abundance over time. In (1), the first term denotes the growth of the parasite population, while the second term denotes its destruction by the host's immune system. In (2), we can see that the host's immune system will grow in response to the growth of the parasite population, until it hits a saturation point. To investigate the impacts of environmental variability on the viability and maintenance of parasite diversity within hosts, we discretized and modified Antia et al.'s (1994) model to include a secondary parasite, which could indirectly compete with the primary parasite through the host's immune response (Eqns. 3-5).

Our Modified Version of Antia et al.'s (1994) Model:

$$P_{i[t+1]} = (1 + r \cdot ts - (1 - e^{-k \cdot I_t \cdot ts}))P_{i[t]} \tag{3}$$
$$P_{j[t+1]} = (1 + r \cdot ts - (1 - e^{-k \cdot I_t \cdot ts}))P_{j[t]} \tag{4}$$
$$I_{[t+1]} = (1 + \rho(\frac{P_i}{P_i + \phi} + \frac{P_j}{P_j + \phi})ts)I_{[t]} \tag{5}$$

Where P_i is our primary parasite, P_j is our secondary parasite, and I is the host's immune system.

In our simulations, we decreased the range of possible values for r_i and r_j from 0.1 - 10.0 to 0.1 - 2.0, and increased the rate at which parasites are destroyed by the host's immune system by a factor of ten (from 10^{-3} to 10^{-2}) to prevent the parasite from killing the host too quickly. Given that we're interested in the mechanisms that affect parasite co-occurrence and diversity, we wanted to prevent transient infections where possible. To write the demographically stochastic version of this model, we wrote the model's growth terms as Poisson processes, and the parasite population's mortality term as a binomial process. To write the environmentally stochastic version of this model, we defined the growth rates of each parasite along thermal performance curves, which were developed in accordance with the Sharpe-Schoolfield model (Schoolfield et al. 1981).

Thermal Performace Curves

We wrote two sets of four thermal performance curves, representing two thermal environments, and four thermal arrangements per environment. One thermal environment had a lower average temperature, while the second had a higher average temperature, representing the thermal conditions within ectotherms and bats, respectively. Our four thermal arrangements represented how each parasite's growth rate (P_i and P_j, r_i and r_j) would respond to the temperature of the system. We wrote our first arrangement such that r_i and r_j would respond identically to the temperature of the system, a second arrangement wherein r_i and r_j would peak on opposite sides of the average temperature of the system, a third arrangement wherein we moved the average temperature of the system to the left to give the first parasite, P_i, a thermal advantage, and a fourth arrangement wherein we shifted the average temperature of the system to the right to give P_j a thermal advantage.

Model Simulations

Within each of the two thermal environments, and each of the four thermal arrangements, we simulated each of our four models (deterministic, demographically stochastic, environmentally stochastic, and demographically and environmentally stochastic). Within the environmentally stochastic, and demographically and environmentally stochastic model simulations, we included two sets of permutations to alter the ways in which we randomly selected the temperature of the system. The first set of permutations varied the magnitude of thermal disturbance within the system and was applied to the low average temperature thermal environment runs to represent rising environmental variation in our climate, while the second set varied the frequency of thermal disturbance within the system and was applied to the high average temperature thermal environment to represent changes in the internal temperatures of bats. We began each simulation with the primary parasite in the system, and for each of our four model simulations, we permuted the time step at which the secondary parasite, P_j, was introduced into the system to determine how environmental variation might affect its ability to invade and co-occur. We ran each permutation of each of our stochastic models one thousand times.

Now, let's get started! 💻

Two Quick Examples...

1. Simulating Time Series Data

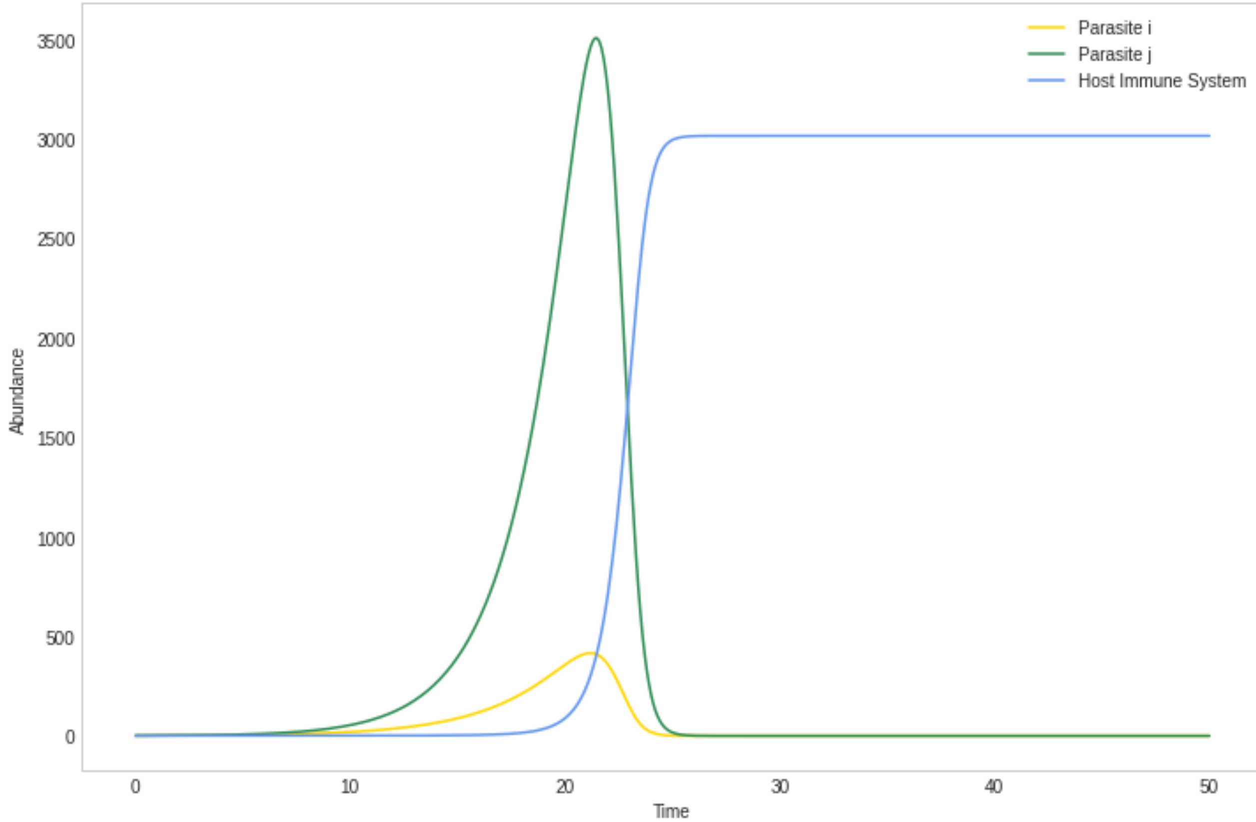
Before we get started in ernest, here's an example of how I would have implemented the deterministic version of my model, as a system of ODEs in Python...

In [186…

```
# Oh hey look! It's that bit of code we always start class with to see mult

# Access options from the iPython core
from IPython.core.interactiveshell import InteractiveShell

# Change the value of ast_node_interactivity
InteractiveShell.ast_node_interactivity = "all"
```

In [187…

```
## An example of how I'd use an ODE solver in Python:

# Requisite packages:
import numpy as np
from scipy.integrate import odeint
import matplotlib.pyplot as plt

# Write the function; system of 3 ODEs
def model(x, t):
    ri = 0.3; rj = 0.4; k = 0.001; p = 1; o = 1000
    dPidt = ri*x[0] - k*x[0]*x[2]
    dPjdt = rj*x[1] - k*x[1]*x[2]
    dIdt = p*x[2]*((x[0]/(x[0]+o)) + (x[1]/(x[1]+o)))
    dxdt = [dPidt, dPjdt, dIdt]
    return dxdt

# Initial conditions/initial population abundances
x0 = [1,1,1]

# Time points for which we want solutions; I want 50 time steps, but soliti
t = np.linspace(0,50,501)

# Solve ODE; uses an lsoda solver, same as package "deSolve" in R
x = odeint(model,x0,t)

# Plot outputs
plt.plot(t, x[:,0], label = 'Parasite i', color = 'gold')
plt.plot(t, x[:,1], label = 'Parasite j', color = 'seagreen')
plt.plot(t, x[:,2], label = 'Host Immune System', color = 'cornflowerblue')
plt.ylabel('Abundance')
plt.xlabel('Time')
plt.legend(loc = 'best')
plt.grid(False)
plt.show()
plt.rcParams['figure.figsize'] = [12, 8]

# We can take a quick look at the output here...
x[:21,:]; # First 20 time steps, t0 to t2 to make sure everything started o
x[150:301,:]; # Time steps 150-300 (t15 to t30) to see the middle bit of th
# I've suppressed the outputs of the above two lines for brevity.
```



2. Getting Co-Occurrence Data from Time Series Data

Now, let's look at a quick example of how I'd get co-occurrence data (a count of how many time steps for which P_i and P_j co-occurred/simultaneously had abundances above 1) out of that time series we just generated...

In [188...

```
x2 = x[:,0:2] # Making a subsetted array including only the parasite popula
x3 = np.where((x2>1).all(axis=1)) # Getting all the rows for which Pi and P
x3[-1][-1] # Is the final time step at which Pi and Pj co-occur, meaning th
```

Out[188]:

```
251
```

Let's add a vertincal line to denote the last time step at which Pi and Pj co-occur.

In [189…

```
plt.plot(t, x[:,0], label = 'Parasite i', color = 'gold')
plt.plot(t, x[:,1], label = 'Parasite j', color = 'seagreen')
plt.plot(t, x[:,2], label = 'Host Immune System', color = 'cornflowerblue')
plt.axvline(x = 25.1, color = 'orchid', label = 'Last time point at which P
plt.ylabel('Abundance')
plt.xlabel('Time')
plt.legend(loc = 'best')
plt.grid(False)
plt.show()
plt.rcParams['figure.figsize'] = [12, 8]
```

Out[189]: [<matplotlib.lines.Line2D at 0x7efe82bdbc40>]

Out[189]: [<matplotlib.lines.Line2D at 0x7efe82bdbe20>]

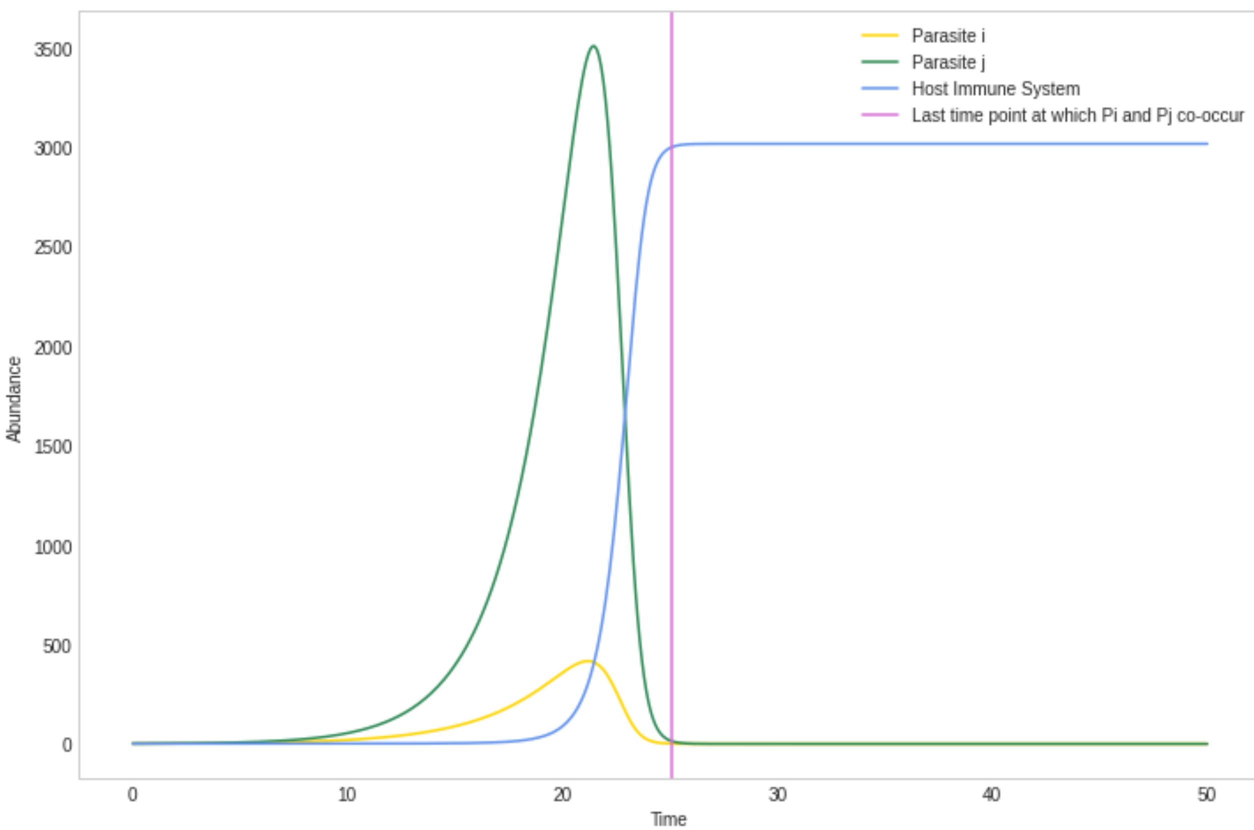
Out[189]: [<matplotlib.lines.Line2D at 0x7efe82bec2b0>]

Out[189]: <matplotlib.lines.Line2D at 0x7efe82bec340>

Out[189]: Text(0, 0.5, 'Abundance')

Out[189]: Text(0.5, 0, 'Time')

Out[189]: <matplotlib.legend.Legend at 0x7efe82dd8970>



Okay, examples are done! Back to our regularly scheduled programming...

Importing and Exploring the Data

After performing all our simulations in R, we saved our outputs first as data frames, then as .rds files. To import our data into Python, we'll using **rpy2**. According to the rpy2 Github repository, rpy2 is an interface to R running embedded in a Python process. rpy2 also includes functionality to deal with pandas DataFrames.

In [190…

```
# Importing pandas so I can work with these data frames, and installing and
import pandas as pd

import sys
!{sys.executable} -m pip install rpy2
import rpy2
import rpy2.robjects as robjects
from rpy2.robjects import pandas2ri
pandas2ri.activate()
rpy2.__version__ # Had to check version because implementation was recently
readRDS = robjects.r['readRDS']
```

```
Requirement already satisfied: rpy2 in /opt/conda/lib/python3.8/site-package
s (3.4.5)
Requirement already satisfied: jinja2 in /opt/conda/lib/python3.8/site-packa
ges (from rpy2) (3.0.3)
Requirement already satisfied: pytz in /opt/conda/lib/python3.8/site-package
s (from rpy2) (2021.3)
Requirement already satisfied: tzlocal in /opt/conda/lib/python3.8/site-pack
ages (from rpy2) (4.1)
Requirement already satisfied: cffi>=1.10.0 in /opt/conda/lib/python3.8/site
-packages (from rpy2) (1.15.0)
Requirement already satisfied: MarkupSafe>=2.0 in /opt/conda/lib/python3.8/s
ite-packages (from jinja2->rpy2) (2.0.1)
Requirement already satisfied: pytz-deprecation-shim in /opt/conda/lib/pytho
n3.8/site-packages (from tzlocal->rpy2) (0.1.0.post0)
Requirement already satisfied: backports.zoneinfo; python_version < "3.9" in
/opt/conda/lib/python3.8/site-packages (from tzlocal->rpy2) (0.2.1)
Requirement already satisfied: pycparser in /opt/conda/lib/python3.8/site-pa
ckages (from cffi>=1.10.0->rpy2) (2.20)
Requirement already satisfied: tzdata; python_version >= "3.6" in /opt/conda
/lib/python3.8/site-packages (from pytz-deprecation-shim->tzlocal->rpy2) (20
21.5)
```

Out[190]:

```
'3.4.5'
```

In [191…

```
# Importing some data as a test
df = readRDS('FinalProj_Data/LowTemp_SD10/Det_Iden_LTLO.rds')
df

df2 = readRDS('FinalProj_Data/LowTemp_SD10/DemPV_I_LTLO.rds')
df2.head(n = 20) # Let's check out the first 20 columns; Does this look rig
df2.info()

df2.iloc[:,0] # Let's take a look at the first column!
```

Out[191]:

```
array([84, 78, 73, 67, 63, 57, 49, 38, 24,  7,  0,  0,  0,  0,  0,  0,  0,
        0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,
        0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0],
      dtype=int32)
```

Out[191]:

	Intro_0	Intro_1	Intro_2	Intro_3	Intro_4	Intro_5	Intro_6	Intro_7	Intro_8	Intro_9	.
1	84	91	64	78	72	55	63	55	34	0	.
2	74	80	75	72	61	66	0	19	0	30	.
3	77	65	81	71	67	56	51	28	49	0	.
4	87	79	66	61	59	65	51	23	21	6	.
5	81	74	72	65	63	65	50	0	30	0	.
6	81	73	76	72	68	57	57	0	18	10	.
7	83	88	72	60	66	56	0	57	14	15	.
8	70	87	80	112	77	61	46	29	10	0	.
9	89	82	75	69	51	47	44	31	21	29	.
10	78	97	60	75	54	54	37	11	0	11	.
11	80	73	72	67	70	49	47	31	51	44	.
12	77	80	73	67	65	61	51	0	31	5	.
13	78	111	65	65	63	61	39	51	27	0	.
14	78	77	79	64	60	55	49	43	20	11	.
15	87	79	98	74	57	56	39	68	18	27	.
16	100	70	77	67	61	60	46	29	17	2	.
17	91	75	76	79	61	62	35	0	2	0	.
18	83	95	78	72	70	44	61	40	28	0	.
19	81	79	67	62	60	50	38	29	24	31	.
20	73	90	74	63	63	48	47	42	39	0	.

20 rows × 50 columns

```
<class 'pandas.core.frame.DataFrame'>
Index: 1000 entries, 1 to 1000
Data columns (total 50 columns):
 #   Column    Non-Null Count  Dtype
---  ------    --------------  -----
 0   Intro_0   1000 non-null   int32
 1   Intro_1   1000 non-null   int32
 2   Intro_2   1000 non-null   int32
 3   Intro_3   1000 non-null   int32
 4   Intro_4   1000 non-null   int32
 5   Intro_5   1000 non-null   int32
 6   Intro_6   1000 non-null   int32
 7   Intro_7   1000 non-null   int32
 8   Intro_8   1000 non-null   int32
 9   Intro_9   1000 non-null   int32
```

```
 10  Intro_10  1000 non-null   int32
 11  Intro_11  1000 non-null   int32
 12  Intro_12  1000 non-null   int32
 13  Intro_13  1000 non-null   int32
 14  Intro_14  1000 non-null   int32
 15  Intro_15  1000 non-null   int32
 16  Intro_16  1000 non-null   int32
 17  Intro_17  1000 non-null   int32
 18  Intro_18  1000 non-null   int32
 19  Intro_19  1000 non-null   int32
 20  Intro_20  1000 non-null   int32
 21  Intro_21  1000 non-null   int32
 22  Intro_22  1000 non-null   int32
 23  Intro_23  1000 non-null   int32
 24  Intro_24  1000 non-null   int32
 25  Intro_25  1000 non-null   int32
 26  Intro_26  1000 non-null   int32
 27  Intro_27  1000 non-null   int32
 28  Intro_28  1000 non-null   int32
 29  Intro_29  1000 non-null   int32
 30  Intro_30  1000 non-null   int32
 31  Intro_31  1000 non-null   int32
 32  Intro_32  1000 non-null   int32
 33  Intro_33  1000 non-null   int32
 34  Intro_34  1000 non-null   int32
 35  Intro_35  1000 non-null   int32
 36  Intro_36  1000 non-null   int32
 37  Intro_37  1000 non-null   int32
 38  Intro_38  1000 non-null   int32
 39  Intro_39  1000 non-null   int32
 40  Intro_40  1000 non-null   int32
 41  Intro_41  1000 non-null   int32
 42  Intro_42  1000 non-null   int32
 43  Intro_43  1000 non-null   int32
 44  Intro_44  1000 non-null   int32
 45  Intro_45  1000 non-null   int32
 46  Intro_46  1000 non-null   int32
 47  Intro_47  1000 non-null   int32
 48  Intro_48  1000 non-null   int32
 49  Intro_49  1000 non-null   int32
dtypes: int32(50)
memory usage: 203.1+ KB
```

Out[191]:
```
1       84
2       74
3       77
4       87
5       81
        ..
996     67
997     80
998     81
999     81
1000    85
Name: Intro_0, Length: 1000, dtype: int32
```

These data show co-occurrence times between our infecting parasites, P_i and P_j. The columns denote the day on which the secondary parasite, P_j, was introduced to the system, while the rows denote the simulation number, out of 1000, within which the period of co-occurrence took place. For example, the value in the first column of the first row says that in our first simulation out of 1000 for which P_i and P_j were introduced at the same time (Intro_0), P_i and P_j co-occurred for 84 time steps, or 8.4 days. Our first test case, df, shows periods of co-occurrence in our deterministic model, while df2 shows periods of co-occurence over 1000 stochastic simulations of our demographically stochastic model. In df2, we may observe the average period of co-occurrence per introduction point by averaging each column. We may also see that when P_j is introduced later, periods of co-occurrence tend to be shorter. Let's evaluate those claims with our test case, df2, before importing the rest of our data.

In [192…
```
ColumnMeans = df2.mean(); ColumnMedians = df2.median()
ColumnMeans[0:11]; ColumnMedians[0:11]
```

Out[192]:
```
Intro_0     80.857
Intro_1     78.734
Intro_2     73.861
Intro_3     68.014
Intro_4     62.594
Intro_5     55.872
Intro_6     45.752
Intro_7     34.197
Intro_8     22.100
Intro_9     11.900
Intro_10     5.191
dtype: float64
```

Out[192]:
```
Intro_0      81.0
Intro_1      79.0
Intro_2      74.0
Intro_3      68.0
Intro_4      63.0
Intro_5      57.0
Intro_6      50.0
Intro_7      38.0
Intro_8      23.0
Intro_9       6.0
Intro_10      0.0
dtype: float64
```

Let's make a quick plot to compare the periods of co-occurrence generated by our deterministic model to the average and median periods of co-occurrence generated by our demographically stochastic model!

In [193…
```
%matplotlib inline
import matplotlib.pyplot as plt
plt.style.use('seaborn-whitegrid')
import numpy as np

# I'm only plotting the first 15 values because after the 12th introduction
Det = np.array(df[0:16]); DemMeans = np.array(ColumnMeans[0:16]); DemMedian

plt.plot(Det, linewidth = 2, color = 'gold')
plt.plot(DemMeans, linewidth = 2, linestyle = 'dashed', color = 'royalblue'
plt.plot(DemMedians, linewidth = 2, linestyle = 'dotted', color = 'deeppink
plt.xlabel('Day on Which Pj Introduced')
plt.ylabel('Time Points for Which Pi and Pj Co-Occurred')
plt.grid(False)
plt.legend(['Deterministic Period of Co-Occurrence (PoC)','Mean Demographic
plt.rcParams['figure.figsize'] = [12, 8]
```

Out[193]:
```
[<matplotlib.lines.Line2D at 0x7efe8b974cd0>]
```

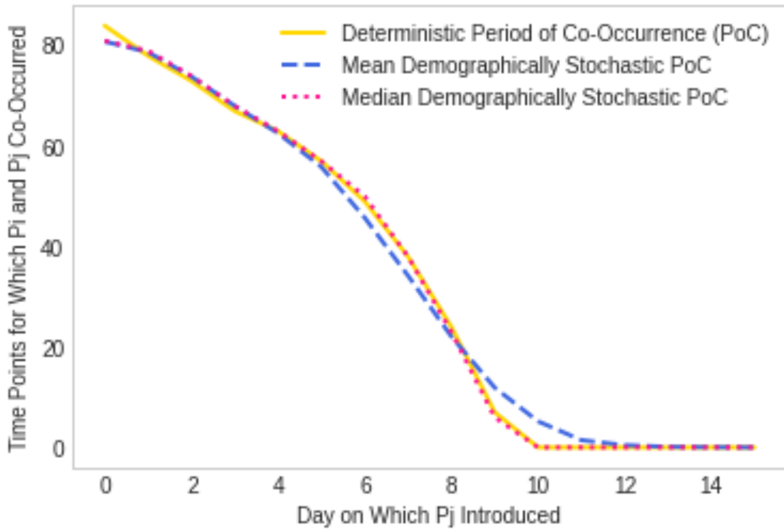
Out[193]:
```
[<matplotlib.lines.Line2D at 0x7efe8b966a90>]
```

Out[193]:
```
[<matplotlib.lines.Line2D at 0x7efe8b974ee0>]
```

Out[193]:
```
Text(0.5, 0, 'Day on Which Pj Introduced')
```

Out[193]:
```
Text(0, 0.5, 'Time Points for Which Pi and Pj Co-Occurred')
```

Out[193]:
```
<matplotlib.legend.Legend at 0x7efeec5499d0>
```



As we can see on our plot, demographic stochasticity seems to have an insignificant impact on parasite co-occurrence within hosts. Now, let's import the rest of our data, and take a look at the impact of environmental variability!

In [194…

```
# Let's get our paths in order...
import os
os.chdir('/home/jovyan/2022-01-IntroPython')
os.getcwd()
```

Out[194]:

```
'/home/jovyan/2022-01-IntroPython'
```

We want to know what our working directory is so we can write our pathnames correctly.

Additionally, if we divorce our pathnames from our device, we can make our work easier to write out, and much easier to reproduce.

In the cell below, I change working directories to import data so I don't have to write out a full pathname like 20 times. There are better ways to do this, and generally, it's not a good idea to mess around with your working directory, but this was the easiest way to accomplish the task after messing around with pyprojroot to no avail. **pyprojroot** is supposed to work similarly to R's **here** package, which enables easy file referencing in project-oriented workflows to remove problematic path dependencies.

In [195…

```
# Okay, now that we (sort of) know what we're doing with rpy2, let's import
# If I'd planned better, I could have named these in a way conducive to imp

os.chdir('/home/jovyan/2022-01-IntroPython/FinalProj_Data/LowTemp_SD10') # 
## Low av. temp
L_I_Det = readRDS('Det_Iden_LTLO.rds')
L_S_Det = readRDS('Det_Semi_LTLO.rds')
L_Pi_Det = readRDS('Det_PiAd_LTLO.rds')
```

```
L_Pj_Det = readRDS('Det_PjAd_LTLO.rds')

L_I_Dem = readRDS('DemPV_I_LTLO.rds')
L_S_Dem = readRDS('DemPV_SI_LTLO.rds')
L_Pi_Dem = readRDS('DemPV_Pi_LTLO.rds')
L_Pj_Dem = readRDS('DemPV_Pj_LTLO.rds')
#### Small magnitude, SD = 10
L10_I_Env = readRDS('EnvPV_Ie10_LTLO.rds')
L10_S_Env = readRDS('EnvPV_SIe10_LTLO.rds')
L10_Pi_Env = readRDS('EnvPV_Pie10_LTLO.rds')
L10_Pj_Env = readRDS('EnvPV_Pje10_LTLO.rds')

L10_I_DemEnv = readRDS('EnvDemPV_Ie10_LTLO.rds')
L10_S_DemEnv = readRDS('EnvDemPV_SIe10_LTLO.rds')
L10_Pi_DemEnv = readRDS('EnvDemPV_Pie10_LTLO.rds')
L10_Pj_DemEnv = readRDS('EnvDemPV_Pje10_LTLO.rds')

os.chdir('/home/jovyan/2022-01-IntroPython/FinalProj_Data/LowTemp_SD20')
#### Large magnitude, SD = 20
L20_I_Env = readRDS('EnvPV_Ie10_LTHO.rds')
L20_S_Env = readRDS('EnvPV_SIe10_LTHO.rds')
L20_Pi_Env = readRDS('EnvPV_Pie10_LTHO.rds')
L20_Pj_Env = readRDS('EnvPV_Pje10_LTHO.rds')

L20_I_DemEnv = readRDS('EnvDemPV_Ie10_LTHO.rds')
L20_S_DemEnv = readRDS('EnvDemPV_SIe10_LTHO.rds')
L20_Pi_DemEnv = readRDS('EnvDemPV_Pie10_LTHO.rds')
L20_Pj_DemEnv = readRDS('EnvDemPV_Pje10_LTHO.rds')

os.chdir('/home/jovyan/2022-01-IntroPython/FinalProj_Data/HighTemp_Each2')
## High av. temp
H_I_Det = readRDS('Det_Iden_HTLO.rds')
H_S_Det = readRDS('Det_Semi_HTLO.rds')
H_Pi_Det = readRDS('Det_PiAd_HTLO.rds')
H_Pj_Det = readRDS('Det_PjAd_HTLO.rds')

H_I_Dem = readRDS('DemPV_I_HTLO.rds')
H_S_Dem = readRDS('DemPV_SI_HTLO.rds')
H_Pi_Dem = readRDS('DemPV_Pi_HTLO.rds')
H_Pj_Dem = readRDS('DemPV_Pj_HTLO.rds')

#### Each = 2
H2_I_Env = readRDS('EnvPV_Ie2_HTLO.rds')
H2_S_Env = readRDS('EnvPV_SIe2_HTLO.rds')
H2_Pi_Env = readRDS('EnvPV_Pie2_HTLO.rds')
H2_Pj_Env = readRDS('EnvPV_Pje2_HTLO.rds')

H2_I_DemEnv = readRDS('EnvDemPV_Ie2_HTLO.rds')
H2_S_DemEnv = readRDS('EnvDemPV_SIe2_HTLO.rds')
H2_Pi_DemEnv = readRDS('EnvDemPV_Pie2_HTLO.rds')
H2_Pj_DemEnv = readRDS('EnvDemPV_Pje2_HTLO.rds')

os.chdir('/home/jovyan/2022-01-IntroPython/FinalProj_Data/HighTemp_Each10')
```

```
#### Each = 10
H10_I_Env = readRDS('EnvPV_Ie10_HTLO.rds')
H10_S_Env = readRDS('EnvPV_SIe10_HTLO.rds')
H10_Pi_Env = readRDS('EnvPV_Pie10_HTLO.rds')
H10_Pj_Env = readRDS('EnvPV_Pje10_HTLO.rds')

H10_I_DemEnv = readRDS('EnvDemPV_Ie10_HTLO.rds')
H10_S_DemEnv = readRDS('EnvDemPV_SIe10_HTLO.rds')
H10_Pi_DemEnv = readRDS('EnvDemPV_Pie10_HTLO.rds')
H10_Pj_DemEnv = readRDS('EnvDemPV_Pje10_HTLO.rds')

os.chdir('/home/jovyan/2022-01-IntroPython/FinalProj_Data/HighTemp_Each20')
#### Each = 20
H20_I_Env = readRDS('EnvPV_Ie20_HTLO.rds')
H20_S_Env = readRDS('EnvPV_SIe20_HTLO.rds')
H20_Pi_Env = readRDS('EnvPV_Pie20_HTLO.rds')
H20_Pj_Env = readRDS('EnvPV_Pje20_HTLO.rds')

H20_I_DemEnv = readRDS('EnvDemPV_Ie20_HTLO.rds')
H20_S_DemEnv = readRDS('EnvDemPV_SIe20_HTLO.rds')
H20_Pi_DemEnv = readRDS('EnvDemPV_Pie20_HTLO.rds')
H20_Pj_DemEnv = readRDS('EnvDemPV_Pje20_HTLO.rds')

## Changing our working directory back...
os.chdir('/home/jovyan/2022-01-IntroPython')
```

Wrangling the Data

Note that I've turned off the echo for the following two code chunks because they have long outputs!

In [196…

```
# Now, let's organise our data so we ca analyse it!
# First, let's make a dictionary of our deterministic periods of co-occurre
# We can put them in a dictionary so we can make associations between the t
CCD = {'Low_Iden': L_I_Det, 'Low_Semi': L_S_Det, 'Low_PiAd': L_Pi_Det, 'Low
# Making the data frame, using our dictionary as the data
ClimateChange_Det = pd.DataFrame(data = CCD)
# Transposing our data frame such that we can read our data in columns. Aft
# ClimateChange_Det.transpose()
# Next, let's make lists out of our stochastic data sets, which are current
ClimateChange_List = [L_I_Dem, L_S_Dem, L_Pi_Dem, L_Pj_Dem,
                     L10_I_Env, L10_S_Env, L10_Pi_Env, L10_Pj_Env,
                     L10_I_DemEnv, L10_S_DemEnv, L10_Pi_DemEnv, L10_Pj_DemE
                     L20_I_Env, L20_S_Env, L20_Pi_Env, L20_Pj_Env,
                     L20_I_DemEnv, L20_S_DemEnv, L20_Pi_DemEnv, L20_Pj_DemE

# Now let's do the same thing for our second, warmer thermal arrangement, m
BD = {'High_Iden': H_I_Det, 'High_Semi': H_S_Det, 'High_PiAd': H_Pi_Det, 'H
Bats_Det = pd.DataFrame(data = BD)
# Bats_Det.transpose()
Bats_List = [H_I_Dem, H_S_Dem, H_Pi_Dem, H_Pj_Dem,
            H2_I_Env, H2_S_Env, H2_Pi_Env, H2_Pj_Env,
            H2_I_DemEnv, H2_S_DemEnv, H2_Pi_DemEnv, H2_Pj_DemEnv,
            H10_I_Env, H10_S_Env, H10_Pi_Env, H10_Pj_Env,
            H10_I_DemEnv, H10_S_DemEnv, H10_Pi_DemEnv, H10_Pj_DemEnv,
            H20_I_Env, H20_S_Env, H20_Pi_Env, H20_Pj_Env,
            H20_I_DemEnv, H20_S_DemEnv, H20_Pi_DemEnv, H20_Pj_DemEnv]
```

In [197…

```
# Now, these are the four objects we care about; let's take a look!
# We can preview our list by "unpacking" it using an "*", and separate its
ClimateChange_Det;
# print(*ClimateChange_List, sep='\n') # I'm commenting these lines out b/c
Bats_Det;
# print(*Bats_List, sep='\n')

# Looks good!
```

Analysing the Data

Now, let's write a couple loops, so we can interate through each of our lists of stochastic data, and average periods of co-occurrence over each group of 1000 stochastic simulations!

As a reminder, each list, ClimateChange_List and Bats_List, contain outputs of stochastic model simulations. Each item in each list contains one set of simulations, contained in a pandas data frame and comprised of 50 columns and 1000 rows. Each column is a day on which the second parasite is introduced to the system, and each row is a stochastic simulation. So, the first column contains the periods of co-occurrence resulting from 1000 stochastic simulations, within which the second parasite was introduced at the same time as the first parasite (t = 0, "Intro_0").

What we want to do, is average each column, to get an average period of co-occurrence per introduction day.

In the for loops below, we iterate over the length of each list, taking the means of each column, in each data frame, in each list item. We store the resulting mean periods of co-occurrence in initially empty pandas data frames.

In [198…

```
ClimateChange_Means = pd.DataFrame() # Empty data frame to populate with me
for i in range(len(ClimateChange_List)):
    ClimateChange_Means[i] = ClimateChange_List[i].mean()

ClimateChange_Means;

Bats_Means = pd.DataFrame()
for i in range(len(Bats_List)):
    Bats_Means[i] = Bats_List[i].mean()

Bats_Means;
```

In [199…

```
# Re-naming our columns so we know what we're looking at! Now we can see ou

ClimateChange_Means.set_axis(['L_I_Dem', 'L_S_Dem', 'L_Pi_Dem', 'L_Pj_Dem',
'L10_I_Env', 'L10_S_Env', 'L10_Pi_Env', 'L10_Pj_Env',
'L10_I_DemEnv', 'L10_S_DemEnv', 'L10_Pi_DemEnv', 'L10_Pj_DemEnv',
'L20_I_Env', 'L20_S_Env', 'L20_Pi_Env', 'L20_Pj_Env',
'L20_I_DemEnv', 'L20_S_DemEnv', 'L20_Pi_DemEnv', 'L20_Pj_DemEnv'], axis = 1

Bats_Means.set_axis(['H_I_Dem', 'H_S_Dem', 'H_Pi_Dem', 'H_Pj_Dem',
'H2_I_Env', 'H2_S_Env', 'H2_Pi_Env', 'H2_Pj_Env',
'H2_I_DemEnv', 'H2_S_DemEnv', 'H2_Pi_DemEnv', 'H2_Pj_DemEnv',
'H10_I_Env', 'H10_S_Env', 'H10_Pi_Env', 'H10_Pj_Env',
'H10_I_DemEnv', 'H10_S_DemEnv', 'H10_Pi_DemEnv', 'H10_Pj_DemEnv',
'H20_I_Env', 'H20_S_Env', 'H20_Pi_Env', 'H20_Pj_Env',
'H20_I_DemEnv', 'H20_S_DemEnv', 'H20_Pi_DemEnv', 'H20_Pj_DemEnv'], axis = 1
```

Out[199]:

	L_I_Dem	L_S_Dem	L_Pi_Dem	L_Pj_Dem	L10_I_Env	L10_S_Env	L10_Pi_Env	L1
Intro_0	80.857	85.889	84.346	87.742	108.152	108.033	106.814	
Intro_1	78.734	83.598	81.484	87.467	105.661	106.682	104.210	
Intro_2	73.861	78.314	76.700	83.316	100.214	102.205	98.856	
Intro_3	68.014	72.960	69.783	78.363	93.879	96.888	93.703	
Intro_4	62.594	67.132	63.703	74.157	86.594	91.003	86.753	
Intro_5	55.872	61.540	53.038	68.908	77.656	83.488	78.949	
Intro_6	45.752	52.770	40.313	62.984	68.207	75.398	71.097	
Intro_7	34.197	41.096	28.803	55.406	57.040	66.175	59.171	
Intro_8	22.100	30.449	16.876	44.781	43.881	56.167	47.807	
Intro_9	11.900	17.856	8.290	33.774	30.228	42.801	34.696	
Intro_10	5.191	9.928	3.657	23.720	18.350	29.854	21.531	
Intro_11	1.446	4.037	1.049	12.738	8.682	18.478	10.294	
Intro_12	0.436	1.757	0.404	7.390	2.997	9.522	5.347	
Intro_13	0.111	0.748	0.064	3.165	1.285	4.273	1.590	
Intro_14	0.036	0.121	0.008	1.351	0.354	1.920	0.661	
Intro_15	0.002	0.060	0.002	0.805	0.126	1.069	0.155	
Intro_16	0.000	0.001	0.000	0.116	0.033	0.294	0.064	
Intro_17	0.000	0.005	0.000	0.103	0.000	0.044	0.003	
Intro_18	0.000	0.000	0.000	0.033	0.002	0.162	0.018	
Intro_19	0.000	0.006	0.000	0.017	0.000	0.000	0.001	

Intro_20	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_21	0.000	0.000	0.000	0.000	0.000	0.032	0.000
Intro_22	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_23	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_24	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_25	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_26	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_27	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_28	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_29	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_30	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_31	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_32	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_33	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_34	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_35	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_36	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_37	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_38	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_39	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_40	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_41	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_42	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_43	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_44	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_45	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_46	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_47	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_48	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_49	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Out[199]:

	H_I_Dem	H_S_Dem	H_Pi_Dem	H_Pj_Dem	H2_I_Env	H2_S_Env	H2_Pi_Env	H

Intro_0	81.062	85.436	84.069	87.177	114.783	115.145	115.310
Intro_1	78.120	82.206	81.225	85.027	110.411	111.617	111.516
Intro_2	73.394	77.265	75.998	81.707	104.758	106.608	106.530
Intro_3	68.288	72.267	70.119	76.624	98.961	101.729	101.273
Intro_4	62.081	67.010	63.113	72.829	92.952	96.148	95.287
Intro_5	55.200	59.744	54.224	67.768	85.190	89.998	88.762
Intro_6	45.634	51.663	42.256	60.701	76.317	82.629	80.918
Intro_7	33.536	38.836	28.476	52.359	66.253	73.503	71.392
Intro_8	21.682	27.582	18.330	41.691	54.683	63.371	60.702
Intro_9	11.470	16.618	8.733	29.972	42.260	51.453	48.525
Intro_10	4.605	8.035	3.975	20.130	27.851	38.577	35.364
Intro_11	1.490	3.482	1.357	10.997	13.613	23.911	20.932
Intro_12	0.318	1.284	0.371	5.543	3.715	10.260	8.067
Intro_13	0.096	0.353	0.054	2.143	0.435	2.952	2.125
Intro_14	0.016	0.112	0.018	0.865	0.014	0.423	0.231
Intro_15	0.002	0.030	0.001	0.292	0.000	0.047	0.007
Intro_16	0.000	0.003	0.000	0.136	0.000	0.000	0.000
Intro_17	0.000	0.001	0.000	0.045	0.000	0.000	0.000
Intro_18	0.000	0.000	0.000	0.024	0.000	0.000	0.000
Intro_19	0.000	0.000	0.000	0.004	0.000	0.000	0.000
Intro_20	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_21	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_22	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_23	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_24	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_25	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_26	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_27	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_28	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_29	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_30	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Intro_31	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_32	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_33	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_34	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_35	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_36	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_37	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_38	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_39	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_40	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_41	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_42	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_43	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_44	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_45	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_46	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_47	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_48	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Intro_49	0.000	0.000	0.000	0.000	0.000	0.000	0.000

50 rows × 28 columns

In [200…

```
# Making some sub-setted data frames to organise our outputs/make them easi
# First, we're going to organise by permutation within each thermal environ
# This will allow us to compare across thermal arrangements.

CC_SD10 = ClimateChange_Means.iloc[:,0:12];
CC_SD10.set_axis(['L_I_Dem', 'L_S_Dem', 'L_Pi_Dem', 'L_Pj_Dem',
'L10_I_Env', 'L10_S_Env', 'L10_Pi_Env', 'L10_Pj_Env',
'L10_I_DemEnv', 'L10_S_DemEnv', 'L10_Pi_DemEnv', 'L10_Pj_DemEnv'], axis = 1

cols = np.array([0,1,2,3,12,13,14,15,16,17,18,19]);
CC_SD20 = ClimateChange_Means.iloc[:,cols];
CC_SD20.set_axis(['L_I_Dem', 'L_S_Dem', 'L_Pi_Dem', 'L_Pj_Dem',
'L20_I_Env', 'L20_S_Env', 'L20_Pi_Env', 'L20_Pj_Env',
'L20_I_DemEnv', 'L20_S_DemEnv', 'L20_Pi_DemEnv', 'L20_Pj_DemEnv'], axis = 1

B_2 = Bats_Means.iloc[:,0:12];
B_2.set_axis(['H_I_Dem', 'H_S_Dem', 'H_Pi_Dem', 'H_Pj_Dem',
'H2_I_Env', 'H2_S_Env', 'H2_Pi_Env', 'H2_Pj_Env',
'H2_I_DemEnv', 'H2_S_DemEnv', 'H2_Pi_DemEnv', 'H2_Pj_DemEnv'], axis = 1, in

cols = np.array([0,1,2,3,12,13,14,15,16,17,18,19]);
B_10 = Bats_Means.iloc[:,cols];
B_10.set_axis(['H_I_Dem', 'H_S_Dem', 'H_Pi_Dem', 'H_Pj_Dem','H10_I_Env', 'H
'H10_I_DemEnv', 'H10_S_DemEnv', 'H10_Pi_DemEnv', 'H10_Pj_DemEnv'], axis = 1

cols = np.array([0,1,2,3,20,21,22,23,24,25,26,27]);
B_20 = Bats_Means.iloc[:,cols];
B_20.set_axis(['H_I_Dem', 'H_S_Dem', 'H_Pi_Dem', 'H_Pj_Dem','H20_I_Env', 'H
'H20_I_DemEnv', 'H20_S_DemEnv', 'H20_Pi_DemEnv', 'H20_Pj_DemEnv'], axis = 1
```

In [201…

```
# Second, we'll organise by thermal arrangement within each thermal environ
# Will allow us to compare across different magnitudes and frequencies of d

cols = np.array([0,4,8,12,16]);
CC_I = ClimateChange_Means.iloc[:,cols];
CC_I.set_axis(['L_I_Dem', 'L10_I_Env', 'L10_I_DemEnv', 'L20_I_Env', 'L20_I_

cols = np.array([1,5,9,13,17]);
CC_S = ClimateChange_Means.iloc[:,cols];
CC_S.set_axis(['L_S_Dem', 'L10_S_Env', 'L10_S_DemEnv', 'L20_S_Env', 'L20_S_

cols = np.array([2,6,10,14,18]);
CC_Pi = ClimateChange_Means.iloc[:,cols];
CC_Pi.set_axis(['L_Pi_Dem', 'L10_Pi_Env', 'L10_Pi_DemEnv', 'L20_Pi_Env', 'L

cols = np.array([3,7,11,15,19]);
CC_Pj = ClimateChange_Means.iloc[:,cols];
CC_Pj.set_axis(['L_Pj_Dem', 'L10_Pj_Env', 'L10_Pj_DemEnv', 'L20_Pj_Env', 'L


cols = np.array([0,4,8,12,16,20,24]);
B_I = Bats_Means.iloc[:,cols];
B_I.set_axis(['H_I_Dem', 'H2_I_Env', 'H2_I_DemEnv', 'H10_I_Env', 'H10_I_Dem

cols = np.array([1,5,9,13,17,21,25]);
B_S = Bats_Means.iloc[:,cols];
B_S.set_axis(['H_S_Dem', 'H2_S_Env', 'H2_S_DemEnv', 'H10_S_Env', 'H10_S_Dem

cols = np.array([2,6,10,14,18,22,26]);
B_Pi = Bats_Means.iloc[:,cols];
B_Pi.set_axis(['H_Pi_Dem', 'H2_Pi_Env', 'H2_Pi_DemEnv', 'H10_Pi_Env', 'H10_

cols = np.array([3,7,11,15,19,23,27]);
B_Pj = Bats_Means.iloc[:,cols];
B_Pj.set_axis(['H_Pj_Dem', 'H2_Pj_Env', 'H2_Pj_DemEnv', 'H10_Pj_Env', 'H10_
```

Results

Visualising the Data

Now, it's time to visualise! We'll be comparing of deterministic periods of co-occurrennce to each of our stochastic simulations, in each thermal environment (low and high average temperatures), across (1) thermal arranngements, and (2) permutations (magnitude and frequencie of thermal disturbance).

Deterministic Periods of Co-Occurrence

In [202…

```
# Requisite dfs:
    # ClimateChange_Det
    # Bats_Det

plt.plot(ClimateChange_Det.iloc[:,0], linewidth = 2, color = 'firebrick')
plt.plot(ClimateChange_Det.iloc[:,1], linewidth = 2, color = 'gold')
plt.plot(ClimateChange_Det.iloc[:,2], linewidth = 2, color = 'seagreen')
plt.plot(ClimateChange_Det.iloc[:,3], linewidth = 2, color = 'cornflowerblu
plt.xlabel('Day on Which Pj Introduced')
plt.ylabel('Time Points for Which Pi and Pj Co-Occurred')
plt.grid(False)
plt.legend(['Identical TPCs','Semi-Identical TPCs', 'Pi-Advantage TPCs', 'P
plt.rcParams['figure.figsize'] = [12, 8]

# This tells us what we want to know, but everything after the 15th introdu
```

Out[202]: [<matplotlib.lines.Line2D at 0x7efe8a755f70>]

Out[202]: [<matplotlib.lines.Line2D at 0x7efe8a755b20>]

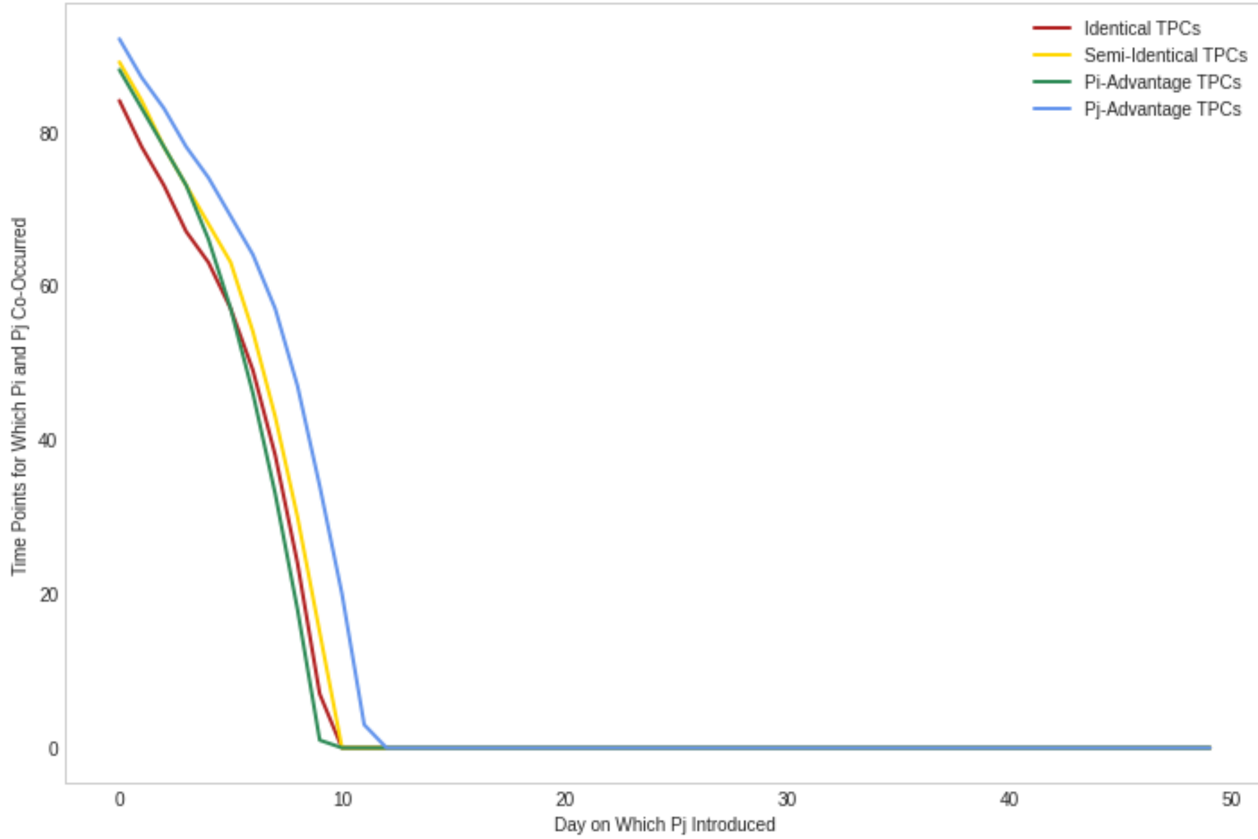
Out[202]: [<matplotlib.lines.Line2D at 0x7efe8a7559d0>]

Out[202]: [<matplotlib.lines.Line2D at 0x7efe8a8d56d0>]

Out[202]: Text(0.5, 0, 'Day on Which Pj Introduced')

Out[202]: Text(0, 0.5, 'Time Points for Which Pi and Pj Co-Occurred')

Out[202]: <matplotlib.legend.Legend at 0x7efe82e26ee0>



In [203…

```
plt.plot(ClimateChange_Det.iloc[:16,0], linewidth = 2, color = 'firebrick')
plt.plot(ClimateChange_Det.iloc[:16,1], linewidth = 2, color = 'gold')
plt.plot(ClimateChange_Det.iloc[:16,2], linewidth = 2, color = 'seagreen')
plt.plot(ClimateChange_Det.iloc[:16,3], linewidth = 2, color = 'cornflowerb
plt.xlabel('Day on Which Pj Introduced')
plt.ylabel('Time Points for Which Pi and Pj Co-Occurred')
plt.grid(False)
plt.legend(['Identical TPCs','Semi-Identical TPCs', 'Pi-Advantage TPCs', 'P
plt.rcParams['figure.figsize'] = [12, 8]
```

Out[203]: `[<matplotlib.lines.Line2D at 0x7efedcb08fd0>]`

Out[203]: `[<matplotlib.lines.Line2D at 0x7efedcb18040>]`

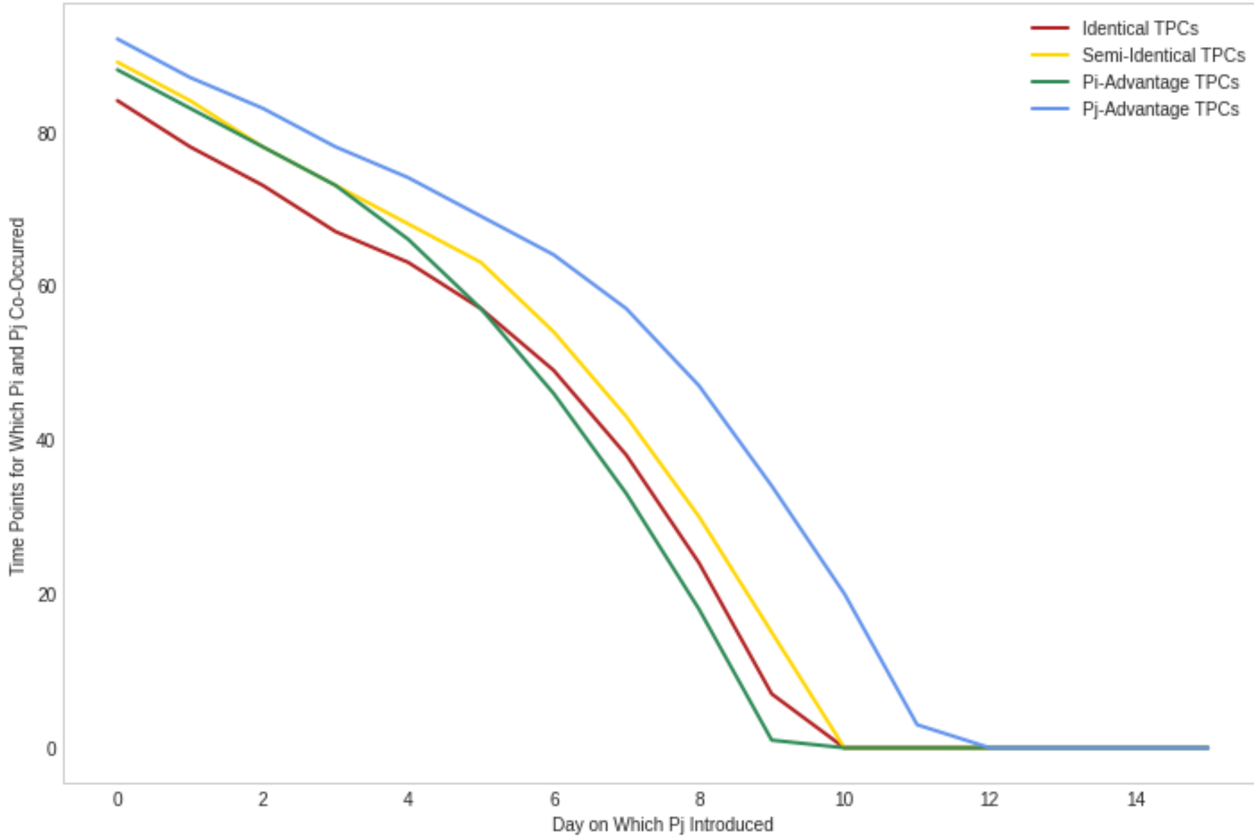
Out[203]: `[<matplotlib.lines.Line2D at 0x7efedcb18460>]`

Out[203]: `[<matplotlib.lines.Line2D at 0x7efedcb18760>]`

Out[203]: `Text(0.5, 0, 'Day on Which Pj Introduced')`

Out[203]: `Text(0, 0.5, 'Time Points for Which Pi and Pj Co-Occurred')`

Out[203]: `<matplotlib.legend.Legend at 0x7efeec471af0>`



Interpretation:

Great! This shows us that in the absence of stochasticity, P_i and P_j can co-occur for a maximum of 92 time steps, or, 9.2 days. This will act as our baseline, against which we'll compare our stochastic simulations. We can also see that our thermal arrangement wherein the secondary parasite, P_j, has the thermal advantage over the primary parasite, P_i, seems to produce the longest periods of co-occurrence, while our thermal arrangements wherein P_i and P_j respond identically to the temperature of the system, and wherein P_i has a thermal advantge over P_j seem to produce the shortest periods of co-occurrence. These outcomes make sense given that P_i has the inherent advantage of being introduced to the system first, which allows its population to grow before the introduction of P_j, making the invasion of P_j more difficult, and the viability and longevity of co-occurrence less probable and shorter.

Deterministic vs. Demographically Stochastic Simulations

In [204…

```
plt.plot(ClimateChange_Det.iloc[:21,0], linewidth = 2, color = 'firebrick')
plt.plot(CC_SD10.iloc[:21,0], linewidth = 2, color = 'tomato', linestyle = 
plt.plot(ClimateChange_Det.iloc[:21,1], linewidth = 2, color = 'gold')
plt.plot(CC_SD10.iloc[:21,1], linewidth = 2, color = 'khaki', linestyle = '
plt.plot(ClimateChange_Det.iloc[:21,2], linewidth = 2, color = 'seagreen')
plt.plot(CC_SD10.iloc[:21,2], linewidth = 2, color = 'mediumseagreen', line
plt.plot(ClimateChange_Det.iloc[:21,3], linewidth = 2, color = 'cornflowerb
plt.plot(CC_SD10.iloc[:21,3], linewidth = 2, color = 'lightblue', linestyle
plt.xlabel('Day on Which Pj Introduced')
plt.ylabel('Time Points for Which Pi and Pj Co-Occurred')
plt.grid(False)
x = np.linspace(start=0, stop=20, num=21);
default_x_ticks = range(len(x));
plt.xticks(default_x_ticks, x)
plt.xticks(rotation=45)
plt.rcParams['figure.figsize'] = [12, 8]
```

Out[204]:
```
[<matplotlib.lines.Line2D at 0x7efedcd60d60>]
```
Out[204]:
```
[<matplotlib.lines.Line2D at 0x7efedcd6e0a0>]
```
Out[204]:
```
[<matplotlib.lines.Line2D at 0x7efedcd6e3d0>]
```
Out[204]:
```
[<matplotlib.lines.Line2D at 0x7efedcd6e220>]
```
Out[204]:
```
[<matplotlib.lines.Line2D at 0x7efedcd6e970>]
```
Out[204]:
```
[<matplotlib.lines.Line2D at 0x7efedcd6e8e0>]
```
Out[204]:
```
[<matplotlib.lines.Line2D at 0x7efedcd6ef10>]
```
Out[204]:
```
[<matplotlib.lines.Line2D at 0x7efedcce2190>]
```
Out[204]:
```
Text(0.5, 0, 'Day on Which Pj Introduced')
```
Out[204]:
```
Text(0, 0.5, 'Time Points for Which Pi and Pj Co-Occurred')
```

Out[204]:
```
([<matplotlib.axis.XTick at 0x7efedcdea9a0>,
  <matplotlib.axis.XTick at 0x7efedcdea970>,
  <matplotlib.axis.XTick at 0x7efedcd60fd0>,
  <matplotlib.axis.XTick at 0x7efedcce2760>,
  <matplotlib.axis.XTick at 0x7efedccdf040>,
  <matplotlib.axis.XTick at 0x7efedccdf640>,
  <matplotlib.axis.XTick at 0x7efedccdfd90>,
  <matplotlib.axis.XTick at 0x7efedccef520>,
  <matplotlib.axis.XTick at 0x7efedccdfdf0>,
  <matplotlib.axis.XTick at 0x7efedcce2c40>,
  <matplotlib.axis.XTick at 0x7efedccef610>,
  <matplotlib.axis.XTick at 0x7efedccc5370>,
  <matplotlib.axis.XTick at 0x7efedccc5ac0>,
  <matplotlib.axis.XTick at 0x7efedccc0250>,
  <matplotlib.axis.XTick at 0x7efedccc09a0>,
  <matplotlib.axis.XTick at 0x7efedccc0c40>,
  <matplotlib.axis.XTick at 0x7efedccc5a90>,
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  <matplotlib.axis.XTick at 0x7efedccd1400>],
 [Text(0, 0, '0.0'),
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  Text(3, 0, '3.0'),
  Text(4, 0, '4.0'),
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  Text(6, 0, '6.0'),
  Text(7, 0, '7.0'),
  Text(8, 0, '8.0'),
  Text(9, 0, '9.0'),
  Text(10, 0, '10.0'),
  Text(11, 0, '11.0'),
  Text(12, 0, '12.0'),
  Text(13, 0, '13.0'),
  Text(14, 0, '14.0'),
  Text(15, 0, '15.0'),
  Text(16, 0, '16.0'),
  Text(17, 0, '17.0'),
  Text(18, 0, '18.0'),
  Text(19, 0, '19.0'),
  Text(20, 0, '20.0')])
```
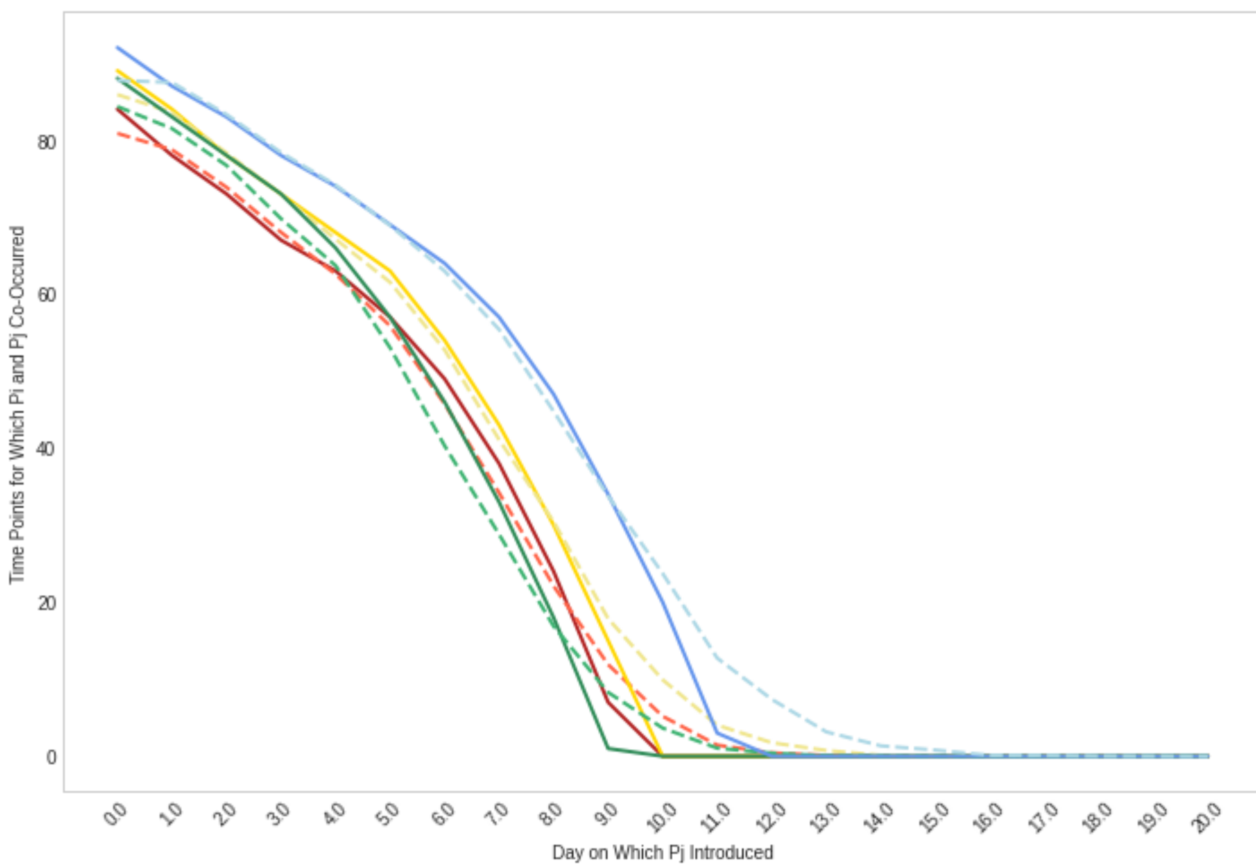

Out[204]:
```
(array([ 0,  1,  2,  3,  4,  5,  6,  7,  8,  9, 10, 11, 12, 13, 14, 15, 16,
        17, 18, 19, 20]),
 [Text(0, 0, '0.0'),
  Text(1, 0, '1.0'),
  Text(2, 0, '2.0'),
  Text(3, 0, '3.0'),
  Text(4, 0, '4.0'),
  Text(5, 0, '5.0'),
  Text(6, 0, '6.0'),
  Text(7, 0, '7.0'),
  Text(8, 0, '8.0'),
  Text(9, 0, '9.0'),
  Text(10, 0, '10.0'),
  Text(11, 0, '11.0'),
  Text(12, 0, '12.0'),
  Text(13, 0, '13.0'),
  Text(14, 0, '14.0'),
  Text(15, 0, '15.0'),
  Text(16, 0, '16.0'),
  Text(17, 0, '17.0'),
  Text(18, 0, '18.0'),
  Text(19, 0, '19.0'),
  Text(20, 0, '20.0')])
```



In the above plot:

- Red lines denote identical TPCs
    - Dashed lines denote demographically stochastic simulations.
- Yellow lines denote semi-identical TPCs
- Green lines denote Pi-Advantage TPCs
- Blue lines denote Pj-Advantage TPCs

P.S. I would have included all this in a legend, but it was getting a bit messy/couldn't figure out a nice way to do so; I'd improve that in the future.

Interpretation:

From this plot, we can see that while demographic stochasticity may alter the tendency for P_i and P_j to co-occur, it does not reuslt in significantly different periods of co-occurrence compared to thosee produced by deterministic simulations. We can also see, as we saw above, that our thermal arrangement wherein the secondary parasite, P_j, has the thermal advantage over the primary parasite, P_i, produces the longest periods of co-occurrence.

Low Average Temperature Environment 🐟

In [205…

```
# Requisite dfs:
    # CC_SD10
    # CC_SD20

plt.plot(CC_SD10.iloc[:21,0], linewidth = 2, color = 'firebrick', linestyle
plt.plot(CC_SD10.iloc[:21,4], linewidth = 2, color = 'firebrick', linestyle
plt.plot(CC_SD10.iloc[:21,8], linewidth = 2, color = 'firebrick', linestyle
plt.plot(CC_SD10.iloc[:21,1], linewidth = 2, color = 'gold', linestyle = 's
plt.plot(CC_SD10.iloc[:21,5], linewidth = 2, color = 'gold', linestyle = 'd
plt.plot(CC_SD10.iloc[:21,9], linewidth = 2, color = 'gold', linestyle = 'd
plt.plot(CC_SD10.iloc[:21,2], linewidth = 2, color = 'seagreen', linestyle
plt.plot(CC_SD10.iloc[:21,6], linewidth = 2, color = 'seagreen', linestyle
plt.plot(CC_SD10.iloc[:21,10], linewidth = 2, color = 'seagreen', linestyle
plt.plot(CC_SD10.iloc[:21,3], linewidth = 2, color = 'cornflowerblue', line
plt.plot(CC_SD10.iloc[:21,7], linewidth = 2, color = 'cornflowerblue', line
plt.plot(CC_SD10.iloc[:21,11], linewidth = 2, color = 'cornflowerblue', lin
plt.title('Within-Host Parasite Co-Occurrence, Low Average Temperature Envi
plt.xlabel('Day on Which Pj Introduced')
plt.ylabel('Time Points for Which Pi and Pj Co-Occurred')
plt.grid(False)
x = np.linspace(start=0, stop=20, num=21);
default_x_ticks = range(len(x));
plt.xticks(default_x_ticks, x)
plt.xticks(rotation=45)
plt.rcParams['figure.figsize'] = [12, 8]
```

```
Out[205]: [<matplotlib.lines.Line2D at 0x7efedcd7b340>]
Out[205]: [<matplotlib.lines.Line2D at 0x7efedcd7b070>]
Out[205]: [<matplotlib.lines.Line2D at 0x7efedcd7b0a0>]
Out[205]: [<matplotlib.lines.Line2D at 0x7efedcd7ba90>]
Out[205]: [<matplotlib.lines.Line2D at 0x7efedcd7bb20>]
Out[205]: [<matplotlib.lines.Line2D at 0x7efedcda5100>]
Out[205]: [<matplotlib.lines.Line2D at 0x7efedcda5340>]
Out[205]: [<matplotlib.lines.Line2D at 0x7efedcda5610>]
Out[205]: [<matplotlib.lines.Line2D at 0x7efedcda58e0>]
Out[205]: [<matplotlib.lines.Line2D at 0x7efedcda5bb0>]
Out[205]: [<matplotlib.lines.Line2D at 0x7efedcda5e80>]
Out[205]: [<matplotlib.lines.Line2D at 0x7efedcda31c0>]
Out[205]: Text(0.5, 1.0, 'Within-Host Parasite Co-Occurrence, Low Average Temperature
          Environment, Magnitude of Thermal Disturbance = Small')
Out[205]: Text(0.5, 0, 'Day on Which Pj Introduced')
```

Out[205]:
```
Text(0, 0.5, 'Time Points for Which Pi and Pj Co-Occurred')
```

Out[205]:
```
([<matplotlib.axis.XTick at 0x7efedcbd1f10>,
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  <matplotlib.axis.XTick at 0x7efedcc3d790>,
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  <matplotlib.axis.XTick at 0x7efedcc3b430>,
  <matplotlib.axis.XTick at 0x7efedcc3bb80>,
  <matplotlib.axis.XTick at 0x7efedcc50310>,
  <matplotlib.axis.XTick at 0x7efedcc50a60>,
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  <matplotlib.axis.XTick at 0x7efedcc50ac0>,
  <matplotlib.axis.XTick at 0x7efedcc3b910>,
  <matplotlib.axis.XTick at 0x7efedcc487f0>,
  <matplotlib.axis.XTick at 0x7efedcc48e50>,
  <matplotlib.axis.XTick at 0x7efedcc615e0>,
  <matplotlib.axis.XTick at 0x7efedcc61d30>,
  <matplotlib.axis.XTick at 0x7efedcc5b4c0>,
  <matplotlib.axis.XTick at 0x7efedcc61850>],
 [Text(0, 0, '0.0'),
  Text(1, 0, '1.0'),
  Text(2, 0, '2.0'),
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  Text(5, 0, '5.0'),
  Text(6, 0, '6.0'),
  Text(7, 0, '7.0'),
  Text(8, 0, '8.0'),
  Text(9, 0, '9.0'),
  Text(10, 0, '10.0'),
  Text(11, 0, '11.0'),
  Text(12, 0, '12.0'),
  Text(13, 0, '13.0'),
  Text(14, 0, '14.0'),
  Text(15, 0, '15.0'),
  Text(16, 0, '16.0'),
  Text(17, 0, '17.0'),
  Text(18, 0, '18.0'),
  Text(19, 0, '19.0'),
  Text(20, 0, '20.0')])
```
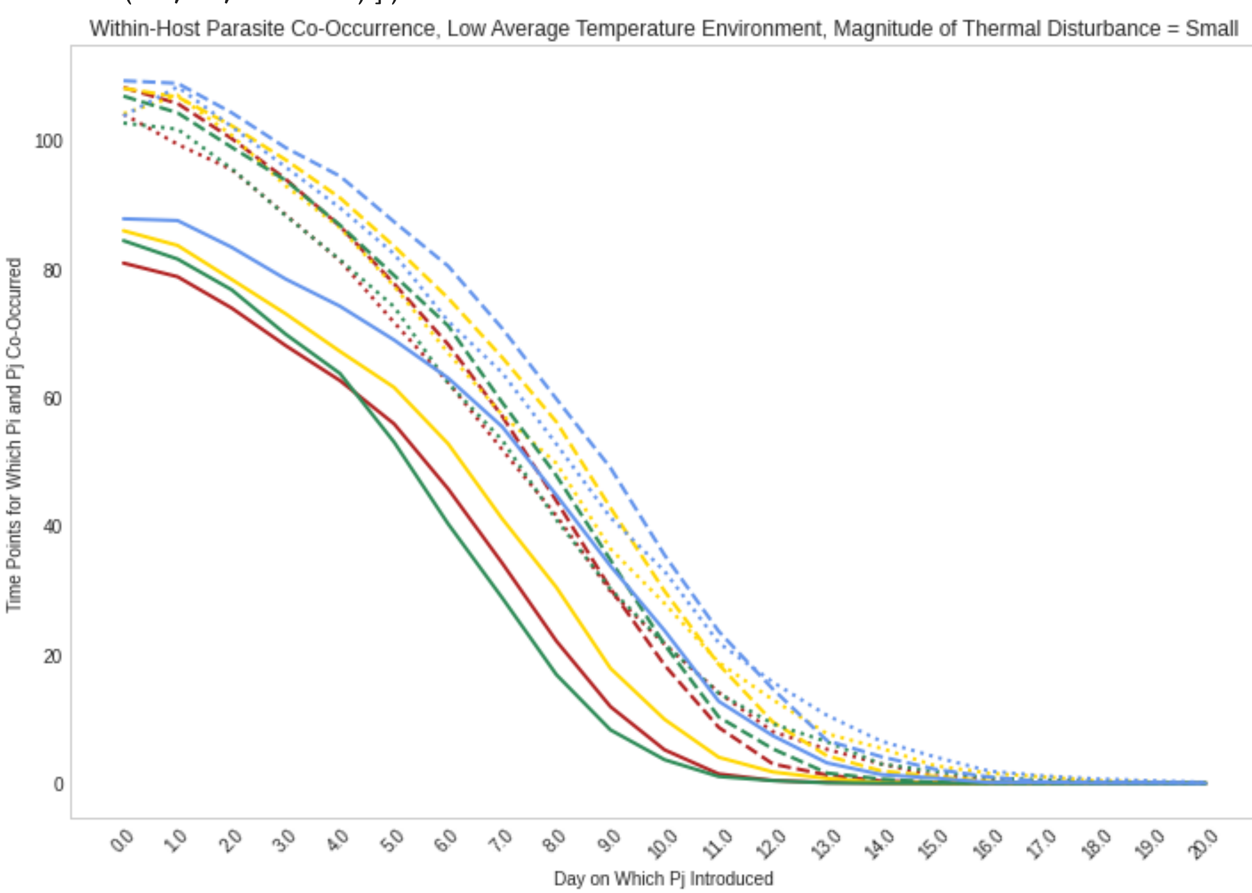

```
Out[205]: (array([ 0,  1,  2,  3,  4,  5,  6,  7,  8,  9, 10, 11, 12, 13, 14, 15, 16,
                  17, 18, 19, 20]),
           [Text(0, 0, '0.0'),
            Text(1, 0, '1.0'),
            Text(2, 0, '2.0'),
            Text(3, 0, '3.0'),
            Text(4, 0, '4.0'),
            Text(5, 0, '5.0'),
            Text(6, 0, '6.0'),
            Text(7, 0, '7.0'),
            Text(8, 0, '8.0'),
            Text(9, 0, '9.0'),
            Text(10, 0, '10.0'),
            Text(11, 0, '11.0'),
            Text(12, 0, '12.0'),
            Text(13, 0, '13.0'),
            Text(14, 0, '14.0'),
            Text(15, 0, '15.0'),
            Text(16, 0, '16.0'),
            Text(17, 0, '17.0'),
            Text(18, 0, '18.0'),
            Text(19, 0, '19.0'),
            Text(20, 0, '20.0')])
```



In [206…

```
plt.plot(CC_SD20.iloc[:21,0], linewidth = 2, color = 'firebrick', linestyle
plt.plot(CC_SD20.iloc[:21,4], linewidth = 2, color = 'firebrick', linestyle
plt.plot(CC_SD20.iloc[:21,8], linewidth = 2, color = 'firebrick', linestyle
plt.plot(CC_SD20.iloc[:21,1], linewidth = 2, color = 'gold', linestyle = 's
plt.plot(CC_SD20.iloc[:21,5], linewidth = 2, color = 'gold', linestyle = 'd
plt.plot(CC_SD20.iloc[:21,9], linewidth = 2, color = 'gold', linestyle = 'd
plt.plot(CC_SD20.iloc[:21,2], linewidth = 2, color = 'seagreen', linestyle
plt.plot(CC_SD20.iloc[:21,6], linewidth = 2, color = 'seagreen', linestyle
plt.plot(CC_SD20.iloc[:21,10], linewidth = 2, color = 'seagreen', linestyle
plt.plot(CC_SD20.iloc[:21,3], linewidth = 2, color = 'cornflowerblue', line
plt.plot(CC_SD20.iloc[:21,7], linewidth = 2, color = 'cornflowerblue', line
plt.plot(CC_SD20.iloc[:21,11], linewidth = 2, color = 'cornflowerblue', lin
plt.title('Within-Host Parasite Co-Occurrence, Low Average Temperature Envi
plt.xlabel('Day on Which Pj Introduced')
plt.ylabel('Time Points for Which Pi and Pj Co-Occurred')
plt.grid(False)
x = np.linspace(start=0, stop=20, num=21);
default_x_ticks = range(len(x));
plt.xticks(default_x_ticks, x)
plt.xticks(rotation=45)
plt.rcParams['figure.figsize'] = [12, 8]
```

```
Out[206]: [<matplotlib.lines.Line2D at 0x7efedcd16970>]
Out[206]: [<matplotlib.lines.Line2D at 0x7efedcb3c2b0>]
Out[206]: [<matplotlib.lines.Line2D at 0x7efedcd16cd0>]
Out[206]: [<matplotlib.lines.Line2D at 0x7efedcd16d00>]
Out[206]: [<matplotlib.lines.Line2D at 0x7efedcd09220>]
Out[206]: [<matplotlib.lines.Line2D at 0x7efedcd091c0>]
Out[206]: [<matplotlib.lines.Line2D at 0x7efedcd097c0>]
Out[206]: [<matplotlib.lines.Line2D at 0x7efedcd09a90>]
Out[206]: [<matplotlib.lines.Line2D at 0x7efedcd09d60>]
Out[206]: [<matplotlib.lines.Line2D at 0x7efedcd18100>]
Out[206]: [<matplotlib.lines.Line2D at 0x7efedcd18340>]
Out[206]: [<matplotlib.lines.Line2D at 0x7efedcd18610>]
Out[206]: Text(0.5, 1.0, 'Within-Host Parasite Co-Occurrence, Low Average Temperature
          Environment, Magnitude of Thermal Disturbance = Large')
Out[206]: Text(0.5, 0, 'Day on Which Pj Introduced')
Out[206]: Text(0, 0.5, 'Time Points for Which Pi and Pj Co-Occurred')
```

Out[206]:
```
([<matplotlib.axis.XTick at 0x7efedcb4e490>,
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  <matplotlib.axis.XTick at 0x7efedcd18c70>,
  <matplotlib.axis.XTick at 0x7efedcd06400>,
  <matplotlib.axis.XTick at 0x7efedcd06b50>,
  <matplotlib.axis.XTick at 0x7efedcd1b2e0>,
  <matplotlib.axis.XTick at 0x7efedcd06e20>,
  <matplotlib.axis.XTick at 0x7efedcd18d30>,
  <matplotlib.axis.XTick at 0x7efedcd1bc70>,
  <matplotlib.axis.XTick at 0x7efedcd28400>,
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  <matplotlib.axis.XTick at 0x7efedcc77ac0>,
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  <matplotlib.axis.XTick at 0x7efedcc8b760>,
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  <matplotlib.axis.XTick at 0x7efedcc83640>,
  <matplotlib.axis.XTick at 0x7efedcc83d90>],
 [Text(0, 0, '0.0'),
  Text(1, 0, '1.0'),
  Text(2, 0, '2.0'),
  Text(3, 0, '3.0'),
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  Text(5, 0, '5.0'),
  Text(6, 0, '6.0'),
  Text(7, 0, '7.0'),
  Text(8, 0, '8.0'),
  Text(9, 0, '9.0'),
  Text(10, 0, '10.0'),
  Text(11, 0, '11.0'),
  Text(12, 0, '12.0'),
  Text(13, 0, '13.0'),
  Text(14, 0, '14.0'),
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  Text(19, 0, '19.0'),
  Text(20, 0, '20.0')])
```

Out[206]:
```
(array([ 0,  1,  2,  3,  4,  5,  6,  7,  8,  9, 10, 11, 12, 13, 14, 15, 16,
        17, 18, 19, 20]),
 [Text(0, 0, '0.0'),
  Text(1, 0, '1.0'),
  Text(2, 0, '2.0'),
  Text(3, 0, '3.0'),
  Text(4, 0, '4.0'),
  Text(5, 0, '5.0'),
  Text(6, 0, '6.0'),
  Text(7, 0, '7.0'),
  Text(8, 0, '8.0'),
  Text(9, 0, '9.0'),
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  Text(14, 0, '14.0'),
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  Text(16, 0, '16.0'),
  Text(17, 0, '17.0'),
  Text(18, 0, '18.0'),
  Text(19, 0, '19.0'),
  Text(20, 0, '20.0')])
```

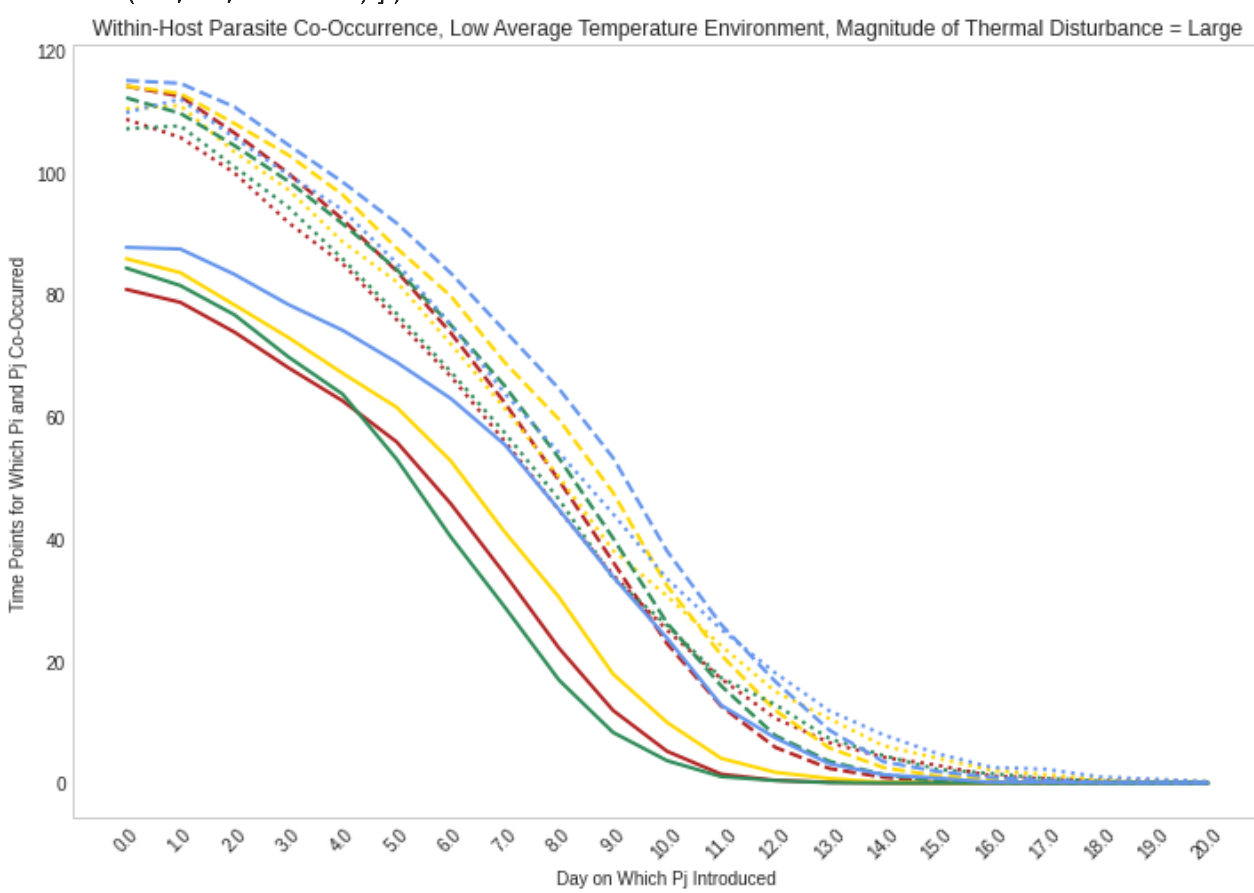

In the above plot:

- Red lines denote identical TPCs
    - Solid lines denote demographically stochastic simulations.
    - Dashed lines denote environmentally stochastic simulations.
    - Dotted lines denote demographically and environmentally stochastic simulations.
- Yellow lines denote semi-identical TPCs
- Green lines denote Pi-Advantage TPCs
- Blue lines denote Pj-Advantage TPCs

Interpretation:

These plots shows us that where demographic stochasticity seems to have little influence on the viability and maintenace of co-occurrence between P_i and P_j, envionmental stochasticity seems to promote both the viability and maintenance of co-occurrence. We see that in our simulations that include environmental stochasticity, the likelihood of co-occurrence at later introduction points is higher and periods of co-occurrence tend to be longer than in deterministic or demographically stochastic simulations.

We also see that when the magnitude of thermal disturbance is larger, this effect is exacerbated, implying that as our climate continues to change and becomes more variable as a consequence, we may see increased co-occurrence between parasite within hosts, increasing within-host parasite diversity. Let's take a closer look at this effect in the next two plots.

Finally, we see, as shown in our previous two plots, that our thermal arrangement wherein the secondary parasite, P_j, has the thermal advantage over the primary parasite, P_i, produces the longest periods of co-occurrence.

In [207…

```
# Identical TPCs
plt.plot(ClimateChange_Det.iloc[:21,0], linewidth = 2, color = 'palevioletr
plt.plot(CC_SD10.iloc[:21,0], linewidth = 2, color = 'goldenrod', linestyle
plt.plot(CC_SD10.iloc[:21,4], linewidth = 2, color = 'midnightblue', linest
plt.plot(CC_SD10.iloc[:21,8], linewidth = 2, color = 'darkgreen', linestyle
plt.plot(CC_SD20.iloc[:21,4], linewidth = 2, color = 'royalblue', linestyle
plt.plot(CC_SD20.iloc[:21,8], linewidth = 2, color = 'seagreen', linestyle
plt.title('Within-Host Parasite Co-Occurrence, Low Average Temperature Envi
plt.xlabel('Day on Which Pj Introduced')
plt.ylabel('Time Points for Which Pi and Pj Co-Occurred')
plt.grid(False)
plt.legend(['Deterministic','Demographically Stochastic', 'Environmentally
            'Demographically and Environmentally Stochastic, Mag. of Dist.
            'Demographically and Environmentally Stochastic, Mag. of Dist.
x = np.linspace(start=0, stop=20, num=21);
default_x_ticks = range(len(x));
plt.xticks(default_x_ticks, x)
plt.xticks(rotation=45)
plt.rcParams['figure.figsize'] = [12, 8]
```

Out[207]:
```
[<matplotlib.lines.Line2D at 0x7efedcc059a0>]
```

Out[207]:
```
[<matplotlib.lines.Line2D at 0x7efedcc05df0>]
```

Out[207]:
```
[<matplotlib.lines.Line2D at 0x7efedcc310d0>]
```

Out[207]:
```
[<matplotlib.lines.Line2D at 0x7efedcc31310>]
```

Out[207]:
```
[<matplotlib.lines.Line2D at 0x7efedcc315e0>]
```

Out[207]:
```
[<matplotlib.lines.Line2D at 0x7efedcc318b0>]
```

Out[207]:
```
Text(0.5, 1.0, 'Within-Host Parasite Co-Occurrence, Low Average Temperature
Environment, Identical Thermal Arrangement')
```

Out[207]:
```
Text(0.5, 0, 'Day on Which Pj Introduced')
```

Out[207]:
```
Text(0, 0.5, 'Time Points for Which Pi and Pj Co-Occurred')
```

Out[207]:
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Out[207]:
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  Text(8, 0, '8.0'),
  Text(9, 0, '9.0'),
  Text(10, 0, '10.0'),
  Text(11, 0, '11.0'),
  Text(12, 0, '12.0'),
  Text(13, 0, '13.0'),
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  Text(18, 0, '18.0'),
  Text(19, 0, '19.0'),
  Text(20, 0, '20.0')])
```

Out[207]:
```
(array([ 0,  1,  2,  3,  4,  5,  6,  7,  8,  9, 10, 11, 12, 13, 14, 15, 16,
        17, 18, 19, 20]),
 [Text(0, 0, '0.0'),
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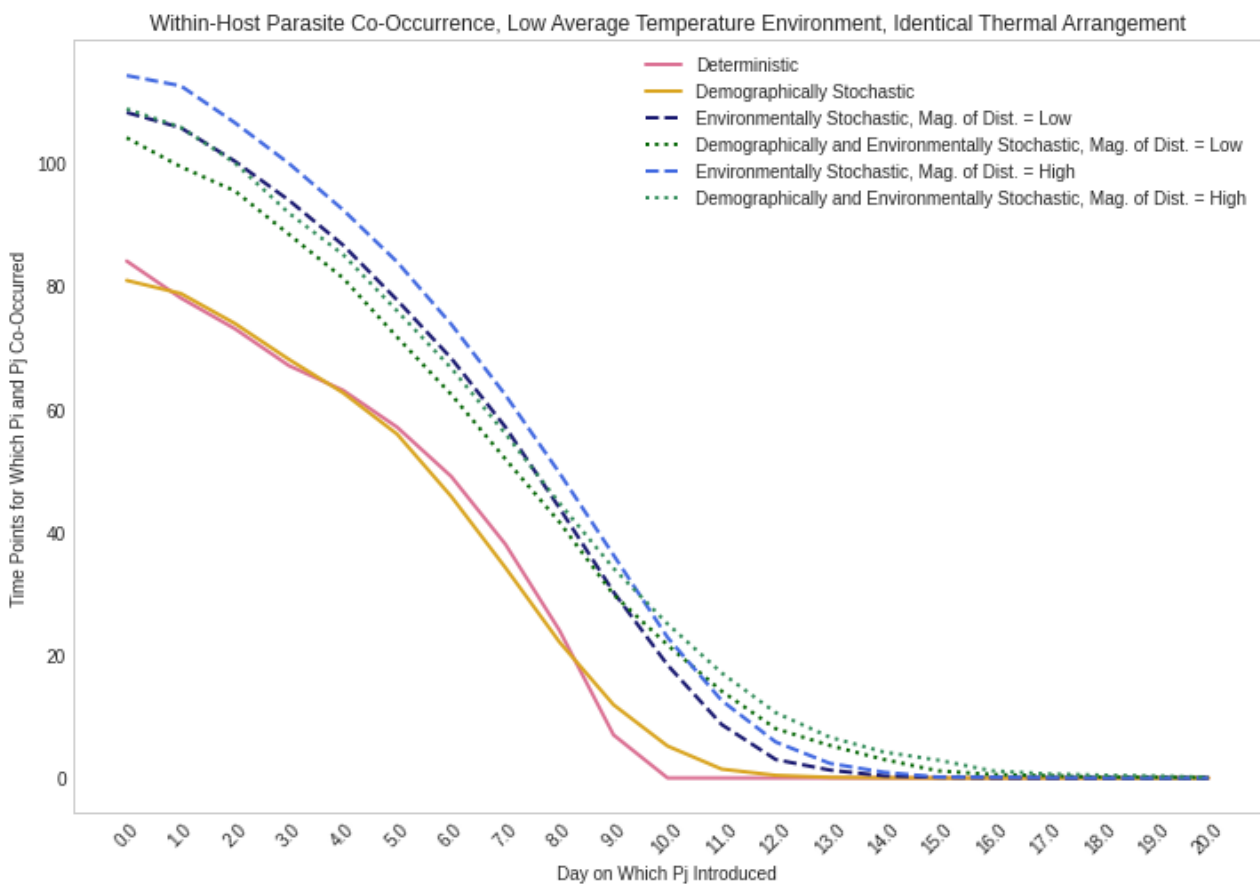
  Text(2, 0, '2.0'),
  Text(3, 0, '3.0'),
  Text(4, 0, '4.0'),
  Text(5, 0, '5.0'),
  Text(6, 0, '6.0'),
  Text(7, 0, '7.0'),
  Text(8, 0, '8.0'),
  Text(9, 0, '9.0'),
  Text(10, 0, '10.0'),
  Text(11, 0, '11.0'),
  Text(12, 0, '12.0'),
  Text(13, 0, '13.0'),
  Text(14, 0, '14.0'),
  Text(15, 0, '15.0'),
  Text(16, 0, '16.0'),
  Text(17, 0, '17.0'),
  Text(18, 0, '18.0'),
  Text(19, 0, '19.0'),
  Text(20, 0, '20.0')])
```



In [208…

```
# Pj-Advantage TPCs
plt.plot(ClimateChange_Det.iloc[:21,3], linewidth = 2, color = 'palevioletr
plt.plot(CC_SD10.iloc[:21,3], linewidth = 2, color = 'goldenrod', linestyle
plt.plot(CC_SD10.iloc[:21,7], linewidth = 2, color = 'midnightblue', linest
plt.plot(CC_SD10.iloc[:21,11], linewidth = 2, color = 'darkgreen', linestyl
plt.plot(CC_SD20.iloc[:21,7], linewidth = 2, color = 'royalblue', linestyle
plt.plot(CC_SD20.iloc[:21,11], linewidth = 2, color = 'seagreen', linestyle
plt.title('Within-Host Parasite Co-Occurrence, Low Average Temperature Envi
plt.xlabel('Day on Which Pj Introduced')
plt.ylabel('Time Points for Which Pi and Pj Co-Occurred')
plt.grid(False)
plt.legend(['Deterministic','Demographically Stochastic', 'Environmentally
            'Demographically and Environmentally Stochastic, Mag. of Dist.
            'Demographically and Environmentally Stochastic, Mag. of Dist.
x = np.linspace(start=0, stop=20, num=21);
default_x_ticks = range(len(x));
plt.xticks(default_x_ticks, x)
plt.xticks(rotation=45)
plt.rcParams['figure.figsize'] = [12, 8]
```

Out[208]:
```
[<matplotlib.lines.Line2D at 0x7efe8a54b400>]
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Out[208]:
```
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```
Out[208]:
```
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Out[208]:
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[<matplotlib.lines.Line2D at 0x7efe8a54bd30>]
```
Out[208]:
```
[<matplotlib.lines.Line2D at 0x7efe8a5600d0>]
```
Out[208]:
```
[<matplotlib.lines.Line2D at 0x7efe8a560310>]
```
Out[208]:
```
Text(0.5, 1.0, 'Within-Host Parasite Co-Occurrence, Low Average Temperature
Environment, Pj-Advantage Thermal Arrangement')
```
Out[208]:
```
Text(0.5, 0, 'Day on Which Pj Introduced')
```
Out[208]:
```
Text(0, 0.5, 'Time Points for Which Pi and Pj Co-Occurred')
```
Out[208]:
```
<matplotlib.legend.Legend at 0x7efe8a5ab340>
```

Out[208]:
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  <matplotlib.axis.XTick at 0x7efe8a5774f0>,
  <matplotlib.axis.XTick at 0x7efe8a577c40>,
  <matplotlib.axis.XTick at 0x7efe8a577d00>,
  <matplotlib.axis.XTick at 0x7efe8a571cd0>,
  <matplotlib.axis.XTick at 0x7efe8a57c370>,
  <matplotlib.axis.XTick at 0x7efe8a57ca90>,
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  <matplotlib.axis.XTick at 0x7efe8a584970>,
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  <matplotlib.axis.XTick at 0x7efe8a50db50>,
  <matplotlib.axis.XTick at 0x7efe8a5152e0>,
  <matplotlib.axis.XTick at 0x7efe8a515a30>],
 [Text(0, 0, '0.0'),
  Text(1, 0, '1.0'),
  Text(2, 0, '2.0'),
  Text(3, 0, '3.0'),
  Text(4, 0, '4.0'),
  Text(5, 0, '5.0'),
  Text(6, 0, '6.0'),
  Text(7, 0, '7.0'),
  Text(8, 0, '8.0'),
  Text(9, 0, '9.0'),
  Text(10, 0, '10.0'),
  Text(11, 0, '11.0'),
  Text(12, 0, '12.0'),
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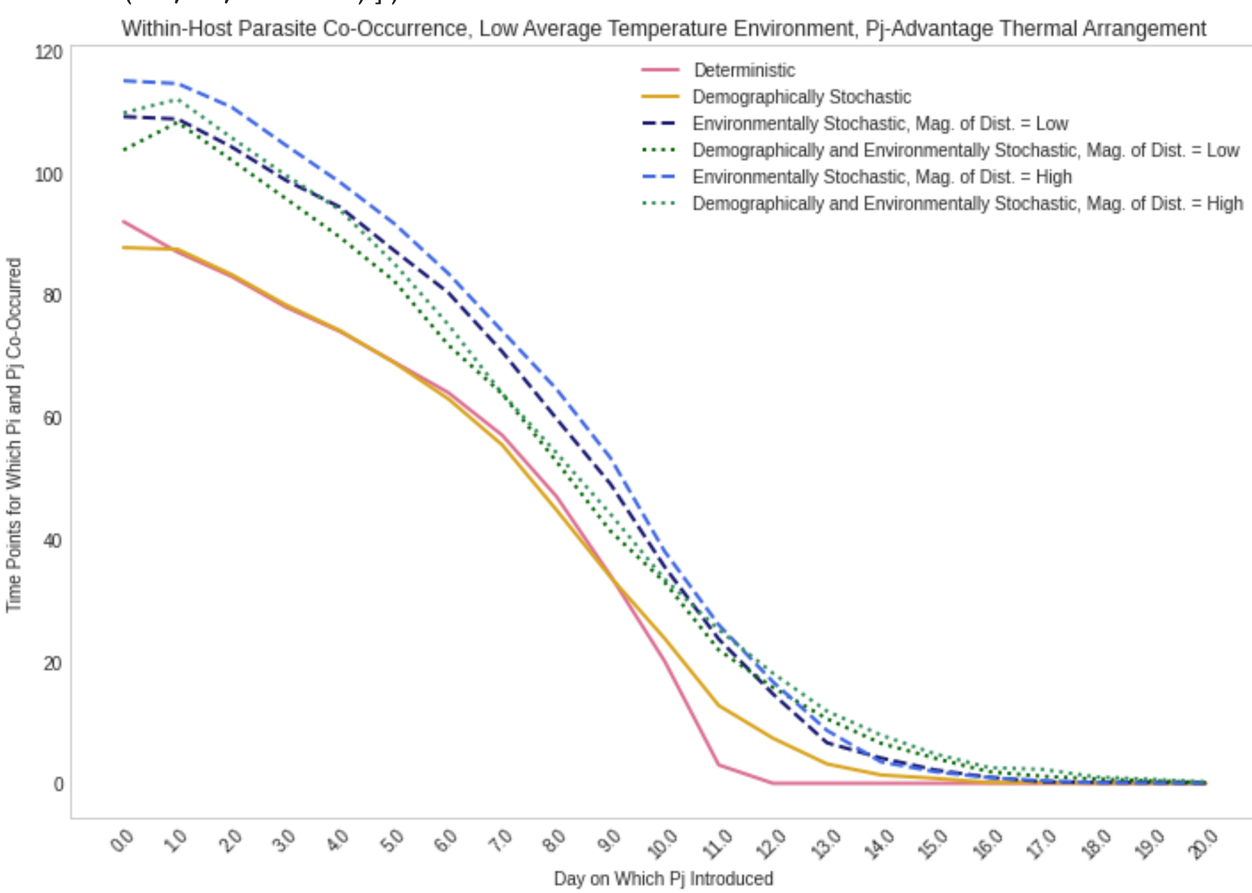
  Text(18, 0, '18.0'),
  Text(19, 0, '19.0'),
  Text(20, 0, '20.0')])
```

Out[208]:
```
(array([ 0,  1,  2,  3,  4,  5,  6,  7,  8,  9, 10, 11, 12, 13, 14, 15, 16,
        17, 18, 19, 20]),
 [Text(0, 0, '0.0'),
  Text(1, 0, '1.0'),
  Text(2, 0, '2.0'),
  Text(3, 0, '3.0'),
  Text(4, 0, '4.0'),
  Text(5, 0, '5.0'),
  Text(6, 0, '6.0'),
  Text(7, 0, '7.0'),
  Text(8, 0, '8.0'),
  Text(9, 0, '9.0'),
  Text(10, 0, '10.0'),
  Text(11, 0, '11.0'),
  Text(12, 0, '12.0'),
  Text(13, 0, '13.0'),
  Text(14, 0, '14.0'),
  Text(15, 0, '15.0'),
  Text(16, 0, '16.0'),
  Text(17, 0, '17.0'),
  Text(18, 0, '18.0'),
  Text(19, 0, '19.0'),
  Text(20, 0, '20.0')])
```



High Average Temperature Environment 🦇

Now, since we have a few frequencies we're using in our simulation, we'll make four plots, one per thermal arrangement, so we can show comparisons between the deterministic, demographically stochastic, environmentally stochastic, and demographically and environmentally stochastic simulations, when the system experiences a thermal disturbance every 2, 10, and 20 time steps (5 times/day, once/day, once/2 days).

In [213…

```
xs = np.linspace(-1, 1)
plt.rcParams['figure.figsize'] = [16, 14]
# Identical TPCs
plt.subplot(2,2,1)
plt.plot(Bats_Det.iloc[:21,0], linewidth = 2, color = 'palevioletred', line
plt.plot(B_2.iloc[:21,0], linewidth = 2, color = 'goldenrod', linestyle = '
plt.plot(B_2.iloc[:21,4], linewidth = 2, color = 'midnightblue', linestyle
plt.plot(B_2.iloc[:21,8], linewidth = 2, color = 'darkgreen', linestyle = '
plt.plot(B_10.iloc[:21,4], linewidth = 2, color = 'royalblue', linestyle =
plt.plot(B_10.iloc[:21,8], linewidth = 2, color = 'seagreen', linestyle = '
plt.plot(B_20.iloc[:21,4], linewidth = 2, color = 'lightsteelblue', linesty
plt.plot(B_20.iloc[:21,8], linewidth = 2, color = 'darkseagreen', linestyle
plt.title('Identical Thermal Arrangement')
plt.xlabel('Day on Which Pj Introduced')
plt.ylabel('Time Points for Which Pi and Pj Co-Occurred')
plt.grid(False)
plt.legend(['Deterministic','Dem. Stoch.', 'Env. Stoch., Freq. of Dist. = H
             'Env. Stoch., Freq. of Dist. = Intermediate', 'Dem. and Env. St
            'Env. Stoch., Freq. of Dist. = Low', 'Dem. and Env. Stoch., Freq
plt.xticks(default_x_ticks, x)
plt.xticks(rotation=45)
# Semi-Identical TPCs
plt.subplot(2,2,2)
plt.plot(Bats_Det.iloc[:21,1], linewidth = 2, color = 'palevioletred', line
plt.plot(B_2.iloc[:21,1], linewidth = 2, color = 'goldenrod', linestyle = '
plt.plot(B_2.iloc[:21,5], linewidth = 2, color = 'midnightblue', linestyle
plt.plot(B_2.iloc[:21,9], linewidth = 2, color = 'darkgreen', linestyle = '
plt.plot(B_10.iloc[:21,5], linewidth = 2, color = 'royalblue', linestyle =
plt.plot(B_10.iloc[:21,9], linewidth = 2, color = 'seagreen', linestyle = '
plt.plot(B_20.iloc[:21,5], linewidth = 2, color = 'lightsteelblue', linesty
plt.plot(B_20.iloc[:21,9], linewidth = 2, color = 'darkseagreen', linestyle
plt.title('Semi-Identical Thermal Arrangement')
plt.xlabel('Day on Which Pj Introduced')
plt.ylabel('Time Points for Which Pi and Pj Co-Occurred')
plt.grid(False)
plt.xticks(default_x_ticks, x)
plt.xticks(rotation=45)
# Pi-Advantage TPCs
plt.subplot(2,2,3)
plt.plot(Bats_Det.iloc[:21,2], linewidth = 2, color = 'palevioletred', line
plt.plot(B_2.iloc[:21,2], linewidth = 2, color = 'goldenrod', linestyle = '
```

```
plt.plot(B_2.iloc[:21,6], linewidth = 2, color = 'midnightblue', linestyle
plt.plot(B_2.iloc[:21,10], linewidth = 2, color = 'darkgreen', linestyle =
plt.plot(B_10.iloc[:21,6], linewidth = 2, color = 'royalblue', linestyle =
plt.plot(B_10.iloc[:21,10], linewidth = 2, color = 'seagreen', linestyle =
plt.plot(B_20.iloc[:21,6], linewidth = 2, color = 'lightsteelblue', linesty
plt.plot(B_20.iloc[:21,10], linewidth = 2, color = 'darkseagreen', linestyl
plt.title('Pi-Advantage Thermal Arrangement')
plt.xlabel('Day on Which Pj Introduced')
plt.ylabel('Time Points for Which Pi and Pj Co-Occurred')
plt.grid(False)
plt.xticks(default_x_ticks, x)
plt.xticks(rotation=45)
# Pj-Advantage TPCs
plt.subplot(2,2,4)
plt.plot(Bats_Det.iloc[:21,3], linewidth = 2, color = 'palevioletred', line
plt.plot(B_2.iloc[:21,3], linewidth = 2, color = 'goldenrod', linestyle = '
plt.plot(B_2.iloc[:21,7], linewidth = 2, color = 'midnightblue', linestyle
plt.plot(B_2.iloc[:21,11], linewidth = 2, color = 'darkgreen', linestyle =
plt.plot(B_10.iloc[:21,7], linewidth = 2, color = 'royalblue', linestyle =
plt.plot(B_10.iloc[:21,11], linewidth = 2, color = 'seagreen', linestyle =
plt.plot(B_20.iloc[:21,7], linewidth = 2, color = 'lightsteelblue', linesty
plt.plot(B_20.iloc[:21,11], linewidth = 2, color = 'darkseagreen', linestyl
plt.title('Pj-Advantage Thermal Arrangement')
plt.xlabel('Day on Which Pj Introduced')
plt.ylabel('Time Points for Which Pi and Pj Co-Occurred')
plt.grid(False)
plt.xticks(default_x_ticks, x)
plt.xticks(rotation=45)
plt.show()
```

```
Out[213]: <AxesSubplot:>
Out[213]: [<matplotlib.lines.Line2D at 0x7efe81dd0df0>]
Out[213]: [<matplotlib.lines.Line2D at 0x7efe81dde2b0>]
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Out[213]: [<matplotlib.lines.Line2D at 0x7efe81ddea60>]
Out[213]: [<matplotlib.lines.Line2D at 0x7efe81dded30>]
Out[213]: [<matplotlib.lines.Line2D at 0x7efe81de70d0>]
Out[213]: [<matplotlib.lines.Line2D at 0x7efe81de7310>]
Out[213]: Text(0.5, 1.0, 'Identical Thermal Arrangement')
Out[213]: Text(0.5, 0, 'Day on Which Pj Introduced')
Out[213]: Text(0, 0.5, 'Time Points for Which Pi and Pj Co-Occurred')
```

Out[213]:
```
<matplotlib.legend.Legend at 0x7efe89fd38e0>
```

Out[213]:
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  <matplotlib.axis.XTick at 0x7efe81d88b20>,
  <matplotlib.axis.XTick at 0x7efe81d88df0>,
  <matplotlib.axis.XTick at 0x7efe81d93d90>,
  <matplotlib.axis.XTick at 0x7efe81df53a0>,
  <matplotlib.axis.XTick at 0x7efe81d8f5b0>,
  <matplotlib.axis.XTick at 0x7efe81d8fd00>,
  <matplotlib.axis.XTick at 0x7efe81da6490>],
 [Text(0, 0, '0.0'),
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  Text(3, 0, '3.0'),
  Text(4, 0, '4.0'),
  Text(5, 0, '5.0'),
  Text(6, 0, '6.0'),
  Text(7, 0, '7.0'),
  Text(8, 0, '8.0'),
  Text(9, 0, '9.0'),
  Text(10, 0, '10.0'),
  Text(11, 0, '11.0'),
  Text(12, 0, '12.0'),
  Text(13, 0, '13.0'),
  Text(14, 0, '14.0'),
  Text(15, 0, '15.0'),
  Text(16, 0, '16.0'),
  Text(17, 0, '17.0'),
  Text(18, 0, '18.0'),
  Text(19, 0, '19.0'),
  Text(20, 0, '20.0')])
```

Out[213]:
```
(array([ 0,  1,  2,  3,  4,  5,  6,  7,  8,  9, 10, 11, 12, 13, 14, 15, 16,
        17, 18, 19, 20]),
 [Text(0, 0, '0.0'),
  Text(1, 0, '1.0'),
  Text(2, 0, '2.0'),
  Text(3, 0, '3.0'),
  Text(4, 0, '4.0'),
  Text(5, 0, '5.0'),
  Text(6, 0, '6.0'),
  Text(7, 0, '7.0'),
  Text(8, 0, '8.0'),
  Text(9, 0, '9.0'),
  Text(10, 0, '10.0'),
  Text(11, 0, '11.0'),
  Text(12, 0, '12.0'),
  Text(13, 0, '13.0'),
  Text(14, 0, '14.0'),
  Text(15, 0, '15.0'),
  Text(16, 0, '16.0'),
  Text(17, 0, '17.0'),
  Text(18, 0, '18.0'),
  Text(19, 0, '19.0'),
  Text(20, 0, '20.0')])
```

Out[213]:
```
<AxesSubplot:>
```

Out[213]:
```
[<matplotlib.lines.Line2D at 0x7efe81d4c3a0>]
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Out[213]:
```
[<matplotlib.lines.Line2D at 0x7efe81d65310>]
```

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Out[213]:
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Out[213]:
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```

Out[213]:
```
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```

Out[213]:
```
Text(0.5, 1.0, 'Semi-Identical Thermal Arrangement')
```

Out[213]:
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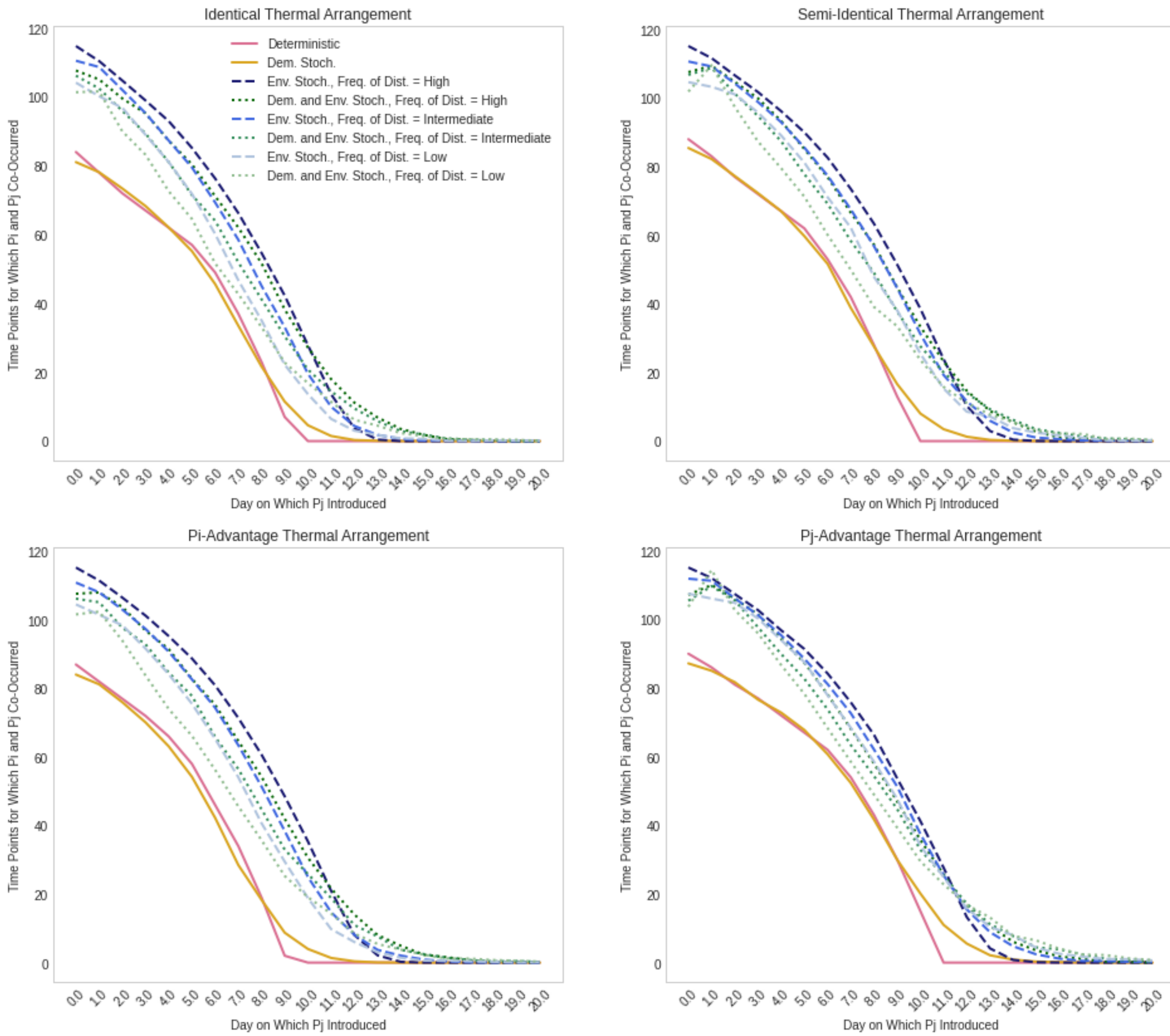

Interpretation:

These plots show us, as before, that environmental stochasticity seems to promote the viability and longevity of co-occurrence. In particular, we can see that as we increase the frequency of thermal disturbance from once every two days to five times/day, we see increases in the viability and longevity of co-occurrence between P_i and P_j, suggesting that environmental variation may be the key to bats' ability to harbour such large communnities of parasites. Additionally, we see, as before, that our thermal arrangement wherein the secondary parasite, P_j, has the thermal advantage over the primary parasite, P_i, produces the longest periods of co-occurrence.

Discussion

Conceptual

While we are beginning to understand the mechanisms that drive spillover events and disease emergence at the between-host level, we have yet to thoroughly investigate the mechanisms that promote parasite diversity and allow parasites to circulate within hosts, creating kindling for the spillover events we observe at the between-host level (Daszak et al. 2000; Daszak et al. 2001; Patz et al. 2004; Plowright et al. 2017; Plowright et al. 2020). Given the predictions of the intermediate disturbance hypothesis, the fact that our climate is becoming more variable, and the additional fact that internal temperature variability is physiological trait unique to a noted reservoir for disease, we set out to investigate the relationship between environmental variability and parasite diversity within-hosts (Vasseur et al. 2014; Calisher et al. 2006; Brook and Dobson 2015; Irving et al. 2021).

In summary, we found that on average, environmental variability can increase the ability of a secondary parasite to invade a single-parasite system, and can promote longer periods of co-occurrence between the primary and secondary parasites within the host. In our low average temperature environment, meant to represent the thermal conditions within ectotherms subject to rising environmental variability, we found that larger changes in thermal conditions increased the viability and longevity of parasite co-occurrence, suggesting that as our climate continues to change, we should pay special attention to ectotherms' propensities to support large communities of microparasites. Moving forward, we hope to develop a more detailed characterization of the relationship between the magnitude of thermal change and parasite co-occurrence. In our high average temperature environment, meant to represent the thermal conditions within bats, whose internal temperatures vary rapidly throughout the day, we found that frequent environmental variations increased the viability and longevity of parasite co-occurrence to a greater degree than did less frequent disturbances. These results suggest that, while it has been theorized that variations in internal temperatures may aid in bats' immune responses, these variations may also allow bats to support uniquely large communities of parasites (Fumagalli et al. 2021; Luo et al. 2021). Further, these results, combined with the frequency with which bats are implicated in zoonotic spillover events suggest that the effects of environmental variability on parasite diversity may scale to the between-host level to have effects on disease emergence. While the impacts of climate change on parasite diversity, and of parasite diversity on global health level remain disputed, these results should give us pause and reason to investigate further (Carlson et al. 2013; Carlson et al. 2017; Cizauskas et al. 2017).

For This Project

There's so much more I would have wanted to do for this project. For example, optimally, I would have wanted to simulate my models and process my resulting time series data to generate my co-occurrece data in Python. However, I wrote my model simulation scripts and my co-occurrence scripts in R, and ran them on a remote server, as they were too computationally intensive to run on my laptop. I've included an examples of how I simulated my deterministic model and got my co-occurrence data from my time series data in my "Methods" section.

I realise that my largest problem, regardless of language, is writing efficient scripts. The best examples of inefficient code I wrote for this project would be my data importing cell, and my data wrangling cells. I realise that I could have made these steps more efficient by naming my data files more carefully, so I could import them using a for loop. I don't know how, specificially, I could have made my data wrangling cells more efficient; I found myself spending a lot of time looking up how to do pretty basic things, so didn't have the time to streamline my process. In general, I find that writing efficient code comes with experience, so hopefully that will come.

References

- Antia, R., Levin, B. R., & May, R. M. (1994). Within-host population dynamics and the evolution and maintenance of microparasite virulence. The American Naturalist, 144(3), 457-472.
- Brook, C. E., & Dobson, A. P. (2015). Bats as 'special'reservoirs for emerging zoonotic pathogens. Trends in microbiology, 23(3), 172-180.
- Brulliard, K. (2020, April 3). "The next pandemic is already coming, unless humans change how we interact with wildlife, scientists say" The Washington Post. https://www.washingtonpost.com/science/2020/04/03/coronavirus-wildlife-environment/.
- Calisher, C. H., Childs, J. E., Field, H. E., Holmes, K. V., & Schountz, T. (2006). Bats: important reservoir hosts of emerging viruses. Clinical microbiology reviews, 19(3), 531-545.
- Carlson, C. J., Burgio, K. R., Dougherty, E. R., Phillips, A. J., Bueno, V. M., Clements, C. F., ... & Getz, W. M. (2017). Parasite biodiversity faces extinction and redistribution in a changing climate. Science advances, 3(9), e1602422.
- Carlson, C. J., Cizauskas, C. A., Burgio, K. R., Clements, C. F., & Harris, N. C. (2013). The more parasites, the better?. Science, 342(6162), 1041-1041.
- Cizauskas, C. A., Carlson, C. J., Burgio, K. R., Clements, C. F., Dougherty, E. R., Harris, N. C., & Phillips, A. J. (2017). Parasite vulnerability to climate change: an evidence-

based functional trait approach. Royal Society open science, 4(1), 160535.

- Connell, J. H. (1978). Diversity in tropical rain forests and coral reefs. Science, 199(4335), 1302-1310.
- Daszak, P., Cunningham, A. A., & Hyatt, A. D. (2000). Emerging infectious diseases of wildlife--threats to biodiversity and human health. Science, 287(5452), 443-449.
- Daszak, P., Cunningham, A. A., & Hyatt, A. D. (2001). Anthropogenic environmental change and the emergence of infectious diseases in wildlife. Acta tropica, 78(2), 103-116.
- Dobson, A., & Carper, R. (1992). Global warming and potential changes in host-parasite and disease-vector relationships.
- Fumagalli, M. R., Zapperi, S., & La Porta, C. A. (2021). Role of body temperature variations in bat immune response to viral infections. Journal of the Royal Society Interface, 18(180), 20210211.
- Irving, A. T., Ahn, M., Goh, G., Anderson, D. E., & Wang, L. F. (2021). Lessons from the host defences of bats, a unique viral reservoir. Nature, 589(7842), 363-370.
- Jones, K. E., Patel, N. G., Levy, M. A., Storeygard, A., Balk, D., Gittleman, J. L., & Daszak, P. (2008). Global trends in emerging infectious diseases. Nature, 451(7181), 990-993.
- Lafferty, K. D. (2009). The ecology of climate change and infectious diseases. Ecology, 90(4), 888-900.
- Luo, J., Greif, S., Ye, H., Bumrungsri, S., Eitan, O., & Yovel, Y. (2021). Flight rapidly modulates body temperature in freely behaving bats. Animal Biotelemetry, 9(1), 1-10.
- Melbourne, B. A., & Hastings, A. (2008). Extinction risk depends strongly on factors contributing to stochasticity. Nature, 454(7200), 100-103.
- Patz, J. A., Daszak, P., Tabor, G. M., Aguirre, A. A., Pearl, M., Epstein, J., ... & Working Group on Land Use Change Disease Emergence. (2004). Unhealthy landscapes: policy recommendations on land use change and infectious disease emergence. Environmental health perspectives, 112(10), 1092-1098.
- Plowright, R. K., Parrish, C. R., McCallum, H., Hudson, P. J., Ko, A. I., Graham, A. L., & Lloyd-Smith, J. O. (2017). Pathways to zoonotic spillover. Nature Reviews Microbiology, 15(8), 502-510.
- Plowright, R., Reaser, J., Locke, H., Woodley, S. J., Patz, J. A., Becker, D., ... & Tabor, G. M. (2020). A call to action: Understanding land use-induced zoonotic spillover to protect environmental, animal, and human health.
- Schoolfield, R. M., Sharpe, P. J. H., & Magnuson, C. E. (1981). Non-linear regression of biological temperature-dependent rate models based on absolute reaction-rate theory. Journal of theoretical biology, 88(4), 719-731.
- Vasseur, D. A., DeLong, J. P., Gilbert, B., Greig, H. S., Harley, C. D., McCann, K. S., ... &

O'Connor, M. I. (2014). Increased temperature variation poses a greater risk to species than climate warming. Proceedings of the Royal Society B: Biological Sciences, 281(1779), 20132612.