Within-host bacterial growth dynamics with both mutation and horizontal gene transfer

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Abstract
The evolution and emergence of antibiotic resistance is a major public health concern. The understanding of the within-host microbial dynamics combining mutational processes, horizontal gene transfer and resource consumption, is one of the keys to solving this problem. We analyze a generic model to rigorously describe interactions dynamics of four bacterial strains: one fully sensitive to the drug, one with mutational resistance only, one with plasmidic resistance only, and one with both resistances. By defining thresholds numbers (i.e. each strain’s effective reproduction and each strain’s transition threshold numbers), we first express conditions for the existence of non-trivial stationary states. We find that these thresholds mainly depend on bacteria quantitative traits such as nutrient consumption ability, growth conversion factor, death rate, mutation (forward or reverse), and segregational loss of plasmid probabilities (for plasmid-bearing strains). Next, concerning the order in the set of strain’s effective reproduction thresholds numbers, we show that the qualitative dynamics of the model range from the extinction of all strains, coexistence of sensitive and mutational resistance strains, to the coexistence of all strains at equilibrium. Finally, we go through some applications of our general analysis depending on whether bacteria strains interact without or with drug action (either cytostatic or cytotoxic).

Keywords Antibiotic resistance · Mathematical modelling · Non-linear dynamical system

Mathematics Subject Classification 37N25 · 34C1 · 34C23 · 92D30
1 Introduction

Antibiotic, or antibacterial, resistance (ABR) is a major public health concern worldwide. In the USA, for instance, it has been estimated that each year, two million people suffer infections from antibiotic-resistant bacteria, 35,000 of which lead to death (CDC 2019). As any trait under natural selection, antibiotic resistance requires that some individual bacteria differ from the sensitive (‘wild type’) genotype. In short, these individuals can emerge due to mutations, which here encompass any genetic change in the bacterial chromosome that lead to resistance, but also through horizontal gene transfer (HGT). Three main mechanisms of HGT have been described with conjugation being the most common among bacteria (Thomas and Nielsen 2005). Indeed, through conjugation Thomas and Nielsen (2005), many bacterial species can transmit plasmids which are self-replicating DNA often encoding drug resistance genes (Philippon et al. 2002; Yates et al. 2006; Martinez 2008; Moellering 2010; Bush and Fisher 2011; Carattoli et al. 2012). The origin of antibiotic resistance, through mutation or HGT is important from epidemiological and evolutionary standpoints. Combination of modern techniques such as whole-genome sequencing and phylogenetic reconstruction have for example revealed the evolutionary history of a \textit{Staphylococcus aureus} lineage that spread in the UK during the 1990s. It turns out that this lineage had acquired resistance both to meticillin and ciprofloxacin – which belong to two distinct antibiotic classes recently introduced into clinical practice – respectively through HGT and point mutation (Charlton et al. 2014).

Several models have been developed to study the evolution of resistance by one or the other mechanism (Blanquart 2019; San Millan et al. 2014; Levin et al. 1979; Handel et al. 2009; Gjini and Brito 2016; Svara and Rankin 2011; Tazzyman and Bonhoeffer 2014; zur Wiesch et al. 2011). We also think that the literature with only one of the processes (i.e. only HGT or only mutation) is so vast that we would not know where to begin since the model used then strongly depends on the question asked. However, few consider the two processes, for instance, Tazzyman and Bonhoeffer studied the difference between chromosomal and plasmid mutation in an emergence context, where stochasticity is strong (Tazzyman and Bonhoeffer 2014). Svara and Rankin (2011) also develop such a setting to study the selective pressures that favour plasmid-carried antibiotic resistance genes. They use mathematical models to analyse plasmid dynamics in response to different antibiotic treatment regimes. Here, we adopt a more formal approach than Svara and Rankin (2011) to investigate the properties of the dynamical system describing interactions between bacteria strains. More precisely, we describe qualitatively within-host interactions dynamics, while taking into account the main quantitative traits of the bacteria life-cycle introduced below.

In this work, we use a system of ordinary differential equations (ODE) to model the interaction dynamics between four bacterial strains that are fully sensitive to the drug ($N_s$), with mutational (or ‘genomic’) resistance only ($N_m$), with plasmidic resistance only ($N_p$), and with both forms of resistances ($N_{m,p}$). Here, $N_j$ refers to the population size of strain $j$ and we denote as $\mathcal{J} = \{s, m, p, m,p\}$ the set of bacteria strains. Each $N_j$-strain is then characterized by a strain-specific nutrient consumption ability, growth conversion factor, death rate and mutation (forward or reverse) probability. Additionally, $N_p$ and $N_{m,p}$-strains can transmit plasmids through HGT and an
offspring from plasmid-bearing strain can be plasmid-free with some probability, a biological process known as segregation.

This article is organized as follows. In Sect. 2 we describe the original model developed in this work. Section 3 is devoted to some general remarks about model properties and threshold asymptotic dynamics. Section 4 investigates the existence of nontrivial stationary states of the model as well as their stability. In particular, we show that the dynamical behavior of the system is not trivial and can range from the extinction of all strains to the coexistence of two or all of them. Section 5 describes how our general analysis can be applied in two situations: (i) bacteria strains interacting without any drug pressure, and (ii) bacteria strains interacting with drug action. Finally, in Sect. 6, we discuss some scenarios that can be captured by the model, as well as the biological implications of model assumptions and limitations.

## 2 The model description

We formulate a general within-host model for interactions between four bacteria strains that are (i) fully sensitive to the drug $N_s$, (ii) with mutational (or ‘genomic’) resistance only $N_m$, (iii) with plasmidic resistance only $N_p$ and (iv) with both resistances $N_{m,p}$. Figure 1 summarizes interactions between the four populations of bacteria strains. We assume that the dynamics of the total bacteria population in the host $N = N_s + N_p + N_m + N_{m,p}$ reads

$$
\dot{N}(t) = \sum_{j \in J} \left( \mu_j B(t) - d_j \right) N_j(t),
$$

where $B(t)$ denotes the concentration of nutrients available at time $t$ for all stains. Parameter $\mu_j$ mimics the capacity of a given $N_j$-strain to take advantage from the resource, while $d_j$ is its death rate.

In the literature, the occurrence of new mutants depends either on (i) the abundance of the parental cells or (ii) both the abundance and growth rate of the parental cells (Loewe et al. 2003; Sniegowski 2004; zur Wiesch et al. 2010). We first assume the latter (the model under assumption (i) will be discussed later). Therefore, the dynamics of interactions between bacteria strains is given by

$$
\begin{align*}
\dot{B}(t) &= \Lambda - dB - B \sum_{j \in J} \beta_j N_j, \\
\dot{N}_s(t) &= \tau_s \beta_s (1 - \varepsilon_s) BN_s - d_s N_s + \varepsilon_m \tau_m \beta_m BN_m + \theta \tau_p \beta_p BN_p - H(N) N_s [N_p + N_{m,p}], \\
\dot{N}_m(t) &= \tau_m \beta_m (1 - \varepsilon_m) BN_m - d_m N_m + \varepsilon_s \tau_s \beta_s BN_s + \theta \tau_{m,p} \beta_{m,p} BN_{m,p} - H(N) N_m [N_{m,p} + N_p], \\
\dot{N}_p(t) &= \tau_p \beta_p (1 - \theta)(1 - \varepsilon_p) BN_p - d_p N_p + \varepsilon_{m,p} (1 - \theta) \beta_{m,p} \tau_{m,p} BN_{m,p} + H(N) N_p [N_{m,p} + N_p], \\
\dot{N}_{m,p}(t) &= \tau_{m,p} \beta_{m,p} (1 - \theta)(1 - \varepsilon_{m,p}) BN_{m,p} - d_{m,p} N_{m,p} + \varepsilon_p (1 - \theta) \tau_p \beta_p BN_p + H(N) N_{m,p} [N_{m,p} + N_p].
\end{align*}
$$

(2.2)
Fig. 1 Flow diagram illustrating the interactions between four bacterial populations. Strain can be drug-sensitive (\(N_s\), in green), mutation-acquired resistant (\(N_m\), in blue), horizontally-acquired resistant (\(N_p\), in red), and doubly resistant (\(N_{mp}\), in purple). These grow on a limiting nutrient concentration (\(B\), in yellow). The nutrient is renewed by a constant inflow \(\Lambda\) and depleted independently from the focal bacteria at a rate \(d\). Bacterial strain \(v \in \{s; m; p; m, p\}\) consumes the nutrient at rate \(\beta_v\), and converts into growth rate through coefficient \(\tau_v\). Strains \(N_s\) and \(N_p\) mutate at rates \(\varepsilon_s\) and \(\varepsilon_p\) respectively, while reverse mutation occur to strains \(N_m\) and \(N_{mp}\) at rates \(\varepsilon_m\) and \(\varepsilon_{mp}\) respectively (dashed lines). Segregational loss of plasmid occurs during cell growth at rate \(\theta\) for strains bearing a plasmid \(N_p\) and \(N_{mp}\) (dotted-dashed lines). Horizontal gene transfers occur from the existing plasmid bearing population at rate \(H(N)\), where \(H(\cdot)\) is the Beddington-DeAngelis functional response defined by \(H(N) = \frac{\alpha}{a_H+N+b_H}\), and wherein \(\alpha\) is the flux rate of HGT (dotted lines). This function covers different mechanisms for HGT: (i) density-dependent, i.e. HGT rate is proportional to the density of the donor; \(a_H = 0; b_H = 1\), (ii) frequency-dependent, i.e. HGT rate is proportional to the frequency of the donor; \(a_H = 0; b_H = 1\) or (iii) a mixed between density- and frequency-dependent; \(a_H > 0; b_H > 0\) (colour figure online)

coupled with initial condition \(N_j(0) \geq 0\) for all \(j \in J\) and \(B(0) \geq 0\).

More precisely, parameters of System (2.2) are summarized in Table 1 and are defined such that:

- Nutrients are produced at a constant rate \(\Lambda\) and washed out at rate \(d\). \(\beta_j\) is the yield constant representing the amount of nutrients taken by the specific \(N_j\)-strain. Then, the \(N_j\)-strain takes advantage from nutrient at rate \(\mu_j = \beta_j \tau_j\); wherein \(\tau_j\) is the conversion rate (how much growth is obtained from a unit of nutrient).
- Upon cell replication, sensitive (\(N_s\)) and resistant with plasmid (\(N_p\)) strains acquire mutations with probabilities \(\varepsilon_s\) and \(\varepsilon_p\) respectively. Reverse mutation from mutational resistant strain (\(N_m\)) and mutational with plasmid (\(N_{mp}\)) also occur upon replication with probabilities \(\varepsilon_m\) and \(\varepsilon_{mp}\) respectively. Note that the mutations considered here are ‘phenotypic mutations’ and that we only allow for two types of mutations that lead to the acquisition or the loss of the drug-resistant phenotype.
- The segregational loss of plasmid occurs during cell growth with probability \(\theta\) for the resistant strain with plasmid (\(N_p\)) and mutational with plasmid (\(N_{mp}\)). Here, we assume that the segregational loss of plasmid is the same for all strains bearing a plasmid (\(N_p\) or \(N_{mp}\)).
We assume that plasmids are acquired from the existing donor population \((N_p + N_{m,p})\) and that conjugation follows a mass action law; i.e. a plasmid is acquired from the existing resistant population at rate \(H(N)[N_{m,p} + N_p]\), where \(H(\cdot)\) is the Beddington-DeAngelis functional response defined by \(H(N) = \frac{\alpha}{a_H + b_H N}\), with \(\alpha\) the flux rate of HGT. This function can capture different mechanisms for HGT: (i) density-dependent, i.e. HGT rate is proportional to the density of the donor; \(b_H = 0; a_H = 1\), (ii) frequency-dependent, i.e. HGT rate is proportional to the frequency of the donor; \(a_H = 0; b_H = 1\) or (iii) a mixed between density- and frequency-dependent; \(a_H > 0; b_H > 0\). Throughout this work, we assume that the flux rate \(\alpha > 0\) for HGT is a small parameter (Levin et al. 1979; Dionisio et al. 2002; Gordon 1992). Finally, note that the focal trait of the model is the antibiotic resistance level (the change of which leads to a compartmental change). The mechanisms involved in antibiotic resistance (e.g. producing an enzyme that denaturates the antibiotic molecules) are not the same as the ones involved in HGT. Therefore, it is more parsimonious to assume that the mutations tracked here do not quantitatively impact the HGT.

System (2.2) will be considered under the following natural assumption

\[
\Lambda > 0, d > 0, d_j > 0, \beta_j \geq 0, \tau_j \geq 0 \quad \text{and} \quad \epsilon_j; \theta \in [0, 1].
\]

It is useful to write System (2.2) into a more compact form. To that end, we identify the vector \((N_s, N_m)^T\) together with \(u\) and \((N_p, N_{m,p})^T\) together with \(v\). Here \(x^T\) is set for the transpose of a vector or matrix \(x\). Then, System (2.2) can be rewritten as

\[
\begin{align*}
\dot{B}(t) &= \Lambda - B \left( d + \langle \beta, (u, v)^T \rangle \right), \\
\dot{u} &= [BG - D - h(u, v)]u + BL_p v, \\
\dot{v} &= \left[ B(G_p - L_p) - D_p \right] v + h(u,v) u,
\end{align*}
\]

wherein we have formally set \(\beta = (\beta_s, \beta_m, \beta_p, \beta_{m,p})^T\), \(h(u, v) = H(N) \langle 1, v \rangle\) and the matrices \(G, G_p, D, D_p \) and \(L_p\) are defined as follows

\[
G = \begin{bmatrix}
\tau_s \beta_s (1 - \epsilon_s) & \epsilon_m \tau_m \beta_m \\
\epsilon_s \tau_s \beta_s & \tau_m \beta_m (1 - \epsilon_m)
\end{bmatrix},
\]

\[
G_p = \begin{bmatrix}
\tau_p \beta_p (1 - \epsilon_p (1 - \theta)) & \epsilon_{m,p} (1 - \theta) \tau_{m,p} \beta_{m,p} \\
\epsilon_p (1 - \theta) \tau_p \beta_p & \tau_{m,p} \beta_{m,p} (1 - \epsilon_{m,p} (1 - \theta))
\end{bmatrix},
\]

\[
D = \text{diag}(d_s, d_m), \quad D_p = \text{diag}(d_p, d_{m,p}), \quad L_p = \theta \text{ diag}(\tau_p \beta_p, \tau_{m,p} \beta_{m,p}),
\]

wherein \(\text{diag}(w)\) is a diagonal matrix the diagonal elements of which are given by \(w\); and \(\langle x, y \rangle\) is set for the usual scalar product of vectors \(x\) and \(y\). The compact form (2.3) is then viewed as the interaction dynamics of two groups of bacteria: one with plasmids \(v = (N_p, N_{m,p})^T\) and one without it \(u = (N_s, N_m)^T\).
### Table 1  Model state variables and parameters

| Variables   | Description                                                                 |
|-------------|-----------------------------------------------------------------------------|
| $B(t)$      | Density of nutrients at time $t$                                            |
| $N_s(t)$    | Density of sensitive strain at time $t$                                     |
| $N_m(t)$    | Density of resistant strain at time $t$ through mutational changes          |
| $N_p(t)$    | Density of resistant strain at time $t$ through Horizontal Gene Transfer (HGT) |
| $N_{m,p}(t)$| Density of resistant strain at time $t$ through mutational changes and HGT   |
| $N(t)$      | Total density of bacteria at time $t$: $N = N_s + N_p + N_m + N_{m,p}$      |

| Parameters   | Description (unit)                                                                 | Value/range [ref.] |
|--------------|----------------------------------------------------------------------------------|--------------------|
| $\beta_j$   | Nutrient consumption by strain $v$ bacteria (mL/cell/day)                        | $10^{-6}$ (Colijn and Cohen 2015) |
| $\tau_j$    | Strain $v$ growth conversion factor (cell/µg)                                   | $10^6$ (Colijn and Cohen 2015) |
| $d_j$        | Strain $v$ washout and death rate (1/day)                                       | 5 (Ankomah and Levin 2014) |
| $d$          | Nutrient washout rate (µg/mL/day)                                               | 5 (Ankomah and Levin 2014) |
| $\Lambda$   | Nutrient renewal rate (µg/mL/day)                                               | 2500 (Ankomah and Levin 2014) |
| $\theta$    | Proportion of segregational plasmid loss for $p$ and $m, p$-strains (dimensionless) | [0,0.25] (Bahl et al. 2004) |
| $\varepsilon_j$ | Resistance-related mutation proportion (dimensionless)                           | $10^{-8}$ (Ankomah and Levin 2014) |
| $\alpha$    | Flux rate of HGT (1/day)                                                         | $10^{-13}$ (Lopatkin et al. 2016) |
| $a_H, b_H$  | Parameters of the function $H$ (dimensionless)                                  | Variable |

*a*Measurements of mutation rate and HGT depend on the specifics of the system under consideration. Estimates quoting here are only for simulations purpose and are not particularly important.

### 3 General remarks, bacteria invasion process and threshold dynamics

In this section, we establish some useful properties of solutions of (2.2) that include the existence of a positive global in time solution of the system and the threshold asymptotic dynamics of the model.

#### 3.1 General remarks

First, in a bacteria-free environment, the nutrient dynamics is such that

$$\dot{B} = \Lambda - dB.$$  \hspace{1cm} (3.1)

Consequently, $B_0 = \frac{\Lambda}{d}$ is the unique positive solution of System (3.1), which can straightforwardly be shown to be globally attractive in $\mathbb{R}_+$; i.e. $B(t) \to B_0$ as $t \to \infty$.

Since System (2.2) is designed to model a biological process, its solutions should remain positive and bounded. The positivity and boundedness of solutions of System (2.2) is provided by the following result (see “Appendix A” for the proof).
Theorem 3.1 There exists a unique continuous solution \( \{ E(t) : \mathbb{R}_+^5 \rightarrow \mathbb{R}_+^5 \}_{t \geq 0} \) to (2.2) such that for any \( \omega_0 \in \mathbb{R}_+^5 \), the orbit of (2.2) passing through \( \omega_0 \) at time \( t = 0 \) \( E(\cdot)\omega_0 : [0, \infty) \rightarrow \mathbb{R}_+^5 \) defined by \( E(t)\omega_0 = (B(t), N_s(t), N_m(t), N_p(t), N_{m,p}(t)) \) with \( E(0)\omega_0 = \omega_0 \) verified

\[
\tau_{\text{max}} B(t) + \sum_{j \in J} N_j(t) \leq \frac{\Lambda \tau_{\text{max}}}{\min(d, d_{\text{min}})},
\]

wherein \( J = \{ s, m, p, m.p \} \); \( \tau_{\text{max}} = \max_{j \in J} \tau_j \) and \( d_{\text{min}} = \min_{j \in J} d_j \).

Recalling that \( u = (N_s, N_m)^T \), \( v = (N_p, N_{m,p})^T \) and setting \( K = \frac{\Lambda \tau_{\text{max}}}{\min(d, d_{\text{min}})} \), we define

\[
\Omega = \left\{ (B, N_s, N_m, N_p, N_{m,p}) \in \mathbb{R}_+^5 \middle| \tau_{\text{max}} B + \sum_{j \in J} N_j \leq K \right\},
\]

\[
X_0 = \left\{ (B, N_s, N_m, N_p, N_{m,p}) \in \Omega : \sum_{j \in J} N_j > 0 \right\}, \quad \text{and} \quad \partial X_0 = \Omega \setminus X_0.
\]

Then the following lemma holds true

Lemma 3.2 Let \( w_0 \) be a given initial data of System (2.2) and set \( E(\cdot)w_0 \) the orbit passing through \( \omega_0 \) at \( t = 0 \). The subsets \( X_0 \) and \( \partial X_0 \) are both positively invariant under the map \( \{ E(t)w_0 : [0, \infty) \rightarrow \mathbb{R}_+^5 \}_{t \geq 0} \); in other words every solution of system (2.2) with initial value in \( X_0 \) (respectively in \( \partial X_0 \)) stays in \( X_0 \) (respectively in \( \partial X_0 \)).

Proof The proof of Lemma 3.2 is straightforward. Indeed, let us first recall that \( B(t) \leq B_0 \) for all time \( t \). Next, the positivity of the map \( E(t)w_0 \) provided by Theorem 3.1 together with Eq. (2.1) give

\[-d_{\text{max}} N(t) \leq \dot{N}(t) \leq B_0 \tau_{\text{max}} \beta_{\text{max}} N(t), \quad \text{for all time} \ t.\]

From where \( N(0) \exp(-d_{\text{max}}t) \leq N(t) \leq N(0) \exp(B_0 \tau_{\text{max}} \beta_{\text{max}} t) \), and the result follows. \( \square \)

3.2 Bacteria invasion process and threshold dynamics

Trivially, the bacteria-free stationary state is given by \( E^0 = (B_0, 0, 0, 0, 0) \). Recall that each \( N_j \)-strain is basically characterized by a specific nutrient consumption ability \( \beta_j \), growth conversion factor \( \tau_j \), death rate \( d_j \), and mutation (forward or reverse) probability \( \varepsilon_j \). Additionally, \( N_p \) and \( N_{m,p} \) can transmit plasmids through HGT and there is generally some probability \( \theta \) that any offspring from plasmid bearing strain will be plasmid-free. The qualitative dynamics of our model is strongly related to the
following threshold numbers

\[ T_j = B_0 \frac{\tau_j \beta_j}{d_j}; \quad \text{for } j \in J, \tag{3.3} \]

and

\[ R_s = T_s(1 - \varepsilon_s), \quad R_m = T_m(1 - \varepsilon_m), \]
\[ R_p = T_p(1 - \varepsilon_p)(1 - \theta), \quad R_{m,p} = T_{m,p}(1 - \theta)(1 - \varepsilon_{m,p}). \tag{3.4} \]

wherein the positive constant \( B_0 \) is the bacteria-free stationary state. A threshold \( T_j \) will be referred to below as the growth threshold of the \( N_j \)-strain in a bacteria-free environment. Indeed, the net growth rate of the \( N_j \)-strain can be written as

\[ B_0 \tau_j \beta_j - d_j \left( T_j - 1 \right). \]

Therefore, the quantity \( (T_j - 1) \) can be seen as the net growth threshold. Regarding the \( R_j \), since they capture not only the growth but also the genetic component of the dynamics, we call them effective reproduction numbers.

The main biological interpretation here is that the \( T_j \)s describe the ecological conditions of invasion while the \( R_j \)s describe both the ecological and micro-evolutionary (or, shortly ‘eco-evolutionary’) conditions of strain persistence, that is their effective genetic contribution to each next generation.

In addition to the \( T_j \)’s and \( R_j \)’s, transitions between strain state variables, imposed by mutations and plasmids segregation, are of great importance for the dynamical behaviour of the model considered here. Therefore, we similarly introduce parameters (referred to as strain transition numbers)

\[ K_{s\rightarrow m} = B_0 \frac{\varepsilon_s \tau_s \beta_s}{d_m}, \quad K_{m\rightarrow s} = B_0 \frac{\varepsilon_m \tau_m \beta_m}{d_s}, \]
\[ K_{p\rightarrow m,p} = B_0 \frac{\varepsilon_p (1 - \theta) \tau_p \beta_p}{d_{m,p}}, \quad K_{m,p\rightarrow p} = B_0 \frac{\varepsilon_{m,p} (1 - \theta) \tau_{m,p} \beta_{m,p}}{d_p} \]
\[ K_{p\rightarrow s} = B_0 \frac{\theta \tau_p \beta_p}{d_s}, \quad K_{m,p\rightarrow m} = B_0 \frac{\theta \tau_{m,p} \beta_{m,p}}{d_m}. \tag{3.5} \]

From the above notations, we can express the threshold criterion for bacteria invasion as follows:

**Theorem 3.3** Assume that mutation rates \( \varepsilon_j \) are sufficiently small. Let \( E(t)w_0 = (B(t), N_s(t), N_m(t), N_p(t), N_{m,p}(t)) \) be the orbit of (2.2) passing through \( \omega_0 \) at time \( t = 0 \). Let us set

\[ T^* = \max_{j \in J} \{ T_j \} \quad \text{and} \quad R^* = \max_{j \in J} \{ R_j \}, \tag{3.6} \]

where thresholds \( T_j \)’s and \( R_j \)’s are defined by (3.3) and (3.4). Then,

(i) The bacteria-free stationary state \( E^0 \) for System (2.2) is locally asymptotically stable if \( R^* < 1 \) and unstable if \( R^* > 1 \).

(ii) The bacteria-free stationary state \( E^0 \) for System (2.2) is globally asymptotically stable if \( T^* < 1 \).
(iii) If \( \min_{j \in J} T^*_j > 1 \), then System (2.2) is uniformly persistent with respect to the pair 
\((X_0, \partial X_0)\), in the sense that there exists \( \delta > 0 \), such that for any \( w_0 \in X_0 \) we have,

\[
\liminf_{t \to \infty} \Delta(E(t)w_0, \partial X_0) \geq \delta.
\]

Here, \( \Delta(\cdot, \cdot) \) is set for the semi-distance defined by \( \Delta(\mathcal{X}, \mathcal{Y}) = \sup_{x \in \mathcal{X}} \inf_{y \in \mathcal{Y}} \| x - y \| \).

Item (ii) of Theorem 3.3 states that bacteria die out when \( T^* < 1 \) and can potentially 
persist with the nutrient if \( T^* > 1 \). Moreover, we always have \( R^* \leq T^* \) and the 
difference \( T^* - R^* \) is of order \( \max(\varepsilon_s, \varepsilon_m, \theta + \varepsilon_p, \theta + \varepsilon_{m,p}) \). Therefore, for sufficiently 
small mutations probabilities (\( \varepsilon_j \)’s) and plasmid loss (\( \theta \)), we have \( \text{sign}(R^* - 1) = \text{sign}(T^* - 1) \). The proof of Theorem 3.3 is given in “Appendix B”.

4 Nontrivial stationary states of model (2.2) and stability results

We have proven that the trivial stationary state \( E^0 \) is always a solution of System (2.2). 
However, we will show that under some conditions, the model can also have nontrivial 
stationary solutions.

Next, to go further in our analysis, we will assume that mutation probabilities, 
\( \varepsilon_j \)’s, and flux rate of HGT, \( \alpha \), are small parameters. For simplicity and without loss 
of generality, we express/standardize parameters \( \varepsilon_j \) and \( \alpha \) as functions of the same 
quantity, let us say \( \eta \), with \( \eta \ll 1 \) a small parameter. This parameter \( \eta \) can be seen as the 
overall contribution of genetic processes to the ecological dynamics. With this notation, 
threshold \( R_j \)’s (3.4) and strain transition numbers \( K_j \)’s (3.5) are of order \( O(\eta^2) \), so 
that all our analysis is of order \( O(\eta^2) \). Importantly, this assumption on small mutation 
probabilities should not be confused with an analysis based on an asymptotically 
smallness point of view (i.e., \( \varepsilon_j \to 0 \) and \( \alpha \to 0 \)). From a biological standpoint, even 
if parameters \( \varepsilon_j \) and \( \alpha \) can reasonably assumed to be small, their order of magnitude 
are quite variable and certainly depends on the species under consideration. However, 
the results presented here are not sensitive to this. Indeed, if for example we have, 
\( \varepsilon_j = 10^{-5} \) and \( \alpha = 10^{-8} \), then our analysis is of order \( O \left( (10^{-5})^2 \right) \). On the contrary, 
if we have \( \varepsilon_j = 10^{-8} \) and \( \alpha = 10^{-5} \), the order of analysis remains \( O \left( 10^{-10} \right) \). Finally, 
note that for our analysis, \( \theta \) is not assumed small, even if from a mathematical point 
of view, it has a role similar to the mutation rates \( \varepsilon_j \)’s.

4.1 Stationary states of the general model (2.2)

Model (2.2) has three possible stationary states. The extinction of all strains \( E^0 \), the 
co-existence of \( N_s \) and \( N_m \) strains \( (E^*_{s-m}) \) and the co-existence of all strains \( (E^*) \).
Let \( r(M) \) be the spectral radius of a given matrix \( M \). Then, the precise result reads as follows
Theorem 4.1  
(i) If $B_0 r \left( D_1^{-1} G \right) > 1$, then the co-existence stationary state of $N_s$ and $N_m$ strains is $E_{s-m}^* = (B^*, N_s^*, N_m^*, 0, 0)$ with

$$\frac{1}{B^*} = r \left( D_1^{-1} G \right) = \frac{1}{2B_0} \left\{ \mathcal{R}_s + \mathcal{R}_m + \left[ (\mathcal{R}_s - \mathcal{R}_m)^2 + 4 \mathcal{K}_{m \to s} \mathcal{K}_{s \to m} \right]^{1/2} \right\},$$

$$\begin{align*}
(N_s^*, N_m^*) &= \frac{d \left( B_0 r \left( D_1^{-1} G \right) - 1 \right)}{\langle \beta_s, \beta_m, \phi_0 \rangle} \phi_0, \\
(N_s^*, N_m^*) &= \frac{d \left( B_0 r \left( D_1^{-1} G \right) - 1 \right)}{\langle \beta_s, \beta_m, \phi_0 \rangle} \phi_0,
\end{align*}$$

wherein $\phi_0 = \left( \mathcal{R}_s - \mathcal{R}_m + \left[ (\mathcal{R}_s - \mathcal{R}_m)^2 + 4 \mathcal{K}_{m \to s} \mathcal{K}_{s \to m} \right]^{1/2}, 2 \mathcal{K}_{s \to m} \right)^T$.

(ii) If $r \left( D_1^{-1} (G_p - L_p) \right) > r \left( D_1^{-1} G \right)$ and $B_0 r \left( D_1^{-1} (G_p - L_p) \right) > 1$, then for small flux rate of HGT $\alpha$, the coexistence of all strains $E^* = (B^*, N_s^*, N_m^*, N_p^*, N_{m-p}^*)$ exists and is such that

$$\begin{align*}
(N_s^*, N_m^*) &= u^0_\alpha + \alpha u^1_\alpha + O(\alpha^2), \\
(N_p^*, N_{m-p}^*) &= v^0_\alpha + \alpha v^1_\alpha + O(\alpha^2), \\
(B^*) &= b^0_\alpha + \alpha b^1_\alpha + O(\alpha^2),
\end{align*}$$

wherein

$$\begin{align*}
1/b^0_\alpha &= r(D_1^{-1} (G_p - L_p)), \\
v^0_\alpha &= \frac{d \left[ B_0/b^0_\alpha - 1 \right]}{\beta \left( -(D_1^{-1} G - 1/b^0_\alpha) \right) \left( D_1^{-1} L_p \phi_0, \phi_0 \right)} \phi_0, \\
u^0_\alpha &= -(D_1^{-1} G - 1/b^0_\alpha) \left( D_1^{-1} L_p v^0_\alpha, v^0_\alpha \right), \\
\phi_0 &= \left( \mathcal{R}_p - \mathcal{R}_{m,p} + \left[ (\mathcal{R}_p - \mathcal{R}_{m,p})^2 + 4 \mathcal{K}_{m \to p} \mathcal{K}_{p \to m} \right]^{1/2}, 2 \mathcal{K}_{p \to m} \right)^T,
\end{align*}$$

and $\mathbb{I}$ denotes the identity matrix of the convenient dimension.

We refer to “Appendix C” for the proof of Theorem 4.1 above.

4.2 Estimates for small mutation probabilities and flux rate of HGT

Let us denote by $E = (B, N_s, N_m, N_p, N_{m-p})$ the state variables of System (2.2). For a given solution $E$ of System (2.2), we denote by $\mathcal{P}(E) = (N_m + N_p + N_{m,p})/N$ the resistance frequency or proportion corresponding to this solution. Further, the proportion $\mathcal{P}(E)$ is decomposed in term of mutational resistance $(\mathcal{P}_m^* = N_m/N)$, plasmidic $(\mathcal{P}_p^* = N_p/N)$ and mutational/plasmidic $(\mathcal{P}_{m,p}^* = N_{m,p}/N)$ such that $\mathcal{P}(E) = \mathcal{P}_m^* + \mathcal{P}_p^* + \mathcal{P}_{m,p}^*$. Next, mostly based on Theorem 4.1 for small mutation probabilities $\varepsilon_j$, we derive simple approximations of resistance frequencies $\mathcal{P}(E_{s-m})$ and $\mathcal{P}(E^*)$ at stationary states $E_{s-m}^* = (B^*, N_s^*, N_m^*, 0, 0)$ and $E^* = (B^*, N_s^*, N_m^*, N_p^*, N_{m,p}^*)$. 

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As explained previously, parameters $\varepsilon_j$ and $\alpha$ are assumed of order $O(\eta)$, with $\eta \ll 1$, and all our analysis is of order $O(\eta^2)$.

Estimates of the proportion of resistance, $\mathcal{P}(E^*_{s-m})$, for small mutation probabilities. We consider two situations: $R_s > R_m$ and $R_s < R_m$, which correspond to situations where a mutation provides a fitness cost or a fitness benefit.

**First case $R_s > R_m$ i.e. $T_s > T_m$ (mutation providing a fitness cost).** We find,

$$
\mathcal{P}(E^*_{s-m}) = \mathcal{P}^*_m = \frac{d_s}{d_m} \frac{T_s}{T_s - T_m} \eta + O(\eta^2),
$$

with $R_s = T_s(1 - \varepsilon_s) > 1$, and $T_s > T_m$. (4.1)

**Second case $R_s < R_m$, i.e. $T_s < T_m$ (mutation providing a fitness benefit).** We find,

$$
\mathcal{P}(E^*_{s-m}) = \mathcal{P}^*_m = 1 - \frac{d_m (T_m - T_s)}{4 B_0 \tau_s \beta_s} \left( \frac{T_s + T_m}{T_s - T_m} - 1 \right) \eta + O(\eta^2),
$$

with $R_m = T_m(1 - \varepsilon_m) > 1$, and $T_m > T_s$. (4.2)

Estimates of $E^*$ for small mutation probabilities and flux rate of HGT. Here, we also have two situations: in one case the mutation somehow ‘compensates’ for the presence of the plasmid ($R_p < R_{m,p}$), whereas in the other mutation and plasmid costs add up ($R_p > R_{m,p}$).

**First case $R_p > R_{m,p}$, i.e. $T_p > T_{m,p}$ (mutation and plasmid cost add up).** The existence of the stationary state $E^*$ is ensured by

$$
R_p > \max(R_s, R_m) \quad \text{and} \quad R_p > 1.
$$

Here, the resistance proportion $\mathcal{P}(E^*)$ is decomposed in term of mutational resistance ($\mathcal{P}^*_m$), plasmidic ($\mathcal{P}^*_p$) and mutational/plasmidic ($\mathcal{P}^*_{m,p}$) such that

$$
\mathcal{P}(E^*) = \mathcal{P}^*_m + \mathcal{P}^*_p + \mathcal{P}^*_{m,p},
$$

wherein

$$
\begin{align*}
\mathcal{P}^*_m &= O(\eta), \\
\mathcal{P}^*_p &= \frac{1}{\left( 1 + \frac{B_0 \theta}{T_p (1-\theta) - T_s} \right) - \frac{B_0 \tau_p \beta_p}{d_s}} + O(\eta), \\
\mathcal{P}^*_{m,p} &= O(\eta),
\end{align*}
$$

with $R_p = T_p(1 - \theta - \varepsilon_p) > 1$, and $T_p(1 - \theta) > \max(T_s, T_m)$. (4.3)

**Second case: $R_p < R_{m,p}$, i.e. $T_p < T_{m,p}$ (mutation compensates for the presence of the plasmid).** Again, the existence of the stationary state $E^*$ is ensured by

$$
R_{m,p} > \max(R_s, R_m) \quad \text{and} \quad R_{m,p} > 1.
$$
Fig. 2 Summary of the qualitative analysis of the general model (2.2). The positive orthant is divided into four zones (A)–(D). In each of them, the feasible stationary states are shown – their notations are boxed if and only if they are locally asymptotically stable (l.a.s.). Note that in zone (D), $E_{s,m}^*$ is l.a.s. providing that (4.5) is satisfied.

Here we have,

$$\mathcal{P}(E^*) = \mathcal{P}_m^* + \mathcal{P}_p^* + \mathcal{P}_{m,p}^*,$$

wherein

$$\begin{align*}
\mathcal{P}_m^* &= \frac{\theta B_0^2 \tau_p \beta_p}{\theta B_0^2 \tau_p \beta_p + d_m \left[T_m.p(1-\theta) - T_m\right]} + O(\eta), \\
\mathcal{P}_p^* &= O(\eta), \\
\mathcal{P}_{m,p}^* &= \frac{d_m \left[T_m.p(1-\theta) - T_m\right]}{\theta B_0^2 \tau_p \beta_p + d_m \left[T_m.p(1-\theta) - T_m\right]} + O(\eta).
\end{align*}$$

(4.4)

4.3 Stability results of the general model (2.2)

Here, we check the local asymptotic stability of stationary states $E_{s,m}^*$ and $E^*$ by linearizing System (2.2) at those points. Stability results are summarised in Figs. 2 and 3 and given by the following theorem (see “Appendix C” for the proof).

**Theorem 4.2** Let mutation probabilities and flux rate of HGT be small enough.

(i) If $\max(\mathcal{R}_p, \mathcal{R}_{m,p}) > 1 > \max(\mathcal{R}_s, \mathcal{R}_m)$ then, Model (2.2) has two stationary states: $E^0$ (unstable) and $E^*$ (locally asymptotically stable -l.a.s. for short).

(ii) If $\max(\mathcal{R}_p, \mathcal{R}_{m,p}) > \max(\mathcal{R}_s, \mathcal{R}_m) > 1$ then, Model (2.2) has three stationary states: $E^0$ (unstable), $E_{s,m}^*$ (unstable) and $E^*$ (l.a.s.).

(iii) If $\max(\mathcal{R}_s, \mathcal{R}_m) > 1$ and $\max(\mathcal{R}_s, \mathcal{R}_m) > \max(\mathcal{R}_p, \mathcal{R}_{m,p})$ then, Model (2.2) has two stationary states: $E^0$ (unstable), $E_{s,m}^* = (B^*, N_s^*, N_m^*, 0, 0)$ which is...
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Fig. 3 Bacterial density chronicles, as decimal logarithm of cell number per mL through time in days, obtained through numerical integration of System (2.2): hierarchy diversity. Each plot (A)–(D) is representative of the asymptotic behavior of the system in the corresponding zone likewise labelled in Fig. 2. Shared parameters between plots are, \( \Lambda = 25, d = d_j = 5, \beta_j = 10^{-6}, \epsilon_j = 10^{-8}, \theta = 0.25, \alpha = 10^{-13}, a_H = 1, b_H = 0, \) with \( j \in J \) (see Table 1 for units). Initial conditions are \( (B, N_s, N_m, N_p, N_{m,p}) (0) = (5, 10, 1, 10, 1) \). With \( k := 10^{-6} \cdot (\tau_s, \tau_m, \tau_p, \tau_m, \tau_p) \), varying parameters are: \( A_k = (0.9, 0.9, 0.9, 0.9), B_k = (0.9, 0.9, 10, 10), C_k = (1.1, 1.1, 1.5, 1.5), D_k = (1.1, 1.1, 0.9, 0.9) \)

l.a.s. provided that the following condition is satisfied

\[
\begin{align*}
\frac{R_p}{\max (R_s, R_m)} + \frac{N^*_s}{d_p(a_H + b_H N^*)} &< 1, \\
\frac{R_{m,p}}{\max (R_s, R_m)} + \frac{N^*_s}{d_{m,p}(a_H + b_H N^*)} &< 1.
\end{align*}
\]

For technical reasons, it is difficult to conclude on the l.a.s. of the equilibrium \( E_{s-m}^* \) without condition (4.5). However, when \( \alpha \) is sufficiently small, this condition is generally satisfied as soon as \( \max (R_p, R_{m,p}) / \max (R_s, R_m) < 1 \). From a biological standpoint, this last inequality is satisfied when propagation via sensitive bacteria or via mutated bacteria is faster than via bacteria that already carry a plasmid.

Further, following Theorem 4.2, note that for plasmids to persist at equilibrium, it is necessary that \( \max (R_p, R_{m,p}) > \max (R_s, R_m) \). The threshold \( R^0_p = \frac{\max (R_p, R_{m,p})}{\max (R_s, R_m)} \) can therefore be viewed as the total number of plasmid-bearing strains arising from one strain bearing such a plasmid and introduced into a plasmid-free environment. \( R^0_p \) is similar to the basic reproduction number \( R_0 \) in epidemiology and serves as a
sharp threshold parameter determining whether or not plasmids can persist by $R_p^0 < 1$ or $R_p^0 > 1$. This also highlights how plasmids differ from mutations: the former are transmitted whereas the latter are not.

Importantly, in epidemiology, the reproduction number depends above all on the life-cycle of the parasite, especially its transmission routes. Actually, the general expression of $R_p^0$ is

$$r(D_p^{-1}(G_p-L_p))$$

and by definition of matrices (2.4), does not depend on the rate of HGT. In other words, the persistence of plasmid-bearing strains $N_p$ and $N_{m,p}$ does not rely on that rate, which is rather amplifying the prevalence of $N_p$ and $N_{m,p}$ at the equilibrium (Theorem 4.1(ii)).

5 Applications

This section describes how our general analysis can be applied in two situations: (i) bacteria strains interacting without any drug pressure, and (ii) bacteria strains interacting with drug action. Due to our model formulation and results, to explore a scenario we only need to analyse the $R_j$s.

5.1 The treatment-free model

Here, we assume that strains $N_j$s interact without any drug action. In such scenario, we further assume that before the treatment, each $N_j$ can potentially grow ($R_j > 1$, for all, $j \in J$). We further assume that there is a fitness cost of bearing a resistance, either through mutation or plasmid (min $\{R_p; R_m\} \leq \max \{R_p; R_m\} < R_s$) and that these costs either add up or compensate each other.

Costs of mutation and plasmid add up. In such situation, we have the following realistic assumption: $1 < R_{m,p} < \min \{R_p; R_m\} \leq \max \{R_p; R_m\} < R_s$. Then, based on Sects. 3.2 and 4 and under the assumptions above, the co-existence of $N_s$ and $N_m$, $E_{s-m}^* = (B^*, N_s^*, N_m^*, 0, 0)$, is the only stable stationary state when mutation rates and flux of HGT are small enough (Fig. 4D). We then have $B^* \simeq B_0/R_s$ and the

![Fig. 4](image-url)
Fig. 5 Bacterial density chronicles, as decimal logarithm of cell number per mL through time in days, obtained through numerical integration of System (2.2) for treatment scenarios: hierarchy diversity. Plots (B–D) correspond to zones labelled in Fig. 2. All parameters are equal to those of 3 except for: B $k = (0.9, 0.8, 1.5, 1.4)$, C $k = (0.9, 0.8, 1.4, 1.5)$, D $k = (0.9, 1.2, 1.1, 1.5)$, where $k := 10^{-6} \cdot (\tau_s, \tau_m, \tau_p, \tau_{m.p})$

corresponding proportion of resistance $P(E_{s-m}^*) = P_m^* = \mathcal{O}(\eta)$ is estimated by (4.1). From a biological standpoint, this means that when the cost of mutation and plasmid add up, in the absence of treatment it is expected that the proportion of resistance is very small at equilibrium.

Costs of mutation and plasmid compensate each other. In this scenario, we can have two cases: in case 1 the strain $N_{m.p}$ performs less well than $N_s$ ($1 < \min \{R_p; R_m\} \leq \max \{R_p; R_m\} < R_{m.p} < R_s$), while in case 2 the compensation is such that strain $N_{m.p}$ performs at least as well as $N_s$ ($1 < \min \{R_p; R_m\} \leq \max \{R_p; R_m\} < R_s \leq R_{m.p}$). Case 1 is similar to the previous paragraph where costs add up leading to a negligible proportion of resistance at equilibrium, while case 2 corresponds to a situation where plasmidic resistance spreads and persists (despite the costs it imposes to its hosts) in an environment that is not necessarily subject to drug pressure (Hughes and Datta 1983; Bergstrom et al. 2000; Lili et al. 2007). Indeed, for case 2, results of 3.2 and 4 suggest plasmid invasion and co-existence of all the strains, $E^* = (B^*, N_s^*, N_{m}^*, N_p^*, N_{m.p}^*)$, is the only stable stationary state when mutation rates and flux of HGT are small enough (Fig. 4C). The corresponding proportion of resistance $P(E^*) \simeq P_m^* + P_{m.p}^*$, wherein proportions $P_m^*$ and $P_{m.p}^*$ estimated by (4.4) are respectively attributable to mutational and mutational/plasmidic resistance.

5.2 The model with drug action

Our model formulation can easily account for the effect of drug action, either cytostatic (acting on the strain death rate $d_j$) or cytotoxic (acting on the strain growth conversion factor $\tau_j$). This makes it possible to discuss some scenarios of Model 2.2 with the assumption of a constant drug pressure. Here, we briefly discuss two scenarios.

The drug is efficient on sensitive and mutational strains only ($R_m < R_s < 1$). In this scenario, evolving drug resistance requires de novo genes that can be only acquired via plasmid (not by mutations). We then have two cases: either the mutation is a compensatory mutation for the plasmid presence ($R_m < R_s < 1 < R_p < R_{m.p}$) or mutation and plasmid costs add up ($R_m < R_s < 1 < R_{m.p} < R_p$). For both cases, the results of Sects. 3.2 and 4 indicate that the co-existence of all strains, $E^*$, is the only stable stationary state. Estimates (4.3) and (4.4) respectively give, for the first case, $P(E^*) \simeq P_m^* + P_{m.p}^*$ (Fig. 5C) and, for the second case, $P(E^*) \simeq P_p^*$ (Fig. 5B);
where proportions $P^*_m$, $P^*_p$ and $P^*_{m,p}$ are attributable to mutational, plasmidic and mutational/plasmidic resistance.

The drug is efficient on sensitive and plasmid-bearing strain only ($R_p < R_s < R_m$). Here, the plasmid is useless but it performs less well than the $N_s$ strain ($R_p < R_s < 1 < R_{m,p} < R_m$). Again, following Sects. 3.2 and 4, only the coexistence stationary state $E^*_{s-m}$ of sensitive en mutational resistance strain is plausible at equilibrium when mutation rates and flux of HGT are small enough. Furthermore, based on estimate (4.2), $E^*_{s-m}$ is mostly a totally mutational resistant stationary state, i.e. $\mathcal{P}(E^*_{s-m}) = P^*_m \approx 1$ (Fig. 5D).

6 Discussion

Mutations are key factors to maintain strain co-existence at equilibrium. Compared to similar studies in the literature, here we do not neglect the evolution of resistance via mutation-selection balance, which we find to substantially impact the qualitative dynamics of the model. The study in Svara and Rankin (2011) reaches the opposite conclusion that the co-existence of $N_s$ and $N_m$ or the co-existence of all strains are not plausible at equilibrium because they neglect mutations probabilities, such that strain transition $K_{s-m}$ or $K_{p-m}$ is zero.

Measurement of the cost of bearing a resistance. Drug resistance is known to be traded-off against other components of the bacterial life-cycle through competitive fitness. But, most studies investigating costs of resistance use growth rate as fitness proxy, which incorporates only a single component of bacterial fitness (Melnyk et al. 2015; Vogwill and MacLean 2015). Indeed, this cost can also act on other bacteria quantitative traits such as the cell’s death rate. In our analysis, the cost of resistance is quantified by the effective reproduction numbers $R_j$s defined by (3.4). These $R_j$s aggregate potential costs on quantitative traits of the bacteria life cycle such as nutrient consumption rate, nutrient conversion factor, bacteria’s death rate, bacteria mutation or plasmid segregation probability.

Occurrence of new mutants. In exponentially growing cells, mutations usually occur during replication (Loewe et al. 2003), but some studies indicate that mutations can be substantially higher in non growing than growing cultures (Sniegowski 2004). Thus, the occurrence of new mutants depends either on the abundance of the parental cells or both the abundance and growth rate of the parental cells (zur Wiesch et al. 2010). In Model (2.2), we have first assumed that the latter is satisfied. However, with our model formulation, we can easily switch to the case where mutations depend on the abundance of the parental cells (see (D.15) for the full model equations). Furthermore, results obtained for Model (2.2) remain valid for Model (D.15) with the thresholds $\mathcal{R}$ and strains transition numbers $\mathcal{K}$ defined as follows

$$
\mathcal{R}_s = \mathcal{T}_s \frac{d_s}{d_s + \varepsilon_s}, \quad \mathcal{R}_m = \mathcal{T}_m \frac{d_m}{d_m + \varepsilon_m},
$$

$$
\mathcal{R}_p = \mathcal{T}_p (1 - \theta) \frac{d_p}{d_p + \varepsilon_p}, \quad \mathcal{R}_{m,p} = \mathcal{T}_{m,p} (1 - \theta) \frac{d_{m,p}}{d_{m,p} + \varepsilon_{m,p}},
$$
and

\[ K_{s \rightarrow m} = \frac{\varepsilon_s}{d_m + \varepsilon_m}, \quad K_{m \rightarrow s} = \frac{\varepsilon_m}{d_s + \varepsilon_s} \]

\[ K_{p \rightarrow m,p} = \frac{\varepsilon_p}{d_m.p + \varepsilon_m.p}, \quad K_{m,p \rightarrow p} = \frac{\varepsilon_{m,p}}{d_p + \varepsilon_p} \]

\[ K_{p \rightarrow s} = B_0 \frac{\theta \tau_p \beta_p}{d_s + \varepsilon_s}, \quad K_{m,p \rightarrow m} = B_0 \frac{\theta \tau_{m,p} \beta_{m,p}}{d_m + \varepsilon_m} \]

and wherein \( T_j \)s are the same as for the previous model (2.2). Note that here, terms \( \varepsilon_j \)s represent mutation rates rather than probabilities as compared to Model (2.2).

**Competition at the plasmid level of selection.** In Model (2.2) we assume that plasmid-bearing strains always carry drug resistance genes. This assumption does not have any impact in the case of the treatment-free model. However, although a significant proportion of plasmid-bearing strains is involved in drug resistance, a small proportion can be ‘non-resistant plasmids’. To focus even more on the question of drug action with the model, it could be interesting to introduce additional bacteria strains with non-resistant plasmids but paying a cost of plasmid carriage, as in Svara and Rankin (2011). This would allow considering competition between plasmidic strains carrying the drug resistance gene with other plasmidic strains that do not carry the resistance gene. Indeed, competition at the plasmid level can be of great importance, since the spread of a resistant plasmid can be slowed or entirely stopped by a nonresistant version of the same plasmid (Tazzyman and Bonhoeffer 2014). This issue will be rigorously investigated in forthcoming work.

**Proof of Theorem 3.1**

The right-hand side of System (2.2) is continuous and locally lipschitz on \( \mathbb{R}^5 \). Using a classic existence theorem, we then find \( T > 0 \) and a unique solution \( E(t) \omega_0 = (B(t), N_s(t), N_m(t), N_p(t), N_{m,p}(t)) \) of (2.2) from \([0, T) \rightarrow \mathbb{R}^5\) and passing through the initial data \( \omega_0 \) at \( t = 0 \). Let us now check the positivity and boundedness of the solution \( E \) on \([0, T)\).

Since \( E(\cdot) \omega_0 \) starts in the positive orthant \( \mathbb{R}^5_+ \), by continuity, it must cross at least one of the five borders \( \{B = 0\}, \{N_j = 0\} \) (with \( j \in J \)) to become negative. Without loss of generality, let us assume that \( E \) reaches the border \( \{N_s = 0\} \). This means we can find \( t_1 \in (0, t) \) such that \( N_j(t) > 0 \) for all \( t \in (0, t_1) \), \( j \in J \) and \( N_s(t_1) = 0 \). Then, the \( \dot{N}_s \) -equation of (2.2) yields \( \dot{N}_s(t_1) = \theta \tau_p \beta_p B(t_1) N_p(t_1) + \varepsilon_m \tau_m \beta_m B(t_1) N_m(t_1) \geq 0 \), from where the orbit \( E(\cdot) \omega_0 \) cannot cross \( \mathbb{R}^5_+ \) through the border \( \{N_s = 0\} \). Similarly, we prove that at any borders \( \{B = 0\}, \{N_j = 0\} \) (with \( j \in J \)), either the resulting vector field stays on the border or points inside \( \mathbb{R}^5_+ \). Consequently, \( E([0, T)) \omega_0 \subset \mathbb{R}^5_+ \).

Recalling that \( N = \sum_{j \in J} N_j \) and adding up the \( \dot{N} \)- and \( \dot{B} \)-equations, it comes

\[ \frac{d}{dt} (\tau_{\text{max}} B + N) \leq \tau_{\text{max}} \Lambda - \min(d, d_{\text{min}}) (\tau_{\text{max}} B + N) \]
For small mutation rates $\varepsilon_j$, the initial phase of the invasion can be described by the linearized system at $E^0$. Since the linearized equations for bacteria populations do not include the one for the nutrient, we then have

\[
\frac{d}{dt} (u, v)^T = J[E^0](u, v)^T,
\]

where $J[E^0] = \begin{pmatrix} B_0G - D & B_0L_p \\ 0 & B_0(G_p - L_p) - D_p \end{pmatrix}$.

We claim that

**Claim B.1** For small mutation rates $\varepsilon_j$, the principal eigenvalue $r(B_0G - D)$ and $r(B_0(G_p - L_p) - D_p)$, of matrices $(B_0G - D)$ and $(B_0(G_p - L_p) - D_p)$ writes

\[
r(B_0G - D) = \frac{1}{2} \left\{ B_0\tau_s\beta_s(1 - \varepsilon_s) - d_s + B_0\tau_m\beta_m(1 - \varepsilon_m) - d_m + \left( (B_0\tau_s\beta_s(1 - \varepsilon_s) - d_s - B_0\tau_m\beta_m(1 - \varepsilon_m) + d_m)^2 + 4\varepsilon_m\varepsilon_s\tau_s\beta_s\tau_m\beta_mB_0^2 \right)^{1/2} \right\}
\]

\[
= \frac{1}{2} \{ d_s(R_s - 1) + d_m(R_m - 1) + |d_s(R_s - 1) - d_m(R_m - 1)| \} + O(\varepsilon_m\varepsilon_s),
\]

i.e.

\[
r(B_0G - D) = \begin{cases} B_0\tau_s\beta_s(1 - \varepsilon_s) - d_s + O(\varepsilon_m\varepsilon_s), & \text{if } d_s(R_s - 1) > d_m(R_m - 1), \\
B_0\tau_m\beta_m(1 - \varepsilon_m) - d_m + O(\varepsilon_m\varepsilon_s), & \text{if } d_s(R_s - 1) < d_m(R_m - 1). \end{cases}
\]

In the same way, we have

\[
r((B_0(G_p - L_p) - D_p)) = \begin{cases} B_0\tau_p\beta_p(1 - \theta)(1 - \varepsilon_p) - d_p + O(\varepsilon_p\varepsilon_{m,p}), & \text{if } d_p(R_p - 1) > d_m,p(R_{m,p} - 1), \\
B_0\tau_m,p\beta_{m,p}(1 - \theta)(1 - \varepsilon_{m,p}) - d_{m,p} + O(\varepsilon_p\varepsilon_{m,p}), & \text{if } d_p(R_p - 1) < d_m,p(R_{m,p} - 1). \end{cases}
\]

Denoting by $\sigma(J[E^0])$ the spectrum of $J[E^0]$, we recall that the stability modulus (Li and Wang 1998) or spectral bound (Engel and Nagel 2001) of $J[E^0]$ is $\sigma_0(J[E^0]) = \max \Re(z) : z \in \sigma(J[E^0])$ and $J[E^0]$ is said to be locally asymptotically stable.
(l.a.s.) if \( s_0(J[E^0]) < 0 \). Following Claim B.1 it comes

\[
\sigma(J[E^0]) = \sigma(B_0G - D) \cup \sigma(B_0(G_p - L_p) - D_p) \simeq \\
\{ B_0 \tau_s \beta_s(1 - \varepsilon_s) - d_s, B_0 \tau_m \beta_m(1 - \varepsilon_m) - d_m, B_0 \tau_p \beta_p(1 - \varepsilon_p)(1 - \theta) - d_p, \\
B_0 \tau_{m,p} \beta_{m,p}(1 - \theta)(1 - \varepsilon_m,p) - d_{m,p} \}
\]

where the last approximation holds for small mutation rates.

Note that, when mutation rates are small enough, we obtain \( s_0(J[E^0]) < 0 \) if and only if \( R^* < 1 \), i.e. \( E^0 \) is l.a.s if \( R^* < 1 \) and unstable if \( R^* > 1 \).

We now check the global stability of \( E^0 \) when \( T^* < 1 \). The \( \dot{B} \)-equation of (2.2) gives \( \dot{B} \leq \Lambda - dB \). Further, \( B_0 \) is a globally attractive stationary state of the upper equation \( \dot{w} = \Lambda - dw \), i.e. \( w(t) \to B_0 \) as \( t \to \infty \). This gives \( w(t) \leq B_0 \) for sufficiently large time \( t \), from where \( B(t) \leq B_0 \) for sufficiently large time \( t \). Combining this last inequality with the total bacteria dynamics described by (2.1), we find

\[
\dot{N} \leq \sum_{j \in J} (\beta_j \tau_j B_0 - d_j) N \leq c_0(T^* - 1) N, \quad \text{with} \quad c_0 > 0 \text{ a positive constant.}
\]

Therefore \( N(t) \leq N(0)e^{c_0(T^*-1)t} \to 0 \) as \( t \to \infty \). This ends the proof of the global stability of \( E^0 \) when \( T^* < 1 \).

Item (iii) of the theorem remains to be checked. To do so we will apply results in Hale and Waltman (1989). Let us first notice that \( E^0 \) is an unstable stationary state with respect to the semiflow \( E \). To complete the proof, it is sufficient to show that \( W^s([E^0]) \cap X_0 = \emptyset \), where \( W^s([E^0]) = \{ w \in \Omega : \lim_{t \to \infty} E(t)w = E^0 \} \) is the stable set of \( [E^0] \). To prove this assertion, let us argue by contradiction by assuming that there exists \( w \in W^s([E^0]) \cap X_0 \). We set \( E(t)w = (B(t), N_s(t), N_m(t), N_p(t), N_{m,p}(t)) \). The \( \dot{N} \)-equation defined by (2.1) gives

\[
\dot{N}(t) = \sum_{j \in J} d_j \left( \frac{T_j B(t)}{B_0} - 1 \right) N_j(t)
\]

\[
\geq d_{\min} \left( \frac{B(t)}{B_0} \min_j T_j - 1 \right) N(t), \quad \text{for all time } t.
\]

Since \( \min_j T_j > 1 \) and it is assumed that \( B(t) \to B_0 \) as \( t \to \infty \), we find that the function \( t \mapsto N(t) = N_s(t) + N_m(t) + N_p(t) + N_{m,p}(t) \) is not decreasing for \( t \) large enough. Hence there exists \( t_0 \geq 0 \) such that \( N(t) \geq N(t_0) \) for all \( t \geq t_0 \). Since \( N(t_0) > 0 \), this prevents the component \( (N_s, N_m, N_p, N_{m,p}) \) from converging to \( (0, 0, 0, 0) \) as \( t \to \infty \). A contradiction with \( E(t)w \to E^0 \). This completes the proof of Theorem 3.3.

**Proof of Theorem 4.1**

The stationary state \( E_{s \to m}^* = (B^*, u^*, 0) \). Here, it is useful to considered the abstract formulation of the model given by (2.3). Setting \( v = 0 \), the \( \dot{u} \)-equation of (2.3) gives

\[
[BG - D]u = 0 \quad \text{i.e.} \quad D^{-1}Gu = u/B.
\]

Since \( D^{-1}G = \begin{bmatrix} R_s/B_0 & K_{s \to m}/B_0 \\ K_{s \to m}/B_0 & R_m/B_0 \end{bmatrix} \),
is a positive and irreducible matrix, from the so-called Perron-Frobenius theorem, $1/B = r(D^{-1}G)$ and $u = c \phi$, where $\phi > 0$ is the eigenvector of $D^{-1}G$ corresponding to $r(D^{-1}G)$ and normalized such that $\|\phi\|_1 = 1$ and $c > 0$ is a positive constant. Notice that $\phi > 0$ means all components of the vector $\phi$ are positive. More precisely, we have

$$B^{-1} = r(D^{-1}G) = \frac{1}{2B_0} \left\{ \mathcal{R}_s + \mathcal{R}_m + \left[ (\mathcal{R}_s - \mathcal{R}_m)^2 + 4K_{m \rightarrow s}K_{s \rightarrow m} \right]^{1/2} \right\},$$

$$\phi = \frac{\phi_0}{\|\phi_0\|_1},$$

with $\phi_0 = \left( \mathcal{R}_s - \mathcal{R}_m + \left[ (\mathcal{R}_s - \mathcal{R}_m)^2 + 4K_{m \rightarrow s}K_{s \rightarrow m} \right]^{1/2}, 2K_{s \rightarrow m} \right)^T$.

Further, from the $\dot{B}$-equation we find $\Lambda - dB = cB ((\beta_s, \beta_m), \phi)$, i.e.

$$c = \frac{d \left( B_0r(D^{-1}G) - 1 \right)}{\langle (\beta_s, \beta_m), \phi \rangle} > 0 \iff B_0r(D^{-1}G) > 1.$$

**Approximation of $P(E^*_{s \leftarrow m})$ for small mutation rates.** Now, let us assume that mutation rates $\varepsilon_j$ are small enough. Without loss of generality, we express parameters $\varepsilon_j$ as functions of the same quantity, let us say $\eta$, with $\eta \ll 1$. We have

$$P(E^*_{s \leftarrow m}) = \frac{2K_{s \rightarrow m}}{\mathcal{R}_s - \mathcal{R}_m + \left[ (\mathcal{R}_s - \mathcal{R}_m)^2 + 4K_{m \rightarrow s}K_{s \rightarrow m} \right]^{1/2} + 2K_{s \rightarrow m}}. \quad (C.2)$$

By setting $\xi = \mathcal{R}_s - \mathcal{R}_m + \left[ (\mathcal{R}_s - \mathcal{R}_m)^2 + 4K_{m \rightarrow s}K_{s \rightarrow m} \right]^{1/2}$, it comes

$$\xi = (\mathcal{T}_s - \mathcal{T}_m) (1 - \eta) + |\mathcal{T}_s - \mathcal{T}_m| \left[ 1 - \eta + \frac{1}{2} \left( \frac{\mathcal{T}_s + \mathcal{T}_m}{\mathcal{T}_s - \mathcal{T}_m} \right)^2 - 1 \right] \eta^2 + O(\eta^3). \quad (C.3)$$

Next, we find a simple approximation of the frequency $P(E^*_{s \leftarrow m})$ for cases $\mathcal{R}_s > \mathcal{R}_m$ and $\mathcal{R}_s < \mathcal{R}_m$, i.e. $\mathcal{T}_s > \mathcal{T}_m$ and $\mathcal{T}_s < \mathcal{T}_m$ for small mutations $\varepsilon_j$'s.

**Case $\mathcal{T}_s > \mathcal{T}_m$.** From estimates (C.2) and (C.3) it comes

$$\begin{cases} P(E^*_{s \leftarrow m}) = \frac{d_s}{d_m} \frac{\mathcal{T}_s}{\mathcal{T}_s - \mathcal{T}_m} \eta + O(\eta^2), \\
\text{with } \mathcal{R}_s = \mathcal{T}_s (1 - \varepsilon_s) > 1, \text{ and } \mathcal{T}_s > \mathcal{T}_m. \end{cases}$$

**Case $\mathcal{T}_s < \mathcal{T}_m$.** From estimates (C.2) and (C.3) it comes

$$\begin{cases} P(E^*_{s \leftarrow m}) = 1 - \frac{d_m (\mathcal{T}_m - \mathcal{T}_s)}{4B_0 \varepsilon_m \beta_s} \left( \frac{\mathcal{T}_s + \mathcal{T}_m}{\mathcal{T}_s - \mathcal{T}_m} \right)^2 - 1 \right) \eta + O(\eta^2), \\
\text{with } \mathcal{R}_m = \mathcal{T}_m (1 - \varepsilon_m) > 1, \text{ and } \mathcal{T}_m > \mathcal{T}_s. \end{cases}$$
The stationary state \( E^* = (B^*, N_s^*, N_m^*, N_p^*, N_{m.p}^*) \). By setting \( u = (N_s, N_m)^T \), \( v = (N_p, N_{m.p})^T \) and taking \( \dot{u} = \dot{v} = 0 \) in (2.3), we have

\[
\begin{align*}
B (Gu + L_p v) &= Du + H(N)[N_p + N_{m.p}] (N_s, N_m)^T, \\
B(G_p - L_p)v &= D_p v - H(N)[N_p + N_{m.p}] (N_s, N_m)^T,
\end{align*}
\]

i.e.

\[
BL(u, v) + \alpha F(u, v) = (u, v),
\]

with

\[
L = D^{-1}G = \begin{bmatrix}
D^{-1}G & 0 \\
0 & D^{-1}(G_p - L_p)
\end{bmatrix},
\]

\[
G = \begin{bmatrix}
G & L_p \\
0 & G_p - L_p
\end{bmatrix};
\]

\[
D = \begin{bmatrix}
D & 0 \\
0 & D_p
\end{bmatrix},
\]

\[
F(u, v) = \frac{N_p + N_{m.p}}{a_H + b_H N} \left[ -D^{-1}uD^{-1}u \right] + \cdots.
\]

Note that the spectrum of \( L \) is \( \sigma(L) = \sigma\left(D^{-1}G\right) \cup \sigma\left(D^{-1}(G_p - L_p)\right) \) and the spectral radius of matrices \( D^{-1}G \) and \( D^{-1}(G_p - L_p) \) are given by

\[
\begin{align*}
r(D^{-1}G) &= \frac{1}{2B_0} \left\{ R_s + R_m + \left[ (R_s - R_m)^2 + 4\kappa_{m\to s}\kappa_{s\to m} \right]^{1/2} \right\}, \\
r(D^{-1}(G_p - L_p)) &= \frac{1}{2B_0} \left\{ R_p + R_{m.p} + \left[ (R_p - R_{m.p})^2 + 4\kappa_{m.p\to p}\kappa_{p\to m.p} \right]^{1/2} \right\}.
\end{align*}
\]

We now introduced a parametric representation of the stationary state \( E^* \) with respect to the small parameter \( \alpha \). Using the Lyapunov–Schmidt expansion (see Cushing 1998 for more details), the expanded variables are

\[
\begin{align*}
u &= u^0 + \alpha u^1 + \cdots, \\
v &= v^0 + \alpha v^1 + \cdots, \\
B &= b^0 + \alpha b^1 + \cdots, \\
F(u, v) &= \frac{N_p^0 + N_{m.p}^0}{a_H + b_H N^0} \left[ -D^{-1}u^0D^{-1}u^0 \right] + \cdots,
\end{align*}
\]

with \( u^0 = (N_s^0, N_m^0) \), \( v^0 = (N_p^0, N_{m.p}^0) \) and \( N^0 = N_s^0 + N_m^0 + N_p^0 + N_{m.p}^0 \).
Evaluating the substitution of expansions (C.5) into the eigenvalue equation (C.4) at $O(\alpha^0)$ produces $b_0 L(u^0, v^0) = (u^0, v^0)$, i.e.

\[
\begin{align*}
\begin{cases}
  b_0 D^{-1} G u^0 + b_0 D^{-1} L_p v^0 = u^0, \\
  b_0 D_p^{-1}(G_p - L_p) v^0 = v^0.
\end{cases}
\end{align*}
\]

Since we are interested in $v_0 > 0$, System (C.6) leads to $b_0 D_p^{-1}(G_p - L_p) v^0 = v^0$. The irreducibility of the matrix $D_p^{-1}(G_p - L_p)$ gives that $(1/b_0, v^0)$ is the principal eigenpair of $D_p^{-1}(G_p - L_p)$. That is $1/b_0 = r(D_p^{-1}(G_p - L_p))$ and $v^0 = c_0 \| \varphi_0 \| / \varphi_0 \parallel$, wherein $c_0$ is a positive constant and

\[
\varphi_0 = \left( \mathcal{R}_p - \mathcal{R}_{m,p} + \left[ (\mathcal{R}_p - \mathcal{R}_{m,p})^2 + 4\mathcal{K}_{m,p\rightarrow p}\mathcal{K}_{p\rightarrow m,p} \right]^{1/2}, 2\mathcal{K}_{p\rightarrow m,p} \right)^T.
\]

Again, System (C.6) gives

\[
(D^{-1} G - 1/b_0) u^0 = - D^{-1} L_p v^0.
\]

Since $D^{-1} L_p v^0 = \text{diag} \left( \mathcal{K}_{p\rightarrow s}, \mathcal{K}_{m,p\rightarrow m} \right) v^0$ which is positive, equation (C.7) can be solved for $u_0 > 0$ iff $1/b_0 > r(D^{-1} G)$ and so $u^0 = -(D^{-1} G - 1/b_0)^{-1} D^{-1} L_p v^0$.

From the $\dot{B}$-equation of the model, the term of order $O(\alpha^0)$ leads to

\[
c_0 = \frac{\| \varphi_0 \|_1 d \left[ B_0/b_0 - 1 \right]}{\left\{ \beta, (-(D^{-1} G - 1/b_0)^{-1} D^{-1} L_p \varphi_0, \varphi_0) \right\}} > 0
\]

\[
\iff B_0/b_0 = B_0 r(D_p^{-1}(G_p - L_p)) > 1.
\]

Consequently, it comes $b_0 > 0$ and $(u^0, v^0) > 0$ are such that

\[
\begin{align*}
\begin{cases}
  1/b_0 = r(D_p^{-1}(G_p - L_p)), \\
  v^0 = \frac{d \left[ B_0/b_0 - 1 \right]}{\left\{ \beta, (-(D^{-1} G - 1/b_0)^{-1} D^{-1} L_p \varphi_0, \varphi_0) \right\}} \varphi_0, \\
  u^0 = -(D^{-1} G - 1/b_0)^{-1} D^{-1} L_p v^0,
\end{cases}
\end{align*}
\]

conditioned by

\[
r(D_p^{-1}(G_p - L_p)) > r(D^{-1} G) \quad \text{and} \quad B_0 r(D_p^{-1}(G_p - L_p)) > 1. \tag{C.8}
\]

Again, evaluating the substitution of expansions (C.5) into the eigenvalue equation (C.4) at $O(\alpha^0)$ produces

\[
(b^0 L - \parallel) (u^1, v^1) = b_1 \left( \frac{N_p^0 + N_{m,p}^0}{a_H + b_H N^0} \right) \left[ - D_p^{-1} u^0 \right].
\]
that is
\[
\begin{align*}
    b^0 D^{-1} G u^1 + b^0 D^{-1} L_p v^1 - u^1 &= -\frac{b^1}{b^0} u^0 + \frac{N_p^0 + N_{\text{m.p}}^0}{a_H + b_H N^0} D^{-1} u^0, \\
    b^0 D_p^{-1} (G_p - L_p) v^1 - v^1 &= -\frac{b^1}{b^0} v^0 - \frac{N_p^0 + N_{\text{m.p}}^0}{a_H + b_H N^0} D^{-1} u^0.
\end{align*}
\] (C.9a) (C.9b)

As $1/b^0$ is a characteristic value of $D_p^{-1}(G_p - L_p)$, $(b^0 D_p^{-1}(G_p - L_p) - \|)$ is a singular matrix. Thus, for (C.9b) to have a solution, the right-hand side of (C.9b) must be orthogonal to the null space of the adjoint $(b^0 D_p^{-1}(G_p - L_p) - \|)^T$ of $(b^0 D_p^{-1}(G_p - L_p) - \|)$. The null space of $(b^0 D_p^{-1}(G_p - L_p) - \|)^T$ is spanned by $\omega_0$, where $\omega_0^T$ is the eigenvector of $(D_p^{-1}(G_p - L_p))^T$ corresponding to the eigenvalue $1/b^0$ and normalized such that $\|\omega_0\|_1 = 1$. The Fredholm condition for the solvability of (C.9b) is $\omega_0 \cdot \left(\frac{b^1}{b^0} v^0 + \frac{N_p^0 + N_{\text{m.p}}^0}{a_H + b_H N^0} D^{-1} u^0\right) = 0$. Which gives
\[
    b^1 = -\frac{b^0}{N_p^0 + N_{\text{m.p}}^0} \omega_0 \cdot D_p^{-1} u^0
\]
and so
\[
\begin{align*}
    (N_s, N_m) &= u^0 + \alpha u^1 + O(\alpha^2), \\
    (N_p, N_{\text{m.p}}) &= v^0 + \alpha v^1 + O(\alpha^2), \\
    B &= b^0 + \alpha b^1 + O(\alpha^2).
\end{align*}
\]

**Approximation of $E^*$ for small mutation and HGT flux rates.** Here we derive a simple approximation of the stationary state $E^*$ when mutation and HGT flux rates $\varepsilon_j$ and $\alpha$ are small. Without loss of generality, we express parameters $\varepsilon_j$ and $\alpha$ as functions of the same quantity, let us say $\eta$, with $\eta \ll 1$. First, we have
\[
1/b^0 = r(D_p^{-1}(G_p - L_p)) = B_0^{-1} \max(\mathcal{R}_p, \mathcal{R}_{\text{m.p}}) + O(\eta^2)
\]
\[
= (1 - \theta)(1 - \eta) B_0^{-1} \max(\mathcal{T}_p, \mathcal{T}_{\text{m.p}}) + O(\eta^2).
\]

Next, we consider two cases $\mathcal{R}_p > \mathcal{R}_{\text{m.p}}$ and $\mathcal{R}_p < \mathcal{R}_{\text{m.p}}$, i.e. $\mathcal{T}_p > \mathcal{T}_{\text{m.p}}$ and $\mathcal{T}_p < \mathcal{T}_{\text{m.p}}$ for small mutations $\varepsilon_j$'s.

**Case $\mathcal{T}_p > \mathcal{T}_{\text{m.p}}$.** Recall that condition (C.8) for the existence of the stationary state $E^*$ simply rewrites
\[
\mathcal{R}_p > \max(\mathcal{R}_s, \mathcal{R}_m) \quad \text{and} \quad \mathcal{R}_p > 1,
\]
which, for small $\eta$, rewrites
\[
(1 - \theta) \mathcal{T}_p > \max(\mathcal{T}_s, \mathcal{T}_m) \quad \text{and} \quad (1 - \theta) \mathcal{T}_p > 1.
\]
We have \( \varphi_0 = ((T_p - T_{m,p})(1 - \theta)(1 - \eta), \eta B_0 \tau_p \beta_p / d_{m,p})^T + O(\eta^2) \) and \( \omega_0 = ((T_p - T_{m,p})(1 - \theta)(1 - \eta), \eta B_0 \tau_m \beta_{m,p} / d_p) + O(\eta^2) \). Which gives the following approximation of the stationary state \( E^* \):

\[
B^* = \frac{B_0}{(1 - \theta) T_p} (1 + \eta) + O(\eta^2),
\]

\[
(N_p^*, N_{m,p}^*) = \frac{c_0}{\Delta_p - m, p + \eta \frac{B_0 \tau_p \beta_p}{d_{m,p}}} \left( \frac{\Delta_p - m, p, \eta \frac{B_0 \tau_p \beta_p}{d_{m,p}}}{\Delta_p - m, p} \right)^T + O(\eta^2),
\]

\[
(N_s^*, N_m^*) = \frac{B_0 \eta \theta}{\Delta_p - s} \left( \frac{\Delta_p - s, \eta \frac{B_0 \tau_p \beta_p}{d_{m,p}} + \Delta_p - s, \eta \frac{B_0 \tau_p \beta_p}{d_{m,p}}}{\Delta_p - m} \right)^T + O(\eta^2)
\]

with \( \Delta_p - m, p = (T_p - T_{m,p})(1 - \theta)(1 - \eta), \Delta_p - m = T_p (1 - \theta)(1 - \eta) - T_m (1 - \eta), \Delta_p - s = T_p (1 - \theta)(1 - \eta) - T_s (1 - \eta) \), \( c_0 = \frac{d (R_p - R_{m,p} + \tau_{s,p}) (R_{p,m} - 1) > 0 \) and \( \beta^* = \beta_p (R_p - R_{m,p}) + \beta_{m,p} K_p \rightarrow m, p \)

\[
+ \frac{B_0}{(R_s - R_p (R_m - R_p)} \{ \beta_s (R_p - R_m) (R_p - R_{m,p}) K_{p,s} \}
\]

\[
+ \beta_m (\{ (R_p - R_{m,p}) K_{s,m} K_{p,s} + (R_p - R_s) K_{m,p} K_{p,m} \}.
\]

From where, \( \mathcal{P}(E^*) = \mathcal{P}_m^* + \mathcal{P}_p^* + \mathcal{P}_m^* \),

\[
\mathcal{P}_m^* = \eta \frac{B_0 \eta \theta}{\Delta_p - m, p N^m} \text{and} \ N^m = \frac{\Delta_p - m, p + \eta \frac{B_0 \tau_p \beta_p}{d_{m,p}} + \frac{B_0 \eta \theta}{\Delta_p - s}}{\Delta_p - s} \frac{B_0 \tau_p \beta_p}{d_{m,p}}
\]

\[
\mathcal{P}_p^* = \eta \frac{B_0 \tau_p \beta_p}{d_{m,p}} (T_p - T_{m,p})(1 - \theta) - T_s (T_p (1 - \theta) - T_m) (T_p - T_{m,p})(1 - \theta) (1 + \frac{B_0 \eta \theta}{\Delta_p - s}) + O(\eta^2).
\]

With the Taylor expansion it comes

\[
\mathcal{P}_m^* = \frac{1}{\Delta_p - m, p, p} \frac{B_0 \tau_p \beta_p}{d_{m,p}} (T_p - T_{m,p})(1 - \theta) (1 + \frac{B_0 \eta \theta}{\Delta_p - s}) + O(\eta^2).
\]

\( \mathcal{P}_p^* \)
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Case $T_p < T_{m,p}$. Again, condition (C.8) for the existence of the stationary state $E^*$ becomes

$$R_{m,p} > \max (R_s, R_m) \quad \text{and} \quad R_{m,p} > 1,$$

which, for sufficiently $\eta$, rewrites

$$(1 - \theta)T_{m,p} > \max (T_s, T_m) \quad \text{and} \quad (1 - \theta)T_{m,p} > 1.$$  

Again, by Taylor expansion, we find

$$B^* = \frac{B_0}{(1 - \theta)T_{m,p}} (1 + \eta) + O(\eta^2),$$

and

$$v^0 = c_0 (0, 1) + O(\eta^2).$$

Since $u^0 = -(D^{-1}G - 1/b^0)D^{-1}L_p v^0$, we then have

$$u^0 = \frac{c_0 \theta B_0^2 \tau_p \beta_p}{d_m \left[T_{m,p}(1 - \theta)(1 - \eta) - T_m(1 - \eta)\right]} (0, 1) + O(\eta^2).$$

From where, $P(E^*) = P^*_m + P^*_p + P^*_{m,p}$, with

$$P^*_m = \frac{\theta B_0^2 \tau_p \beta_p}{\theta B_0^2 \tau_p \beta_p + d_m \left[T_{m,p}(1 - \theta) - T_m\right]} + O(\eta),$$

$$P^*_p = O(\eta),$$

$$P^*_{m,p} = \frac{d_m \left[T_{m,p}(1 - \theta) - T_m\right]}{\theta B_0^2 \tau_p \beta_p + d_m \left[T_{m,p}(1 - \theta) - T_m\right]} + O(\eta).$$

**Proof of Theorem 4.2**

The linearized system at a given stationary state $E^* = (B^*, u^*, v^*)$ writes

$$(\dot{B}, \dot{u}, \dot{v})^T = J[E^*](B, u, v)^T$$

(D.12)
wherein \( J[E^*] \) is defined by the Jacobian matrix associated to (D.12) and is given by

\[
J[E^*] = \begin{pmatrix}
-\left[ d + \langle \beta_1, (u^*, v^*) \rangle \right] & -B^*(\beta_s, \beta_m) & -B^*(\beta_p, \beta_{m,p}) \\
Gu^* + L_p v^* & B^*G - D - M[E^*] & -N[E^*] + B^*L_p \\
(G_p - L_p)v^* & M[E^*] & B^*(G_p - L_p) - D_p + N[E^*]
\end{pmatrix},
\]

\[
M[E^*] = \begin{pmatrix}
H(N^*)(N^*_p + N^*_m,p) + \xi_s^* & \xi^*_m & H(N^*)(N^*_p + N^*_m,p) + \xi^*_m \\
N^*_m + \xi^*_m & H(N^*)N^*_m + \xi^*_m & H(N^*)N^*_m + \xi^*_m
\end{pmatrix},
\]

\[
N[E^*] = \begin{pmatrix}
H(N^*)N^*_s + \xi^*_s & H(N^*)N^*_s + \xi^*_s & H(N^*)N^*_s + \xi^*_s
\end{pmatrix},
\]

(D.13)

with \( \xi^*_s = H'(N^*)N^*_s(N^*_p + N^*_m,p) \), and \( \xi^*_m = H'(N^*)N^*_m(N^*_p + N^*_m,p) \). Without loss of generality, and when necessary, we express parameters \( \varepsilon \) and \( \alpha \) as functions of the same quantity, let us say \( \eta \), with \( \eta \ll 1 \).

Recall that the stability modulus of a matrix \( M \) is \( s_0(M) = \{ \max \text{Re}(z) : z \in \sigma(M) \} \) and \( M \) is said to be locally asymptotically stable (l.a.s.) if \( s_0(M) < 0 \) (Li and Wang 1998).

**Stability of \( E^*_{s-m} \).** At point \( E^*_{s-m} \), the Jacobian matrix \( J[E^*_{s-m}] \) writes

\[
J[E^*_{s-m}] = \begin{pmatrix}
Z[E^*_{s-m}] & X[E^*_{s-m}] \\
0 & Y[E^*_{s-m}]
\end{pmatrix},
\]

with

\[
Z[E^*_{s-m}] = \begin{pmatrix}
-\left[ d + \langle \beta_s, (u^*, v^*) \rangle \right] & -B^*(\beta_s, \beta_m) \\
Gu^* & B^*G - D
\end{pmatrix},
\]

\[
X[E^*_{s-m}] = \begin{pmatrix}
-B^*(\beta_p, \beta_{m,p}) \\
-N[E^*_{s-m}] + B^*L_p
\end{pmatrix},
\]

\[
Y[E^*_{s-m}] = B^*(G_p - L_p) - D_p + N[E^*_{s-m}].
\]

Then, \( E^*_{s-m} \) is unstable if \( s_0(Y[E^*_{s-m}]) > 0 \) and a necessary condition for the stability of \( E^*_{s-m} \) is that \( s_0(Y[E^*_{s-m}]) < 0 \). By setting \( h_j^* = \frac{N^*}{a_H + b_H N^*} \), with \( j = s, m \); note that

\[
Y[E^*_{s-m}] = \begin{pmatrix}
B^*\tau^*_p(1 - \varepsilon)(1 - \theta) - d_p + \alpha h_j^* & B^*(\varepsilon_{m,p} - 1) + \tau_{m,p} \beta_{m,p} + \alpha \eta_j^* \\
B^*\varepsilon^*_p(1 - \theta)\tau^*_p + \alpha \eta_m^* & B^*(\varepsilon_{m,p} - 1) - d_{m,p} + \alpha \eta_m^*
\end{pmatrix}
\]
and eigenvalues $z_1, z_2$ of $Y[E^*_{s-m}]$ are such that

$$z_1 = B^* \tau_p \beta_p (1 - \epsilon_p) (1 - \theta) - d_p + \alpha h^*_s + O(\eta^2)$$

$$= d_p \left( \frac{B^*}{B_0} R_p + \frac{\alpha h^*_s}{d_p} - 1 \right) + O(\eta^2).$$

$$z_2 = B^* \tau_{m,p} \beta_{m,p} (1 - \epsilon_{m,p}) (1 - \theta) - d_{m,p} + \alpha h^*_m + O(\eta^2)$$

$$= d_{m,p} \left( \frac{B^*}{B_0} R_{m,p} + \frac{\alpha h^*_m}{d_{m,p}} - 1 \right) + O(\eta^2).$$

From where, for sufficiently small mutation and flux of HGT rates, we have

$$s_0(Y[E^*_{s-m}]) < 0 \iff \begin{cases} \frac{R_p}{\max(R_s, R_m)} + \frac{h^*_s}{d_p} < 1, \\ \frac{R_{m,p}}{\max(R_s, R_m)} + \frac{h^*_m}{d_{m,p}} < 1. \end{cases}$$

Next, it remains to check the stability of the block matrix $Z[E^*_{s-m}]$:

$$Z[E^*_{s-m}] = \begin{pmatrix}
-d + \beta_s N^*_s + \beta_m N^*_m & -B^* \tau_s \beta_s & -B^* \tau_{m,p} \\
\tau_s \beta_s (1 - \epsilon_s) N^*_s + \epsilon_m \tau_m \beta_m N^*_m & B^* \tau_s \beta_s (1 - \epsilon_s) - d_s & B^* \tau_{m,p} \beta_{m,p} \\
\epsilon_s \tau_s \beta_s N^*_s + \tau_m \beta_m (1 - \epsilon_m) N^*_m & B^* \tau_s \beta_s & B^* \tau_{m,p} (1 - \epsilon_{m,p}) - d_{m,p}
\end{pmatrix}.$$  

Again, recalling that $(N^*_s, N^*_m) = \frac{d(B_{0f}(D^{-1}G) - 1)}{(\beta_s, \beta_m, \phi_0)} \phi_0$, the expansion of the matrix $Z[E^*_{s-m}]$ takes the form $Z[E^*_{s-m}] = Z^0 + \eta Z^\eta$, wherein

$$Z^0 = \begin{pmatrix}
-d + \beta_s n^0_s & -B^0 \tau_s \beta_s & -B^0 \tau_{m,p} \\
\tau_s \beta_s n^0_s & B^0 \tau_s \beta_s - d_s & 0 \\
0 & 0 & B^0 \tau_{m,p} (1 - \epsilon_{m,p}) - d_{m,p}
\end{pmatrix}.$$  

with $n^0_s = \frac{c^0}{2} (T_s - T_m + |T_s - T_m|), \frac{1}{\beta_0} = \frac{1}{2c_0} (T_s + T_m + |T_s - T_m|)$, and where $c^0$ is a positive constant (which does not depend on $\eta$). We first assume that $T_s > T_m$. Then, eigenvalues $z^0_k (k = 1, 2, 3)$ of $Z^0$ are such that $z^0_1 = b^0 \tau_{m,p} \beta_m - d_m$, and $z^0_2, z^0_3$ are solution of

$$z^2 + \left[ d + \beta_s n^0_s + d_s - b^0 \tau_s \beta_s \right] z + b^0 \tau_s \beta_s^2 n^0_s + (d + \beta_s n^0_s) (d_s - b^0 \tau_s \beta_s) = 0.$$  

Since $d_s - b^0 \tau_s \beta_s = d_s \left( 1 - \frac{2}{T_s + T_m + |T_s - T_m|} T_s \right) \geq 0$, coefficients of the previous polynomial are positive and so $R_e(z^0_2) < 0, R_e(z^0_3) < 0$. Moreover, $z^0_1 = d_m \left( \frac{2}{T_s + T_m + |T_s - T_m|} T_m - 1 \right) \leq 0$, from where $s_0(Z^0) < 0$, which gives $s_0(Z[E^*_{s-m}]) < 0$ for $\eta$ sufficiently small (Kato 1976). Consequently, for small $\eta$, $E^*_{s-m}$ is l.a.s if and only if $s_0(Y[E^*_{s-m}]) < 0$.  

\( \square \) Springer
Stability of $E^*$. Let

$$
\begin{align*}
    u^* &= (x_s^*, x_m^*) + O(\eta), \\
v^* &= (x_p^*, x_{m,p}^*) + O(\eta), \\
    B^* &= b_0^* + O(\eta).
\end{align*}
$$

Then $J[E^*]$ takes the form $J[E^*] = J_0^* + \eta J_1^*$, with $J_0^*$ =

$$
\begin{pmatrix}
    - (d + \sum_j \beta_j x_j^s) & -b_0^* \beta_s & -b_0^* \beta_m & -b_0^* \beta_p & -b_0^* \beta_{m,p} \\
    \mu_s x_s^s + \theta \mu_p x_p^s & b_0^* \mu_s - d_s & 0 & b_0^* \theta \mu_p & 0 \\
    \mu_m x_m^m + \theta \mu_m x_{m,p}^m & 0 & b_0^* \mu_m - d_m & 0 & b_0^* \theta \mu_{m,m} \\
    (1 - \theta) \mu_p x_p^m & 0 & 0 & b_0^* (1 - \theta) \mu_p - d_p & 0 \\
    (1 - \theta) \mu_m x_{m,p}^m & 0 & 0 & 0 & b_0^* (1 - \theta) \mu_{m,m} - d_{m,m}
\end{pmatrix}
$$

(D.14)

Recall that, for $\eta$ sufficiently small, the existence of $E^*$ is ensured by

$$(1 - \theta) \max (T_p, T_{m,p}) > \max (T_s, T_m).$$

If $T_p > T_{m,p}$, from (C.10), we have $b_0^* = \frac{B_0}{(1 - \theta)T_p}$, $x_m^m = x_{m,p}^m = 0$, and $J_0^*$ rewrites $J_0^*$ =

$$
\begin{pmatrix}
    - (d + \sum_j \beta_j x_j^s) & -b_0^* \beta_s & -b_0^* \beta_m & -b_0^* \beta_p & -b_0^* \beta_{m,m} \\
    \mu_s x_s^s + \theta \mu_p x_p^s & b_0^* \mu_s - d_s & 0 & b_0^* \theta \mu_p & 0 \\
    \mu_m x_m^m + \theta \mu_m x_{m,p}^m & 0 & b_0^* \mu_m - d_m & 0 & b_0^* \theta \mu_{m,m} \\
    (1 - \theta) \mu_p x_p^m & 0 & 0 & b_0^* (1 - \theta) \mu_p - d_p & 0 \\
    (1 - \theta) \mu_m x_{m,p}^m & 0 & 0 & 0 & b_0^* (1 - \theta) \mu_{m,m} - d_{m,m}
\end{pmatrix}
$$

Denoting by $\sigma(\cdot)$ the spectrum of a given matrix, we have

$$
\sigma(J_0^*) = \{ b_0^* (1 - \theta) \mu_m - d_m, b_0^* \mu_m - d_m \} \cup \sigma(Y_0^*),
$$

where

$$
Y_0^* = \begin{pmatrix}
    - (d + \sum_j \beta_j x_j^s) & -b_0^* \beta_s & -b_0^* \beta_p \\
    \mu_s x_s^s + \theta \mu_p x_p^s & b_0^* \mu_s - d_s & 0 \\
    (1 - \theta) \mu_p x_p^m & 0 & 0
\end{pmatrix}
$$

Since $b_0^* (1 - \theta) \mu_m - d_m = d_m (T_m/(1 - \theta) T_p - 1) < 0$ and $b_0^* \mu_m - d_m = d_m (T_m/(1 - \theta) T_p - 1) < 0$, then $E^*$ is l.a.s. iff $s_0(Y_0^*) < 0$. The characteristic polynomial of $Y_0^*$ writes $\pi(z) = z^2 + \pi_2 z^2 + \pi_1 z + \pi_0$, with

$$
\begin{align*}
    \pi_2 &= d + \beta_s x_s^s + \beta_p x_p^p + d_s - b_0^* \mu_s, \\
    \pi_1 &= (d + \beta_s x_s^s + \beta_p x_p^p)(d_s - b_0^* \mu_s) + b_0^* \beta_s (\mu_s x_s^s + \theta \mu_p x_p^s) + b_0^* \beta_p (1 - \theta) \mu_p x_p^s, \\
    \pi_0 &= (1 - \theta) \mu_p x_p^m (b_0^*)^2 \beta_s \theta \mu_p + (d_s - b_0^* \mu_s) b_0^* \beta_p.
\end{align*}
$$
By the Routh–Hurwitz stability criterion we deduce that $\pi$ is a stable polynomial (i.e. $s_0(Y_0^*) < 0$), and then $E^*$ is l.a.s.\).

If $T_p < T_{m,p}$, again from (C.11), we have $b_0^* = \frac{b_0}{(1-\theta)T_{m,p}}$, $x_s^* = x_p^* = 0$, and the characteristic polynomial of $J_0^*$ writes $|J_0^* - zI| = (b_0^*\mu_s - d_s - z)(b_0^*(1-\theta)\mu_p - d_p - z)\times$

\[
\begin{vmatrix}
-\left( d + \sum_j \beta_j x_j^* \right) - z & -b_0^*\beta_m & -b_0^*\beta_{m,p} \\
\mu_m x_m^* + \theta \mu_m p x_m^*_{m,p} & b_0^*\mu_m - d_m - z & b_0^*\theta \mu_{m,p} \\
(1-\theta)\mu_{m,p} x_{m,p}^* & 0 & -z
\end{vmatrix}
\]

Same arguments as previously lead to the local stability of $E^*$.

**The model with mutations depending on the abundance of the parental cells**

When the occurrence of new mutants depends on the abundance of the parental cells, the model writes

\[
\dot{B}(t) = \Lambda - dB - B \sum_{j \in J} \beta_j N_j,
\]

\[
\dot{N}_s(t) = \tau_s \beta_s B N_s - (d_s + \epsilon_s) N_s + \epsilon_m N_m + \theta \tau_p \beta_p B N_p - H(N) N_s \left[ N_p + N_{m,p} \right], \\
\dot{N}_m(t) = \tau_m \beta_m B N_m - (d_m + \epsilon_m) N_m + \epsilon_s N_s + \theta \tau_p \beta_p B N_{m,p} - H(N) N_m \left[ N_{m,p} + N_p \right], \\
\dot{N}_p(t) = \tau_p \beta_p (1-\theta) B N_p - (d_p + \epsilon_p) N_p + \epsilon_m N_{m,p} + H(N) N_p \left[ N_m + N_{m,p} \right],
\]

\[
\dot{N}_{m,p}(t) = \tau_m \beta_m p (1-\theta) B N_{m,p} - (d_m + \epsilon_m p) N_{m,p} + \epsilon_p N_p + H(N) N_{m,p} \left[ N_m + N_p \right],
\]

wherein state variables and model parameters are the same as for Model (2.2).

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