The *Pseudomonas aeruginosa* polysaccharide PSL is a social but non-cheatable trait in biofilms

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Abstract
Biofilm extracellular polysaccharides are compounds secreted by microorganisms into the surrounding environment and which are important for surface attachment and maintaining structural integrity within biofilms. They have been suggested to be metabolically costly to produce, and because they are secreted, to act as co-operative shared resources within biofilm communities. These assumptions have not been experimentally well-examined. Here we empirically test the cooperative nature of the PSL polysaccharide, which is crucial for the formation of biofilms in *Pseudomonas aeruginosa*. We show that: (1) PSL provides population level benefits in biofilms, for both growth and antibiotic tolerance; (2) the benefits of PSL production are social and are shared with other cells; (3) the benefits of PSL production appear to be preferentially directed towards cells which produce PSL; (4) cells which do not produce PSL are unable to successfully exploit cells which produce PSL. Taken together, this suggests that PSL is a social but non-exploitable trait, and that growth within biofilms selects for PSL-producing strains.

Introduction
The growth and proliferative success of many bacteria, including human pathogens, depends upon their ability to form biofilms in their respective environmental niches. Biofilms are multicellular three dimensional biomass structures, held together by extracellular matrix molecules that encapsulate cells and cause them to aggregate. These extracellular polysaccharides (EPS) which are secreted by the bacteria, typically function as adhesins that are used to attach to a surface and to maintain the three-dimensional biofilm structure, and sometimes aid in protection against a variety of stresses, including dehydration, antibiotics, and predators [1, 2]. The production of EPS represents a problem from an evolutionary perspective [3], because it appears to be a type of co-operative behaviour that can potentially provide a benefit to all cells in the community, and not just to those that produce EPS. Consequently, the question arises: "what prevents the invasion of potential cheats that do not produce EPS?".

A possible solution to this problem is that EPS production may not be an exploitable co-operative trait. Xavier & Foster showed, in an individual based simulation, that if the production of EPS facilitated growth into areas where nutrient availability was greater, then EPS producing lineages could spatially smother and outcompete non-producers [4]. In this case, EPS production was costly, but the benefits were preferentially provided to nearby cells, which were likely to be EPS-producing clone mates. Some empirical support for this particular mechanism has been demonstrated in *Vibrio cholerae*, where it has been shown that EPS producing lineages are able to displace non-producers [5]. In addition, EPS producers in *V. cholerae* are also able to share other secreted public goods with each other, which provides another benefit that is preferentially directed towards other EPS producers [6, 7, 8]. However, the generality of these explanations for the evolutionary stability of EPS production remains unclear, and the work on *V. cholerae* represents the only empirical study to measure the social costs and benefits of EPS production. In addition, EPS produced by other bacterial species can vary greatly in both their chemical structure and the biological

roles they play within biofilms. Furthermore, many species produce more than one type of EPS that are sometimes but not necessarily co-regulated. This means that there may be differences in the social nature of different types of EPS, and for different bacterial species.

Pseudomonas aeruginosa is an opportunistic pathogen that causes various biofilm infections such as chronic respiratory infections of cystic fibrosis (CF), keratitis, and chronic wound infections. *P. aeruginosa* is known to produce at least three different types of EPS as major components of its biofilm matrix: alginate, PEL, and PSL polysaccharides [9, 10]. Alginate production is inversely regulated with PSL [11, 12], and is not expressed to high levels in the majority of non-CF isolates [13, 14]. In contrast, PSL is expressed in most *P. aeruginosa* natural and clinical isolates [13]. PSL is a crucial adhesive scaffolding component of the biofilm matrix, promoting both cell-to-cell interactions and surface attachment [15, 16, 17]. Here we test the social nature of PSL and find that (1) PSL production is not metabolically costly to *P. aeruginosa* cells; (2) PSL+ strains are significantly fitter than PSL- strains in mixed culture biofilms and PSL- strains cannot act as social cheats; (3) the benefit of producing PSL is enhanced when there are many PSL- cells present; (4) biofilms containing a high proportion of PSL- cells are more susceptible to antibiotics; (5) relatedness in biofilms does not matter since PSL+ strains are favoured in conditions of high and low relatedness. More generally we highlight that not all components of the biofilm matrix should be considered as shared resources.

Results

PSL provides a population level benefit in biofilms. We first asked whether PSL provides fitness benefits to a *P. aeruginosa* population growing in biofilms or planktonic/unattached cultures compared to that of populations of mutants that do not produce PSL. In order to simultaneously monitor both unattached and biofilm populations, we modified a previously described bead method [18]. This model allowed us to grow biofilms on 7 mm plastic beads in test tubes, harvest biofilm cells from the beads, and directly aspirate unattached cells from the liquid media (Fig. S1). Unattached cells were likely to include planktonic, unattached cellular aggregates, biofilm defective, and/or dispersed cells which can be transient and inseparable or indistinguishable. In this paper we unify them and refer to this sub-population as 'unattached cells'. We used two strains: a PSL+ strain that constitutively produces PSL, and a PSL- mutant that produces no PSL. PSL expression has been shown to induce the intracellular secondary messenger molecule c-di-GMP, which controls multiple biofilm-associated genes [19]. Consequently, to ensure that our results are due to PSL and not c-di-GMP, we constitutively elevated c-di-GMP (Δ*wspF* background) in both our strains, but nevertheless found that our results are c-di-GMP-independent because identical results were recorded using non-Δ*wspF* backgrounds (Fig. S2).

Our results show that PSL provides a population level benefit in biofilms but not in unattached populations (Fig. 1A). Consistent with previous reports [13, 15, 16, 17, 20], we found that over 4 days of growth, PSL mutants formed significantly less biomass and therefore poorer biofilms compared to the corresponding wild type (PSL+) (Fig. 1A; $F_{(1,15)} = 11.26$, p

= 0.0043). In contrast, we found no significant differences in final population density between the PSL+ and the PSL- strain in the unattached population of cells ($F_{(1,16)} = 0.67$, $p = 0.4251$).

In order to confirm that our unattached population results were not biased by cells that had detached from biofilms, we also performed an experiment where we added no beads and therefore the analyses were all performed on purely unattached cells. Again we found no significant differences in final population density between PSL+ and PSL- strains (Fig. S3). Since we found that a significant biomass was achieved after 1 day of biofilm growth, and in order to minimise the occurrence of rapid spontaneous mutations that can develop and accumulate in mature biofilms of *P. aeruginosa* [20], we carried out all subsequent experiments with 24 hour cultures.

PSL provides social benefits in biofilms. We then asked whether the production of PSL provides social benefits to other cells within a biofilm. We tested this in unattached populations and in biofilms, by growing the PSL- strain with either other PSL- cells or PSL+ cells in a 1:1 ratio. We found that approximately 100-fold more PSL- cells could attach and form biofilms in the presence of PSL+ compared to when PSL- was co-cultured with PSL- (Fig. 1B; $p < 0.0001$). In contrast, in unattached populations, we found that the fitness of PSL- cells was not influenced by co-culturing with PSL+ (Fig. 1B; $p > 0.08$). This indicates that the production of PSL provides some benefits to cells that do not produce it in biofilms, but not in unattached populations. Consistent with PSL+ providing a benefit to PSL- cells, we found that when we co-cultured PSL+ and PSL- strains on glass microscope slides (rather than beads), PSL- cells co-aggregated with PSL+ cells and incorporated themselves into the biofilm during the early stages of biofilm formation (Fig. 1C).

PSL mutants do not act as social cheats within biofilms. We next tested whether PSL- strains could act as social cheats, i.e. whether these strains increased in frequency when growing in mixed cultures with the PSL+ strain. We varied the starting ratios of PSL-:PSL+ cells from 0.1 to 10,000, because theory predicts that the fitness of cheats should be frequency-dependent, with cheats being better able to exploit co-operators when the cheats are rarer [21]. In biofilms, we found that the relative fitness of the PSL- cells was either equal to or lower than that of the PSL+ strain, suggesting that the PSL- cells were not able to outcompete the PSL+ cells (i.e. to cheat). The relative fitness of the PSL- strain was negatively correlated with its starting frequency in the population (Fig. 2A; $R^2 \approx 0.7329$). At high starting frequencies of PSL+, the relative fitness of the PSL- strain was not significantly different from that of the PSL+ strain. As the starting frequency of the PSL- strain was increased, the relative fitness of the PSL- strain became lower than that of the PSL- strain. In contrast, we found that in unattached populations, the relative fitness of the PSL- strain did not differ significantly from the PSL+ strain, irrespective of the starting ratio (Fig. 2A; $R^2 \approx 0.0853$).

We also tested whether the presence of the PSL- strain adversely affected biofilm production in mixed cultures. Given that PSL- strains are unable to form biofilms with the same biomass

as PSL+ strains (Fig. 1), we expected a high starting frequency of PSL- strains would adversely affect biofilm production. In contrast to this expectation, we found that the final biomass did not significantly change as we varied the starting ratio of PSL-:PSL+ cells from 0.1 to 1000 (Fig. 2B; $R^2 \approx 0.1524$). This result indicates the final biomass is determined by the PSL+ cells, which dominate long-time biofilm growth independently of the starting ratio between PSL- and PSL+. To allow us to microscopically visualise growth of the PSL- and PSL+ strain in co-inoculated biofilms, we performed a biofilm flow cell experiment with a mixed PSL+ and PSL- population. Consistent with Fig. 1C, PSL- cells appeared to co-aggregate with PSL+ cells and incorporate themselves into the early-stage biofilms (Fig. 3A and B). However, over time, the PSL+ cells covered and outcompeted the PSL- cells (Fig. 3C and D).

PSL provides population level benefits against antibiotics. PSL is known to play a role in tolerance to antibiotics including aminoglycosides [20, 22] (Fig. S4). We tested the social consequences of this tolerance by examining the effect of adding gentamicin at a concentration previously known to affect biofilm (100 μg/ml) [23] to populations that contained a variable ratio of PSL- mutants. In the absence of gentamicin, we found that the frequency of PSL- mutants did not influence the biomass of biofilm, consistent with Fig. 2B (Fig. 4A; $R^2 \approx 0.0462$). In contrast, when we added gentamicin, the biofilm biomass was negatively correlated with the fraction of PSL- mutants in the starting population (Fig. 4A). When there were more PSL- than PSL+ cells in the starting population, the addition of gentamicin led to a significant drop in viable biofilm biomass. In cases where the starting ratio of PSL-:PSL+ was greater than 10, the addition of gentamicin reduced the population to below our threshold detection level. Examining in more detail the populations which showed partial killing, we found that PSL+ cells had a significantly higher level of survival than the PSL- cells (Fig. 4B; $p < 0.02$).

Relatedness does not influence the outcome of a selection experiment. We complemented the above fitness assays with a multi-generational selection experiment. A number of previous studies on microbial social traits such as siderophore production and quorum sensing, have shown that the relative fitness of individuals that do and do not perform social traits depends upon population structure [24, 25, 26, 27]. Specifically, populations, which have a relatively high relatedness between cells, favour genotypes that support co-operative traits. Conversely, populations with relatively low relatedness between cells, favour less co-operative cheating genotypes. However, our observation that PSL- is not able to cheat PSL+ in mixed cultures, suggests that relatedness might not matter for the evolution of PSL in the same way.

We tested this hypothesis with a selection experiment over 5 days, in which we started with a mixed population of PSL+ and PSL- cells, and manipulated both relatedness (low/high) and whether cells were growing in biofilms (on beads) or in cultures with no beads (the entire population is unattached) (Fig. S5). In each round of growth, we subdivided the population into a number of subpopulations. We varied relatedness by initiating each subpopulation with either a single clone, to give relatively high relatedness, or with multiple clones, to give

relatively low relatedness. Consequently, in the high relatedness treatment the PSL+ and PSL- strains become segregated into separate populations, while the low relatedness treatment keeps them mixed together in the same population. We started our experiments with a 1:1 ratio of PSL-:PSL+, and carried out six rounds of growth.

We found that, in contrast to previous selection experiments on microbial social traits, relatedness had no significant ($F_{[1, 20]} = 1.69$, $p > 0.05$) influence on the outcome of our selection experiment (Fig. 5). Instead, we found that the relative fitness of the PSL- and PSL+ strains were determined by whether the subpopulations were grown as biofilms or in unattached populations. Specifically, the PSL+ strain was significantly ($F_{[1, 20]} = 542.7$, $p < 0.0001$) favoured in biofilms but not in unattached populations in bead-less cultures (Fig. 5). Consequently, our selection experiment provides further support for our conclusion that PSL+ is favoured in biofilms, and that PSL- strains are unable to cheat PSL+ strains.

Discussion

EPS are important components of the bacterial extracellular matrix, and EPS production has long been considered to constitute a co-operative social behaviour. Despite this, little empirical work has been performed to test this. We examined the social nature of the PSL polysaccharide produced by *P. aeruginosa* and found that: (1) PSL production provides a benefit at the group level to cells growing in biofilms (Fig. 1A); (2) PSL production provides no benefit or cost to cells growing in unattached populations (Fig. 1A and 2A); (3) PSL- strains are able to grow better as biofilms when in a mixed culture with PSL+ cells (Fig. 1B); (4) PSL+ strains are able to outcompete PSL- strains when in mixed culture biofilms, such that PSL- strains cannot successfully exploit (cheat) the PSL production of the PSL+ strain (Fig. 2A); (5) the relative fitness of the PSL- strain is lower when the PSL+ strain is rarer (negative frequency dependence; Fig. 2A); (6) the presence of PSL- cells has a negligible influence on overall biofilm productivity (Fig. 2B); (7) biofilms containing a higher proportion of PSL+ cells are less susceptible to antibiotics (Fig. 4A); (8) PSL+ cells are better able to survive antibiotics when growing in a mixed culture biofilm with PSL- cells (Fig. 4B); (9) in a selection experiment, the relative success of PSL+ versus PSL- was not influenced by relatedness, for growth in biofilms (Fig. 5).

Overall, our results suggest that in biofilms, the production of PSL is a social trait, which provides benefits at the individual and group level, but that it cannot be successfully cheated by individuals who do not produce it despite some evidence that the PSL- subpopulation benefits from the presence of PSL in the biofilm matrix. Our experiments suggest that the fitness benefits of producing PSL accrue mainly to the producing cell and to other PSL+ cells. This contrasts with previous studies in *P. aeruginosa,* where it has been shown that siderophore production and quorum sensing (QS) are social traits that can be readily exploited by cheats *in vitro, in vivo* and in biofilms [24, 25, 27, 28]. We suggest that this is because siderophores and QS-dependent public goods are freely diffusible secreted products that provide shared benefits to both producing and non-producing cells. In contrast, since its

primary function is adhering to cells and attached surfaces, PSL likely has limited diffusive properties in the biofilm biomass. PSL was previously shown to localise primarily to the periphery of the biofilm microcolonies, encapsulating the cells [29]. In addition, some PSL is known to be tightly associated to the cell surface [30], although some is likely to be diffusible, and serves as an intercellular signalling molecule [19]. This signalling property of PSL also promotes co-ordinated, community-level gene expression towards PSL production, since PSL has been shown to promote its own expression in a feed-forward manner, similar to that of an auto-induction regulatory cascade.

Our work shows both similarities and differences with a previous individual-based simulation of biofilms which studied competition between strains that do and do not produce EPS [4]. In this paper, the following parameters and observations were made: (1) EPS production is costly where mono-cultures of EPS- strains have a higher growth rate than EPS+; (2) secretion of EPS allows producing cells to push descendants into more oxygen-rich environments which suffocates non-producers; (3) EPS producers most easily invade biofilms containing a high proportion of non-producers. We did not find that PSL production has a significant effect on bacterial fitness. When we compared PSL+ and PSL- strains in unattached populations, we found no significant differences in growth (Fig. 1A). It is possible that in our culturing condition, growth is limited by other factors, such as the availability of essential minerals and metal ions. We did find that, in biofilms, PSL producing cells grow over the top of non-producing cells (Fig. 3C and D). However, it is hard to disentangle whether this is a property of the oxygen/nutrient gradient, or whether it is the property of differing adhesive strengths between PSL+ and PSL- cells, as PSL- cells are less adhesive and are more prone to be detached from the biofilm biomass in constant flow conditions when exposed on the surface. Detachment was not a consideration of the Xavier and Foster model.

Our experiments suggest that PSL production cannot be cheated, and hence should be favoured even in low relatedness mixed cultures. Therefore, we tested the effect of relatedness on selection for PSL production in biofilms, using a selection experiment (Fig. 5). In our experiment, high relatedness implied that cultures were established with either PSL+ or PSL- strains. Under these conditions, cells will interact with genetically identical cells, and PSL- cells cannot interact with PSL+ cells. In contrast, low relatedness implies that cultures can be comprised of both PSL+ and PSL- strains, such that PSL- cells can theoretically exploit the PSL+ cells. We found that relatedness had no effect on our results; PSL+ strains were favoured in conditions of high and low relatedness in biofilms but not in non-biofilm populations. Therefore in mixed culture biofilms, a PSL producer always wins, in contrast to previous work on siderophore production and QS [24, 25, 27, 28]. In these previous studies, high relatedness led to wild type cells increasing in frequency and low relatedness led to mutants being able to exploit wild type cells. Our selection experiment provides further evidence that the benefits of producing PSL directly affect the producing cells and that PSL production is not exploitable by non-producing cheats.

We further demonstrated that PSL helps protect biofilm communities against environmental insults. When biofilms contain a high proportion of PSL- cells, this leads to a significant increase in the susceptibility to antibiotics (Fig. 4A). Within these biofilms, PSL+ cells showed a higher level of survival than the PSL- cells (Fig. 4B), indicating that the protection provided to the cells by PSL is most beneficial for the producing cells. This is likely due to PSL being both cell-associated and released into the media [11]. While PSL- cells can readily access released PSL, they do not have access to cell-associated PSL. One possibility is that there are functional differences for providing antibiotic tolerance between cell-associated PSL and released PSL. Alternatively, the relative PSL concentration may simply be higher in closer proximity to the cell surface, providing a higher level of protection against antibiotics. The exact mechanism of antibiotic tolerance by PSL is not known, and this therefore remains an open question.

Arguments have been made previously, that *P. aeruginosa* cells, even when they are in the 'planktonic' phase, have biofilm-like features [3129]. In our bead biofilm model, the unattached cell population, particularly those cells which constitutively express EPS, contain large numbers of cellular aggregates, as seen previously in shaken liquid cultures [19, 2918, 26]. However, our results clearly distinguish the social evolutionary differences between the cells in the biofilm and unattached cells, thus providing evidence that unattached cells, whether they are aggregated or not, are definitively distinct from surface-attached biofilm cells. This raises the question whether aggregates represent a type of biofilm, are 'biofilm-like', or represent a different growth mode altogether. This is an important question since *P. aeruginosa* biofilms growing on infected contact lens, catheters, and other medical implants form surface-associated biofilms, but within the cystic fibrosis sputum, the bacteria are thought to grow as suspended aggregates [32, 33, 3430].

Most strains of *P. aeruginosa*, like many other microbial species, are capable of producing multiple biofilm EPS molecules [13, 3512]. Of these, PSL and PEL are co-regulated by several intracellular regulatory factors including c-di-GMP [3631] and both contribute to biofilm development in a majority of *P. aeruginosa* strains including PAO1 [13]. Intriguingly, in additional experiments, we found that the social aspects of PEL production are different from those of PSL, pointing towards PEL as being a completely private and non-social good (Fig. S6). This is in contrast to recent work inspecting the competitive fitness of PEL producers using the PA14 strain, which showed community-level benefits in some circumstances [37]. PA14 has a deletion mutation in the *psl* promoter through *pslD* gene, and the nature of biofilm formation in this strain, which uses PEL polysaccharide as the sole EPS, appears to have diverged from that of other *P. aeruginosa* isolates. It remains to be seen to what degree in PA14, PEL production has compensated for the loss of PSL on the social evolutionary scale. These results highlight the importance of recognising diverse roles and effects of different EPS as social traits within biofilms. The extracellular matrix is the material that keeps microbial cells together in a biofilm community, influencing their social interactions and evolution. As such we believe it holds an important foundation for our understanding of the multicellularity of unicellular organisms.

Methods

Bacterial strains and growth conditions. The bacterial strains and plasmids we used and constructed for this study are listed in Table S1. We propagated *Escherichia coli* and *P. aeruginosa* strains in Lysogeny Broth (LB) at 37°C unless otherwise specified. The concentrations of antibiotics we used for *E. coli* were: 50 μg/ml carbenicillin and 10 μg/ml gentamicin, and for *P. aeruginosa*: 300 μg/ml carbenicillin and 100 μg/ml gentamicin. We induced P_{BAD}-*psl* strains for PSL over-expression by adding 1 % w/v L-arabinose. PSL is involved in a feed-forward regulation system where the expression of PSL induces the intracellular levels of c-di-GMP, which in turns over-expresses PSL [19]. To avoid c-di-GMP being inadvertently triggered in our biofilm system, which would potentially affect the interpretations of our results when other c-di-GMP-induced gene products become involved, all strains used in our studies were conducted using a Δ*wspF* mutation background. Δ*wspF* mutants express biologically maximal intracellular c-di-GMP levels due to the constitutive activation of diguanylate cyclase WspR [38].

Fluorescent strain construction. We chromosomally labelled *P. aeruginosa* strains with either GFP or mCherry using the Tn7 delivery system [39]. We electroporated 1 μl pTNS3 + 1 μl pUC18-mini-Tn7T2-PA1/04/03::*gfp* or pUC18-mini-Tn7T2-PA1/04/03::*mcherry* into a respective electrocompetent *P. aeruginosa* strain as previously described [40] and selected for gentamicin resistance. We removed the construct backbone by electroporating 1 μl pFLP2 and selecting for carbenicillin resistance. Upon sucrose counter-selection to identify the loss of the *sacB* gene-containing pFLP2 by streaking for single colonies on LB (no salt) plus 10 % sucrose at 30°C, we confirmed the strains for carbenicillin and gentamicin sensitivities.

Bead biofilm culture system. We grew biofilm cultures on plastic beads as previously described [18] but with several modifications (Figure S1). We used this system because it allowed us to simultaneously study biofilm and unattached populations. This system differs from traditional flow cell models in that it is closed, and unattached populations are not lost due to flow. Therefore any differences that we observe are reflective of biofilm vs unattached populations instead of 'biofilm cells being the only ones left', which can occur in a flow cell system. We streaked *P. aeruginosa* strains to obtain single colonies on M9 + 3.062 g/l sodium citrate (M9 citrate) agar at 37°C for 2 days. We picked individual fresh colonies and grew these to logarithmic phase ($OD_{600} \approx 0.5$) in M9 citrate broth at 37°C with shaking. We then diluted these cultures to $OD_{600} \approx 0.05$ into 3 ml M9 citrate containing one or more (up to three) 7mm plastic beads (Lascells) in standard culture tubes into independent triplicates. We then grew the cultures at 37°C with shaking at 200 rpm for 24 hours. We directly aspirated unattached cells from the liquid broth portion of the culture. We collected biofilm cells by retrieving the beads from the tubes, and gently washed the beads in 10 ml PBS by five inversions which we repeated three times. We determined the colony forming units (CFU) of the biofilms by recovering the cells by water bath sonication in 1 ml PBS for 10 min. We vortexed the sonicated samples for 10 sec prior to serial dilution and plating.

Antibiotic killing assays. For antibiotic killing assays (Fig. 4),we first grew bead biofilm cultures for 24 hours in the absence of gentamicin. Half the cultures were then introduced to 100 μg/ml gentamicin (final concentration), and the other half were left untreated. We then further incubated the cultures for 24 more hours at 37°C with shaking prior to harvesting the cells for analyses.

Determining ratios of PSL+ and PSL- cells in mixed cultures. To distinguish between PSL+ and PSL- cells, we introduced a single chromosomal copy of constitutively expressed GFP or mCherry genes to each strain. We then used quantitative real-time PCR and primers specifically designed against GFP or mCherry genes to accurately assess the numbers of each strains present in a sample. In order to avoid the effects of PEL, which is co-regulated with PSL, interfering with or convoluting PSL-dependent phenotypes, we conducted all experiments using Δ*pel* mutant backgrounds.

Quantitative real-time PCR. We collected genomic DNA (gDNA) from biofilm cells from washed beads without the sonication steps by directly applying lysing reagents to the beads. We isolated unattached bacterial gDNA by pelleting 1 ml of the liquid cultures. We then stored pellets and beads at -20°C until DNA extraction. We extracted gDNA using a GenElute^{TM} Bacterial Genomic DNA Kit (Sigma) according to the manufacturer's protocol except for the elution buffer which we diluted 100-fold to prevent EDTA interfering with the subsequent DNA polymerase reactions. We performed real-time PCR as previously described [19] using Syber Green PCR Master Mix (Applied Biosystems). The primers we used are listed in Table S2. We generated standard curves for *gfp* and *mcherry* genes using quantitatively determined gDNA from Δ*pel* Δ*psl* GFP strain and Δ*pel* Δ*psl* mCherry strain respectively.

Flow cell growth and confocal microscopy of biofilms. We grew mixed Δ*pel* Δ*psl* and Δ*pel* aggregates in a continuous flow cell system as described previously [41]. We produced the mixed aggregates by mixing exponential growing liquid cultures, adjusted to an OD_{600} of 0.001, 1:1 in LB media. This mix was then incubated overnight shaken at 180 rpm. We diluted the aggregate-containing culture to an OD_{600} of 0.01 before inoculating the flow cells with 27G syringes. We used a flow rate of 3 ml hour^{-1} of M9 minimal media buffered with 10 % v/v A10 phosphate buffer supplemented with 0.3 mM glucose. With a Zeiss Imager.Z2 microscope with LSM 710 CLSM and the accompanying software Zeiss Zen 2010 v. 6.0, we found aggregates containing a mix of the GFP- and the mCherry-tagged cells. We imaged these aggregates over time with z-stack intervals of 1 μm. 3D projections of images were produced in Imaris (Bitplane, Switzerland). We quantified biomass of the two tagged populations with the open source software FIJI (LOCI) and the plugin Voxel_Counter (NIH).

Biofilm selection experiment. In order to determine potential fitness of PSL production, we performed a selection experiment over 6 rounds of growth, with four different treatment regimens; relatively low and relatively high relatedness (Lr and Hr, respectively) (Fig. S5). The Hr treatment started with three 3 ml subpopulations of diluted logarithmic phase PSL+ cells and PSL- cells (n = 6). In contrast, the Lr treatment started with six subpopulations of a

3 ml 1:1 mix of PSL+ and PSL- cells (n = 6). We grew cultures at 37ºC with shaking at 200 rpm for 24 hours in the presence/absence of plastic beads. We recovered biofilm cells as detailed previously and pooled together prior to serial dilution and plating. We recovered 1ml of unattached cells from the liquid media *in lieu* of plastic beads, and subjected to the same treatment (omitting the three wash stages). We determined the ratio of PSL+ and PSL- cells in each treatment regimen phenotypically; PSL+ and PSL- cells have rugose and smooth colony morphologies, respectively. For Hr treatments we then randomly selected six clones to inoculate 3 ml M9 citrate and progress to the next round, whereas for LR treatments, we randomly took a sweep of multiple colonies. We grew cultures at 37ºC with shaking at 200 rpm for 24 hours in the presence/absence of plastic beads adding an additional round of selection. We repeated this experiment six times, with six selection lines per treatment regimen.

Mathematical formula and statistics. We determined relative fitness (*w*) of the PSL- strain using the following formula: $w = x_2 (1 - x_1)/x_1 (1 - x_2)$, where x_1 is the starting mutant proportion of the population and x_2 is the end mutant proportion [21]. All error bars denote standard errors of the mean. One-on-one comparative *p* values were determined using unpaired *t* tests and analysed with GraphPad Prism, regression analyses on Microsoft Excel, and one-way and two-way analyses of variants were performed on VassarStats (http://vassarstats.net/).

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Competing financial interests

The authors declare no competing or conflicts of financial interests associated with this manuscript.

References

1. Flemming HC. Biofilms and Environmental-Protection. *Water Sci Technol* **27**, 1-10 (1993).

2. Flemming HC, Neu TR, Wozniak DJ. The EPS matrix: the "house of biofilm cells". *J Bacteriol* **189**, 7945-7947 (2007).

3. Boyle KE, Heilmann S, van Ditmarsch D, Xavier JB. Exploiting social evolution in biofilms. *Curr Opin Microbiol* **16**, 207-212 (2013).

4. Xavier JB, Foster KR. Cooperation and conflict in microbial biofilms. *Proc Natl Acad Sci U S A* **104**, 876-881 (2007).

5. Schluter J, Nadell CD, Bassler BL, Foster KR. Adhesion as a weapon in microbial competition. *ISME J* **9**, 139-149 (2015).

6. Drescher K, Nadell CD, Stone HA, Wingreen NS, Bassler BL. Solutions to the public goods dilemma in bacterial biofilms. *Curr Biol* **24**, 50-55 (2014).

7. Nadell CD, Bassler BL. A fitness trade-off between local competition and dispersal in *Vibrio cholerae* biofilms. *Proc Natl Acad Sci U S A* **108**, 14181-14185 (2011).

8. Nadell CD, Drescher K, Wingreen NS, Bassler BL. Extracellular matrix structure governs invasion resistance in bacterial biofilms. *ISME J* **9**, 1700-1709 (2015).

9. Franklin MJ, Nivens DE, Weadge JT, Howell PL. Biosynthesis of the *Pseudomonas aeruginosa* Extracellular Polysaccharides, Alginate, Pel, and Psl. *Front Microbiol* **2**, 167 (2011).

10. Ryder C, Byrd M, Wozniak DJ. Role of polysaccharides in *Pseudomonas aeruginosa* biofilm development. *Curr Opin Microbiol* **10**, 644-648 (2007).

11. Byrd MS*, et al.* Genetic and biochemical analyses of the *Pseudomonas aeruginosa* Psl exopolysaccharide reveal overlapping roles for polysaccharide synthesis enzymes in Psl and LPS production. *Mol Microbiol* **73**, 622-638 (2009).

12. Jones CJ, Ryder CR, Mann EE, Wozniak DJ. AmrZ modulates *Pseudomonas aeruginosa* biofilm architecture by directly repressing transcription of the *psl* operon. *J Bacteriol* **195**, 1637-1644 (2013).

13. Colvin KM*, et al.* The Pel and Psl polysaccharides provide *Pseudomonas aeruginosa* structural redundancy within the biofilm matrix. *Environ Microbiol* **14**, 1913-1928 (2012).

14. Wozniak DJ*, et al.* Alginate is not a significant component of the extracellular polysaccharide matrix of PA14 and PAO1 *Pseudomonas aeruginosa* biofilms. *Proc Natl Acad Sci U S A* **100**, 7907-7912 (2003).

15. Friedman L, Kolter R. Two genetic loci produce distinct carbohydrate-rich structural components of the *Pseudomonas aeruginosa* biofilm matrix. *J Bacteriol* **186**, 4457-4465 (2004).

16. Jackson KD, Starkey M, Kremer S, Parsek MR, Wozniak DJ. Identification of *psl*, a locus encoding a potential exopolysaccharide that is essential for *Pseudomonas aeruginosa* PAO1 biofilm formation. *J Bacteriol* **186**, 4466-4475 (2004).

17. Matsukawa M, Greenberg EP. Putative exopolysaccharide synthesis genes influence *Pseudomonas aeruginosa* biofilm development. *J Bacteriol* **186**, 4449-4456 (2004).

18. Poltak SR, Cooper VS. Ecological succession in long-term experimentally evolved biofilms produces synergistic communities. *ISME J* **5**, 369-378 (2011).

19. Irie Y*, et al.* Self-produced exopolysaccharide is a signal that stimulates biofilm formation in *Pseudomonas aeruginosa*. *Proc Natl Acad Sci U S A* **109**, 20632-20636 (2012).

20. Kirisits MJ, Prost L, Starkey M, Parsek MR. Characterization of colony morphology variants isolated from *Pseudomonas aeruginosa* biofilms. *Appl Environ Microbiol* **71**, 4809-4821 (2005).

21. Ross-Gillespie A, Gardner A, West SA, Griffin AS. Frequency dependence and cooperation: theory and a test with bacteria. *Am Nat* **170**, 331-342 (2007).

22. Billings N*, et al.* The Extracellular Matrix Component Psl Provides Fast-Acting Antibiotic Defense in *Pseudomonas aeruginosa* Biofilms. *PLoS Pathog* **9**, e1003526 (2013).

23. Bowler LL, Zhanel GG, Ball TB, Saward LL. Mature *Pseudomonas aeruginosa* biofilms prevail compared to young biofilms in the presence of ceftazidime. *Antimicrob Agents Chemother* **56**, 4976-4979 (2012).

24. Diggle SP, Griffin AS, Campbell GS, West SA. Cooperation and conflict in quorum-sensing bacterial populations. *Nature* **450**, 411-414 (2007).

25. Griffin AS, West SA, Buckling A. Cooperation and competition in pathogenic bacteria. *Nature* **430**, 1024-1027 (2004).

26. Maclean RC, Brandon C. Stable public goods cooperation and dynamic social interactions in yeast. *J Evol Biol* **21**, 1836-1843 (2008).

27. Rumbaugh KP, Trivedi U, Watters C, Burton-Chellew MN, Diggle SP, West SA. Kin selection, quorum sensing and virulence in pathogenic bacteria. *Proc Biol Sci* **279**, 3584-3588 (2012).

28. Popat R, Crusz SA, Messina M, Williams P, West SA, Diggle SP. Quorum-sensing and cheating in bacterial biofilms. *Proc Biol Sci* **279**, 4765-4771 (2012).

29. Borlee BR, Goldman AD, Murakami K, Samudrala R, Wozniak DJ, Parsek MR. *Pseudomonas aeruginosa* uses a cyclic-di-GMP-regulated adhesin to reinforce the biofilm extracellular matrix. *Mol Microbiol* **75**, 827-842 (2010).

30. Ma L, Jackson KD, Landry RM, Parsek MR, Wozniak DJ. Analysis of *Pseudomonas aeruginosa* conditional Psl variants reveals roles for the Psl polysaccharide in adhesion and maintaining biofilm structure postattachment. *J Bacteriol* **188**, 8213-8221 (2006).

31. Schleheck D*, et al. Pseudomonas aeruginosa* PAO1 preferentially grows as aggregates in liquid batch cultures and disperses upon starvation. *PloS one* **4**, e5513 (2009).

32. Kragh KN*, et al.* Role of Multicellular Aggregates in Biofilm Formation. *mBio* **7**, (2016).

33. Melaugh G*, et al.* Shaping the Growth Behaviour of Biofilms Initiated from Bacterial Aggregates. *PloS one* **11**, e0149683 (2016).

34. Staudinger BJ*, et al.* Conditions associated with the cystic fibrosis defect promote chronic *Pseudomonas aeruginosa* infection. *Am J Respir Crit Care Med* **189**, 812-824 (2014).

35. Colvin KM*, et al.* The *pel* polysaccharide can serve a structural and protective role in the biofilm matrix of *Pseudomonas aeruginosa*. *PLoS Pathog* **7**, e1001264 (2011).

36. Hickman JW, Harwood CS. Identification of FleQ from *Pseudomonas aeruginosa* as a c-di-GMP-responsive transcription factor. *Mol Microbiol* **69**, 376-389 (2008).

37. Madsen JS*, et al.* Facultative control of matrix production optimizes competitive fitness in *Pseudomonas aeruginosa* PA14 biofilm models. *Appl Environ Microbiol* **81**, 8414-8426 (2015).

38. Hickman JW, Tifrea DF, Harwood CS. A chemosensory system that regulates biofilm formation through modulation of cyclic diguanylate levels. *Proc Natl Acad Sci U S A* **102**, 14422-14427 (2005).

39. Choi KH*, et al.* A Tn7-based broad-range bacterial cloning and expression system. *Nat Methods* **2**, 443-448 (2005).

40. Choi KH, Kumar A, Schweizer HP. A 10-min method for preparation of highly electrocompetent *Pseudomonas aeruginosa* cells: application for DNA fragment transfer between chromosomes and plasmid transformation. *J Microbiol Methods* **64**, 391-397 (2006).

41. Crusz SA*, et al.* Bursting the bubble on bacterial biofilms: a flow cell methodology. *Biofouling* **28**, 835-842 (2012).

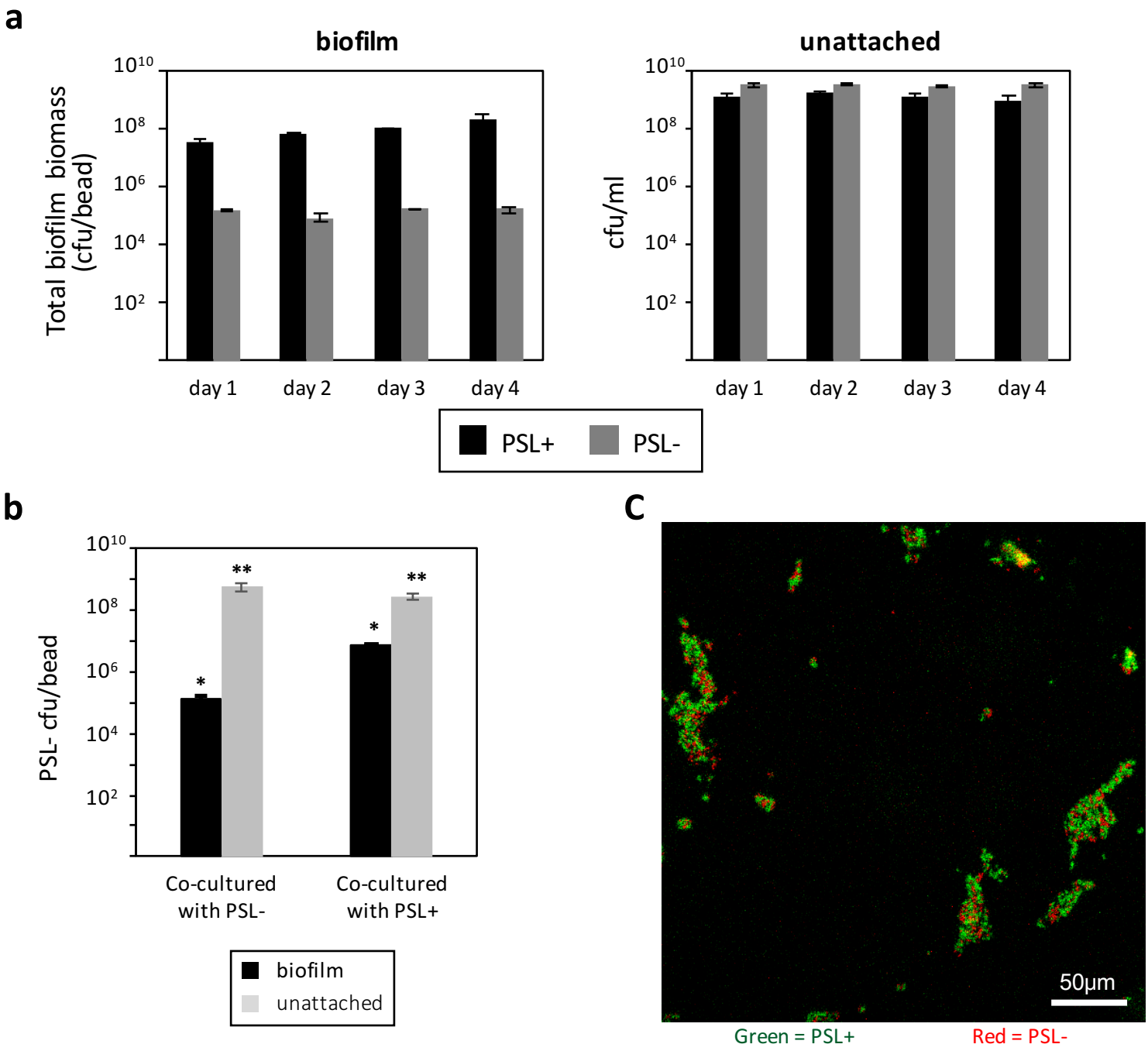


Figure 1. PSL production provides community benefits to cells grown in biofilms. (a) PSL- strain is significantly defective in biofilm formation on beads compared to PSL+, but no major differences are seen between their growth in the unattached fractions. (b) PSL- co-cultured with PSL+ at a 1:1 ratio increases their proportional numbers in a biofilm (* $p < 0.0001$; ** $p > 0.08$). (c) Confocal micrograph image of surface attached populations of PSL-/PSL+ 1:1 co-cultures. PSL- cells (red) co-aggregate with PSL+ cells (green).

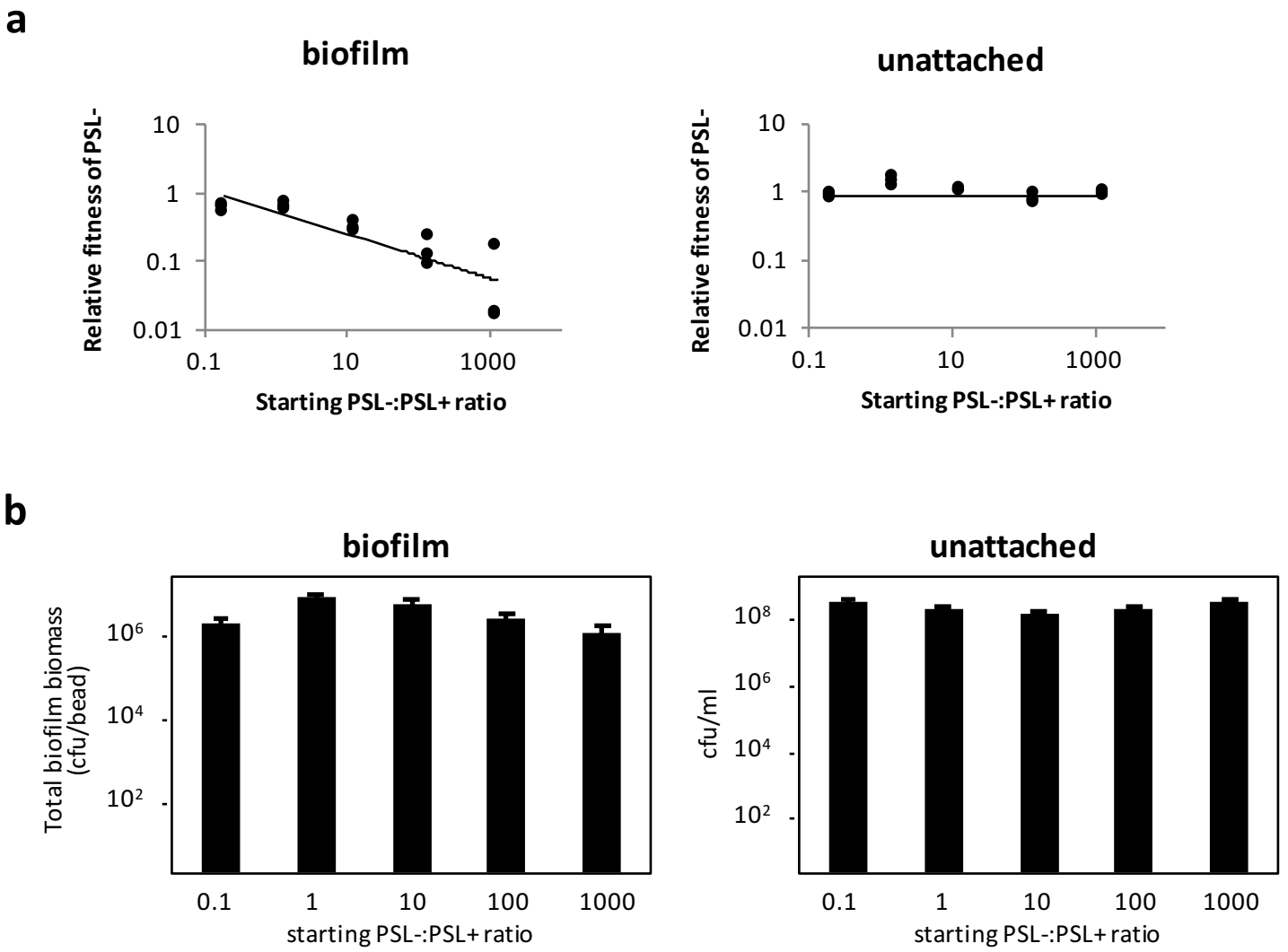


Figure 2. PSL mutants are not social cheats within biofilms. (**a**) The relative fitness of PSL- cells was equal or lower than the PSL+ strain across all starting frequencies of the mutant in mixed cultures in biofilms. PSL- strain fitness was equal to PSL+ strain fitness across all starting frequencies in unattached populations. (**b**) PSL-/PSL+ co-culture biomass remained similar across all starting ratios in both biofilm and unattached populations.

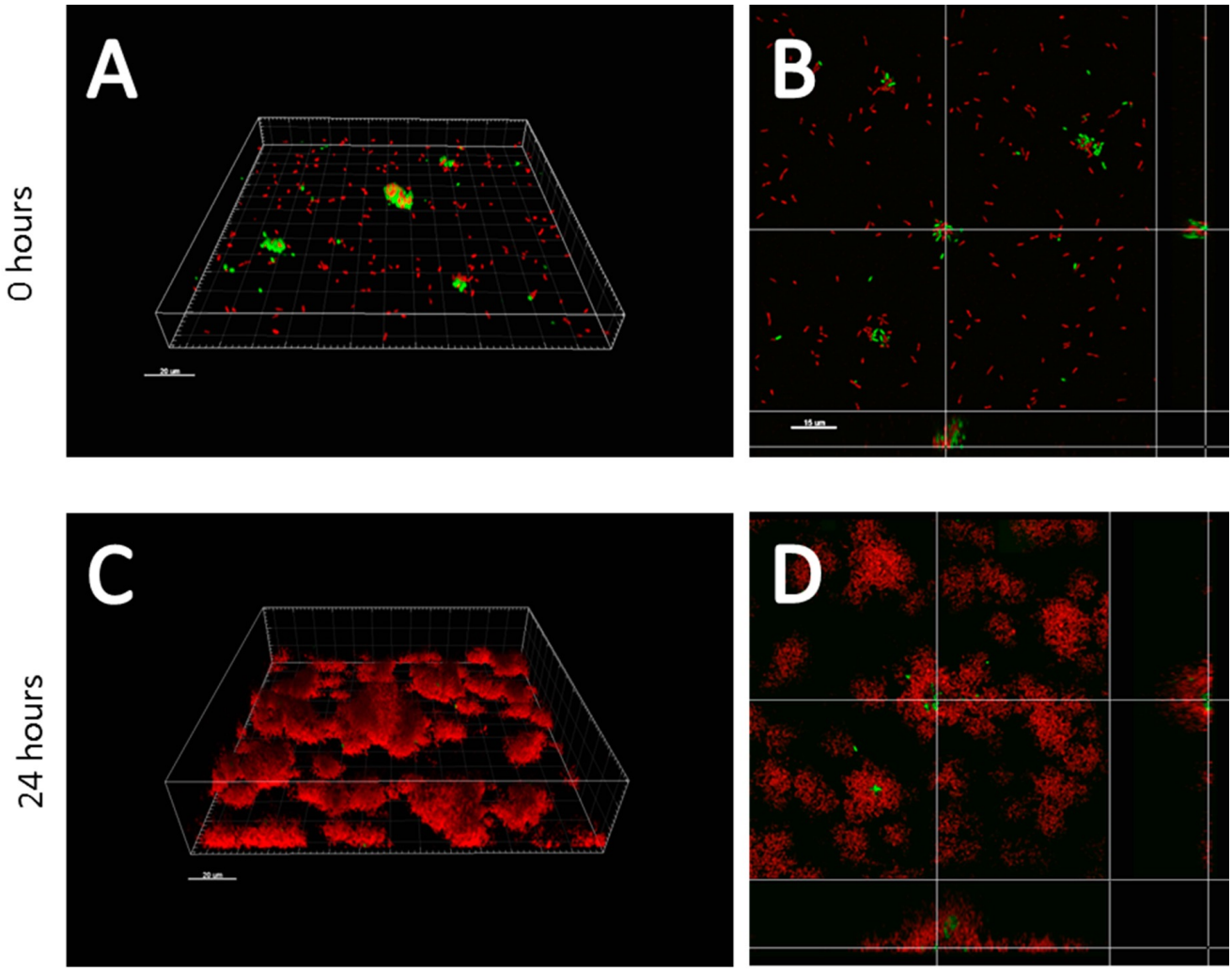
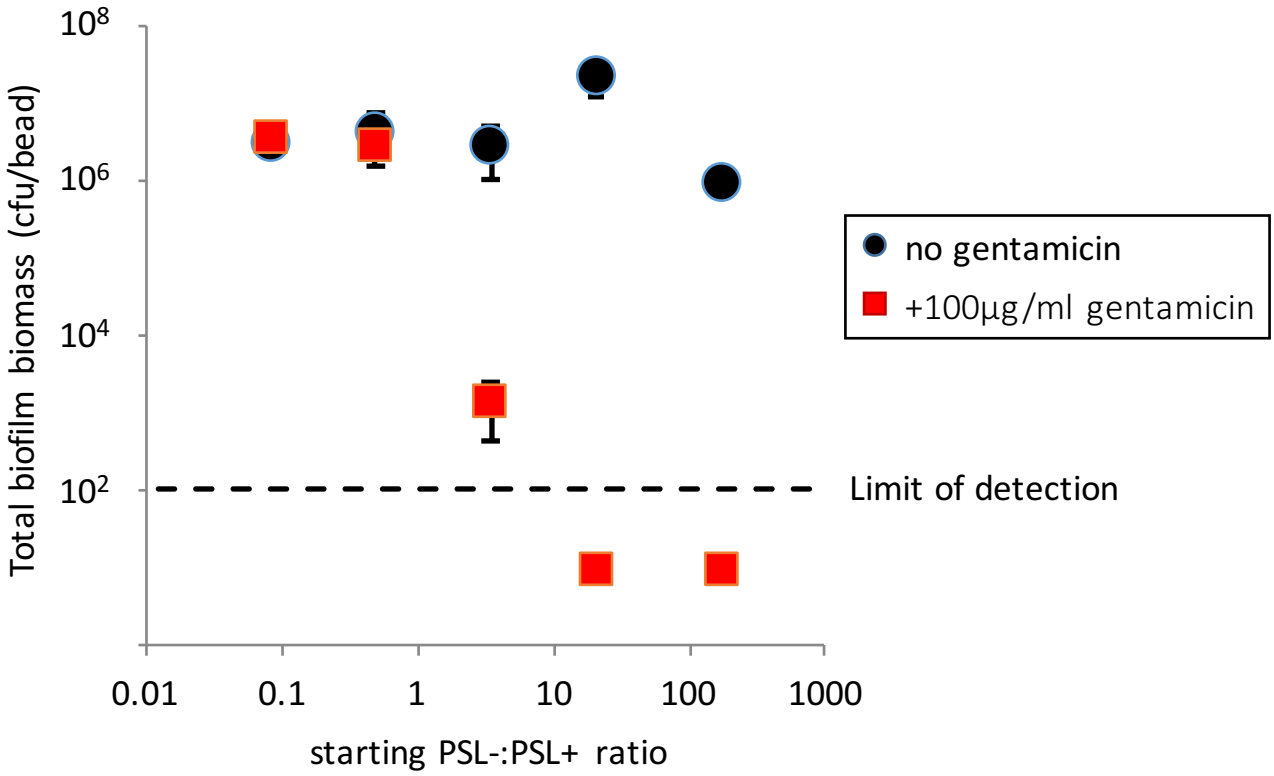


Figure 3. The PSL+ strain smothers and outcompetes the PSL- strain during biofilm growth. Confocal micrograph image of PSL-/PSL+ (1:1) mixed population biofilms at 0 hours (**a** and **b**) and 48 hours (**c** and **d**). PSL- cells are only attached to the surface as co-aggregates with PSL+, and they are eventually outcompeted by PSL+ when the biofilm matures. **a** and **c** are 3D rendered images and **b** and **d** represent corresponding open-box top-down views. Red = PSL+ cells. Green = PSL- cells.

a



b

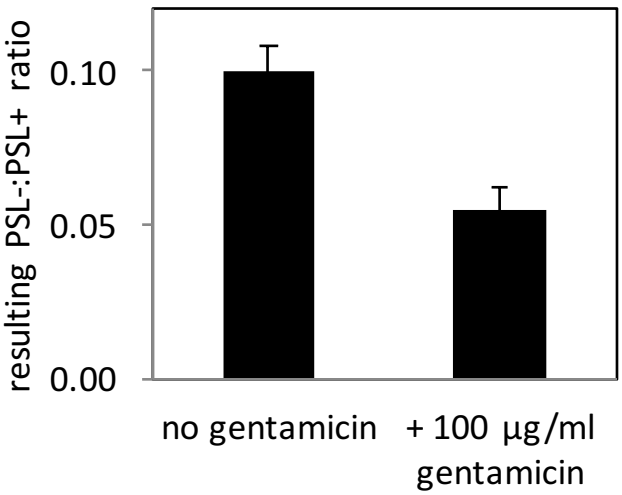


Figure. 4. PSL production results in increased tolerance towards antibiotics. (**a**) Whilst PSL-/PSL+ mixed biofilms yielded consistent biomass regardless of the starting ratio of the two strains, treatment of the mixed biofilm with a high concentration of gentamicin eliminated the entire biofilm population when the starting proportion of PSL- cells increased above PSL+. (**b**) In the intermediate PSL-:PSL+ co-culture ratio, where mixed biofilm was partially eradicated, there were less PSL- cells in the surviving biofilm in the presence of gentamicin. ($p < 0.02$).

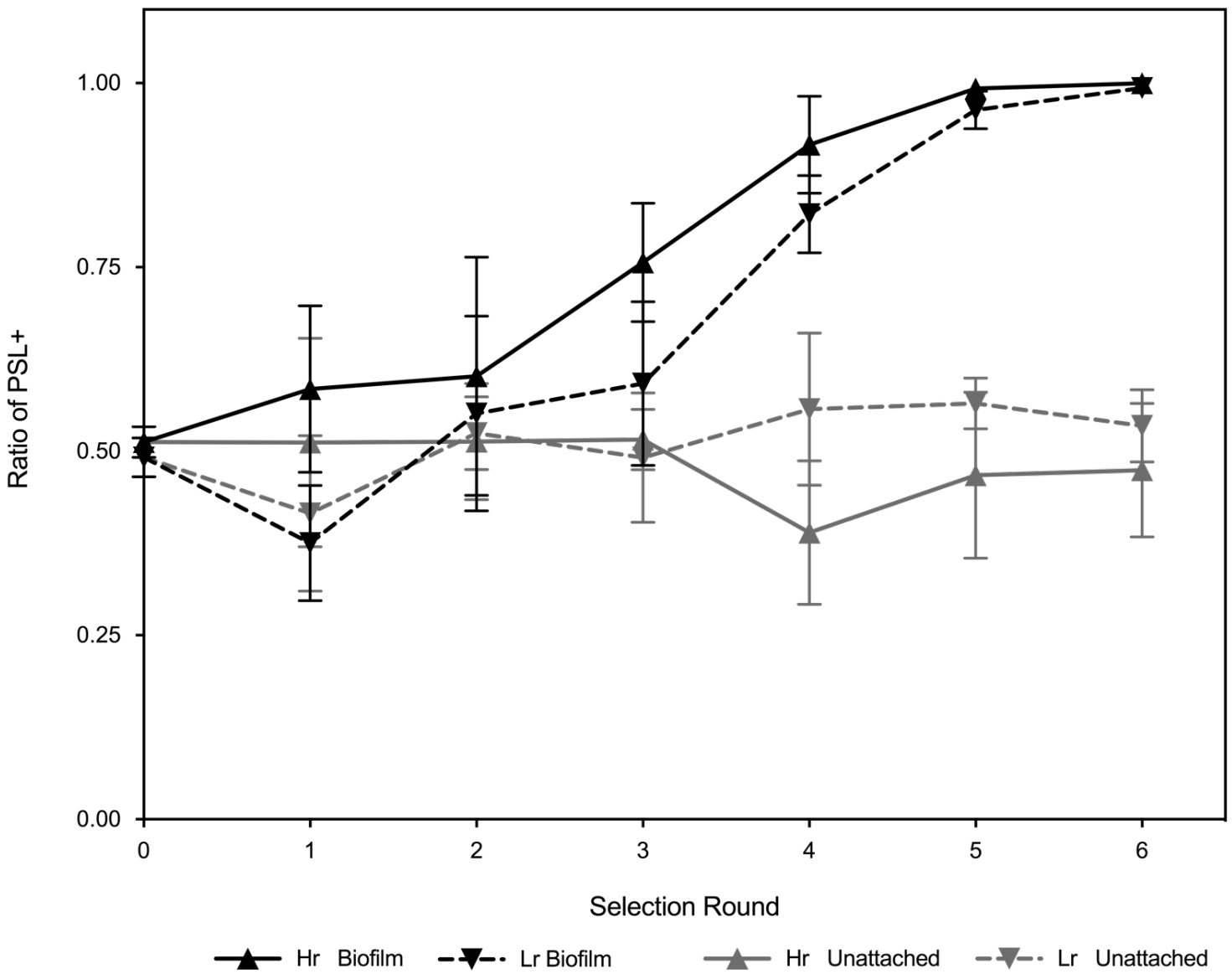


Figure. 5. PSL production is favoured in high and low relatedness conditions in biofilms. PSL+ cells have a selective advantage under conditions promoting biofilm formation (black), however this observation is not reciprocated for unattached conditions (grey). The concurrent loss of PSL- cells from both low related and high related biofilm populations through subsequent selection rounds, suggests there is a strong selection towards PSL+ strains (under biofilm-promoting conditions only) as PSL- strains are unable to cheat on PSL+ strains.

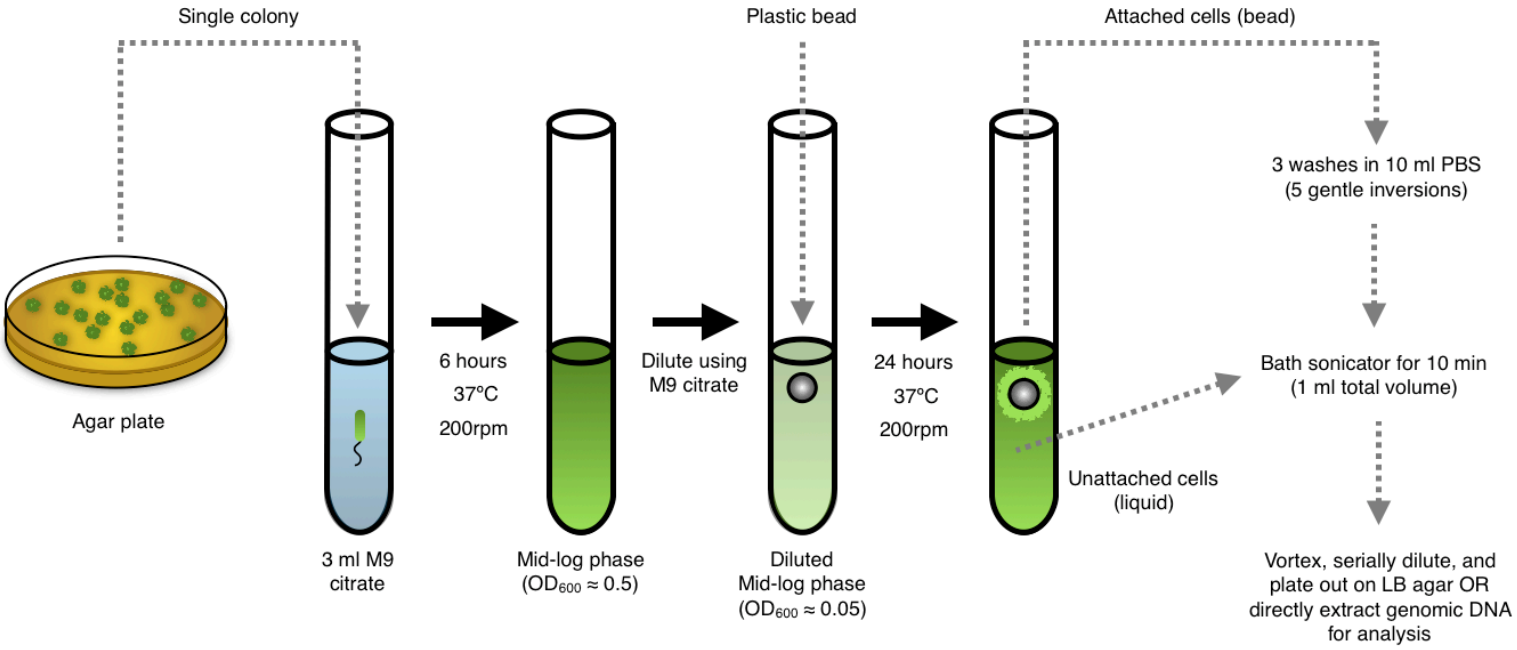


Figure S1. Schematic of the bead biofilm system.

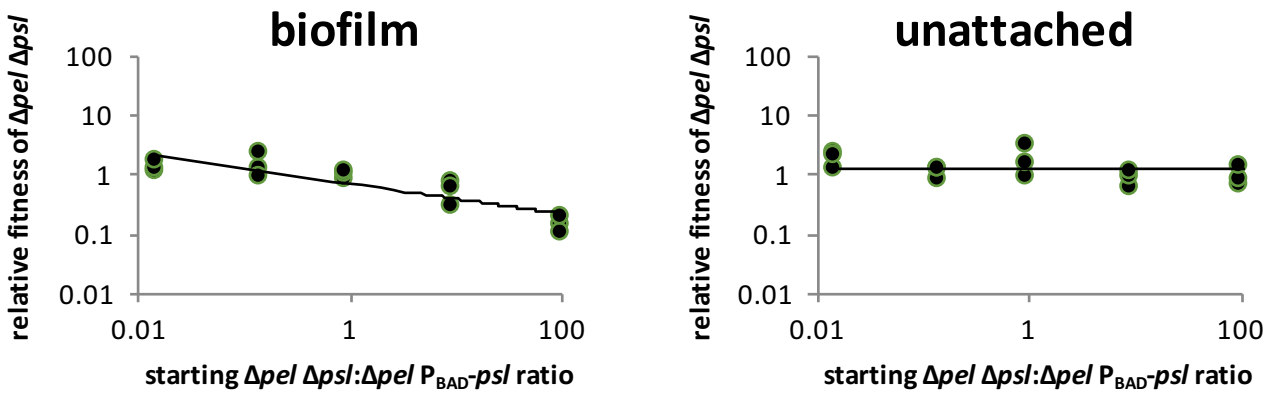


Figure S2. PSL-dependent social traits are independent of c-di-GMP. While the experiments in the main figures were performed using Δ*wspF* to remove c-di-GMP and other c-di-GMP-regulated factors from playing a role in our interpretations, repeating the experiment without mutating *wspF* yielded identical results for both biofilm populations (left panel) and unattached populations (right panel) with the results shown in Fig. 2A, despite Δ*pel* Δ*psl* having low intracellular c-di-GMP and Δ*pel* P_{BAD}-*psl* having high intracellular c-di-GMP. The cultures were grown in 1% L-arabinose.

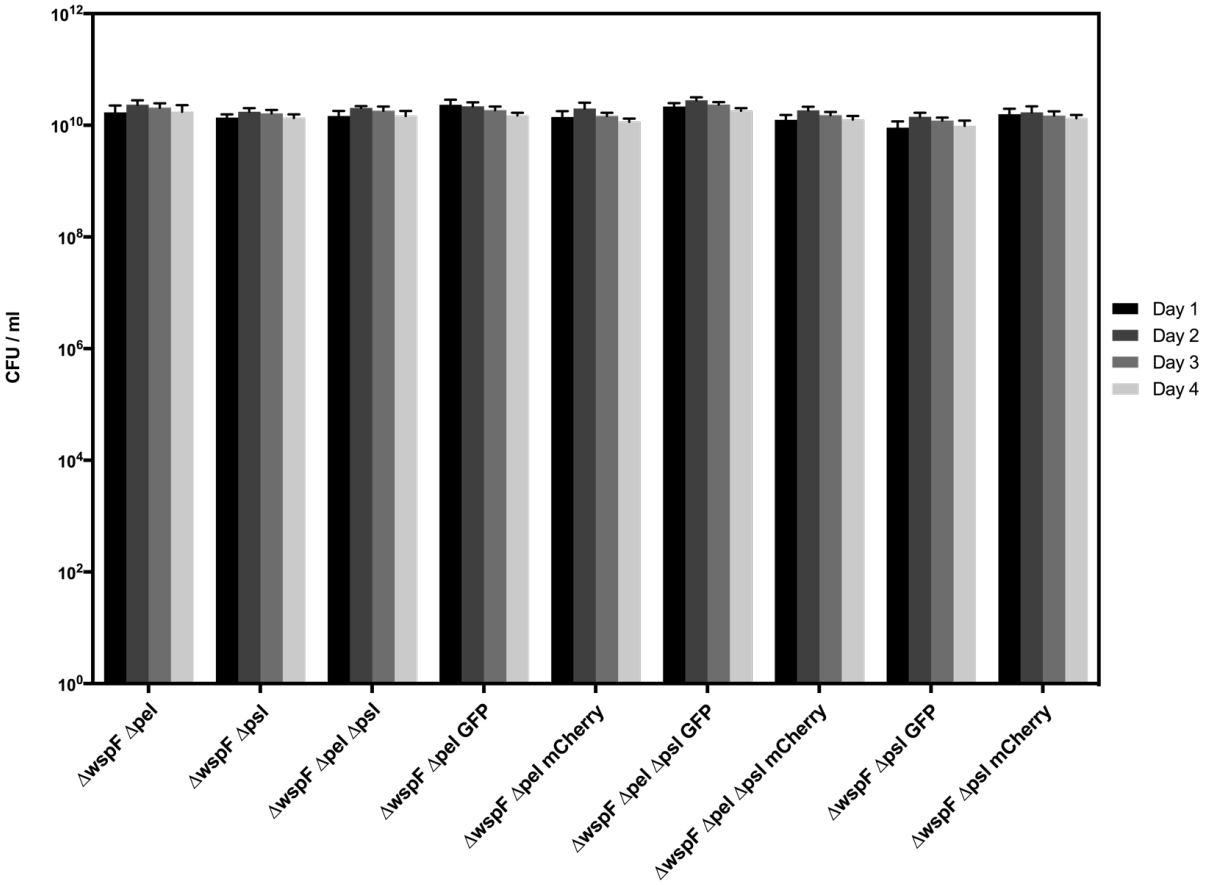


Figure S3. EPS mutant strains show no observable differences in growth over four-days in bead-less culture tubes.

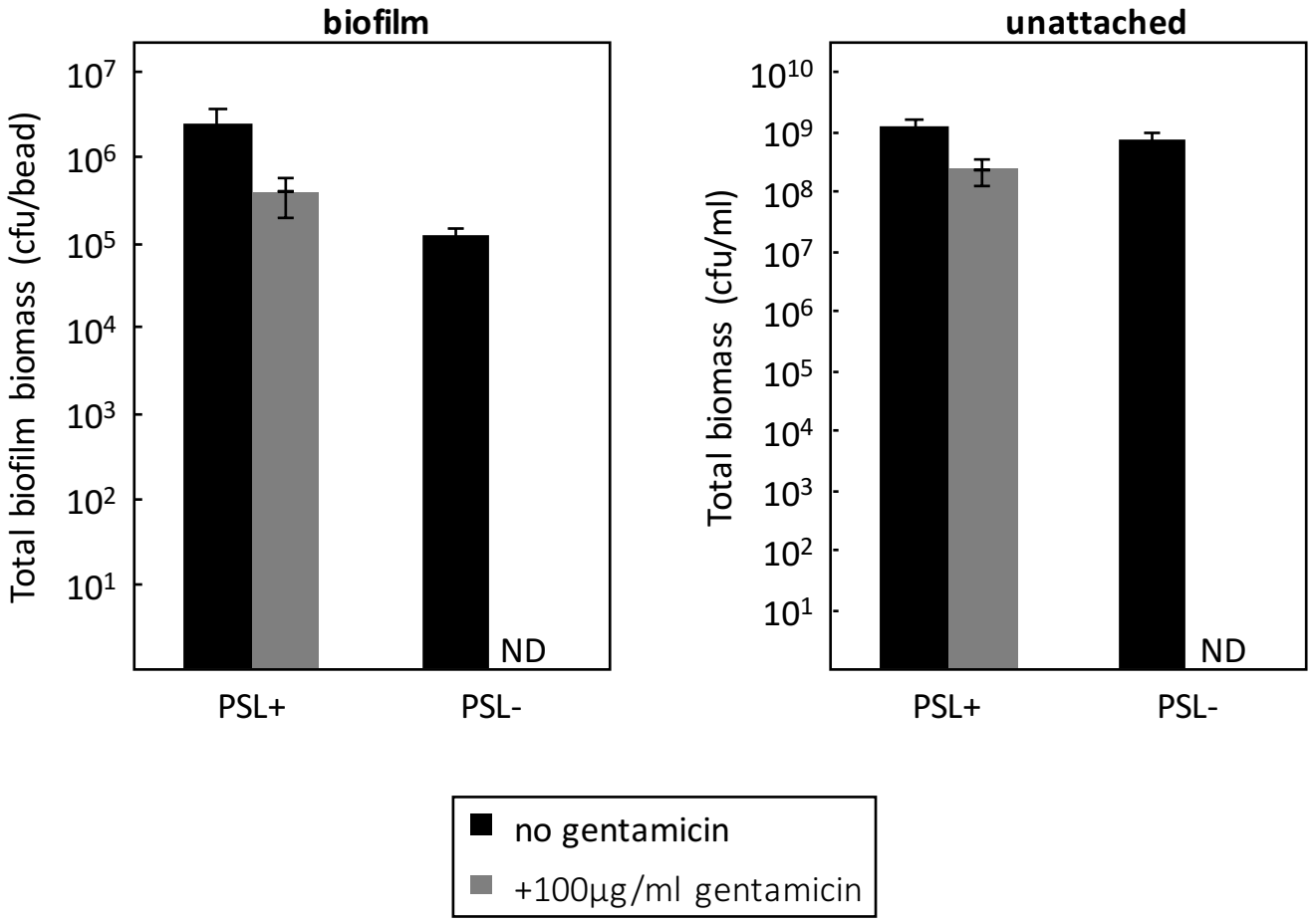


Figure S4. PSL expression protects cells from bactericidal concentration of gentamicin. 100 µg/ml gentamicin was added directly to 24 hours bead biofilm cultures and incubated for an additional 24 hours at 37°C with 200 rpm shaking. Resulting populations from both biofilm and unattached cells were tested for viability by serial dilution and plating. ND = not detected.

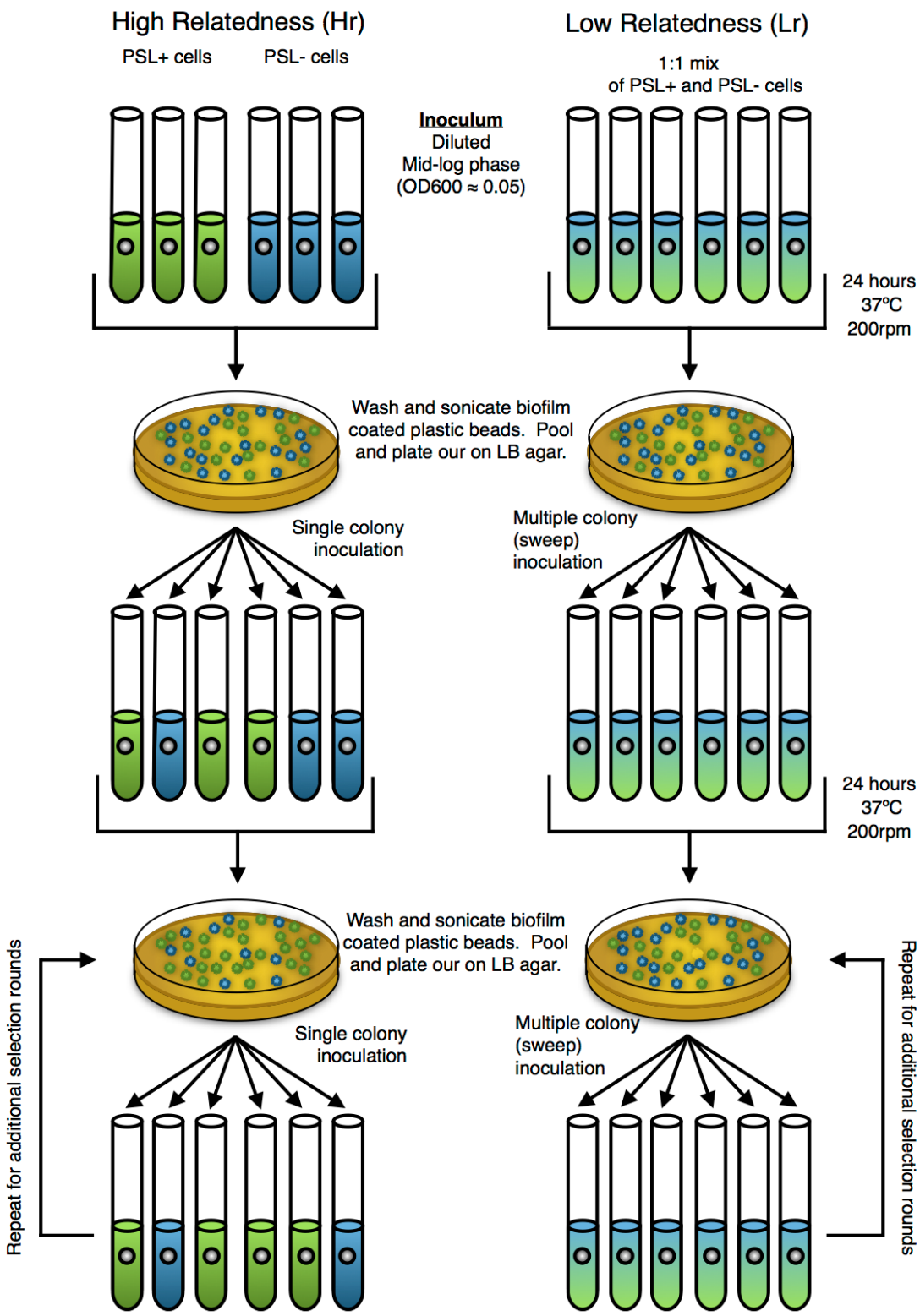
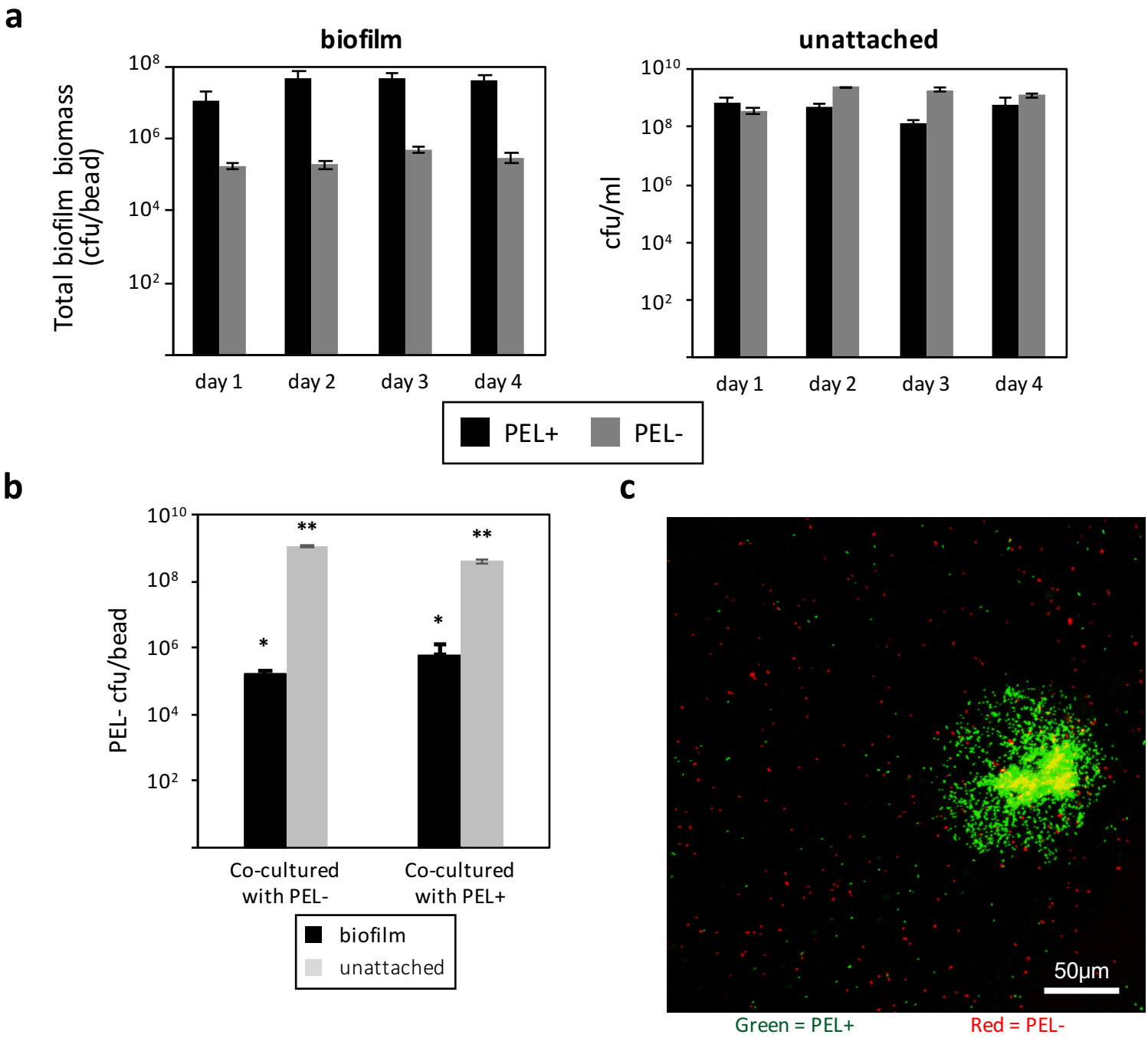
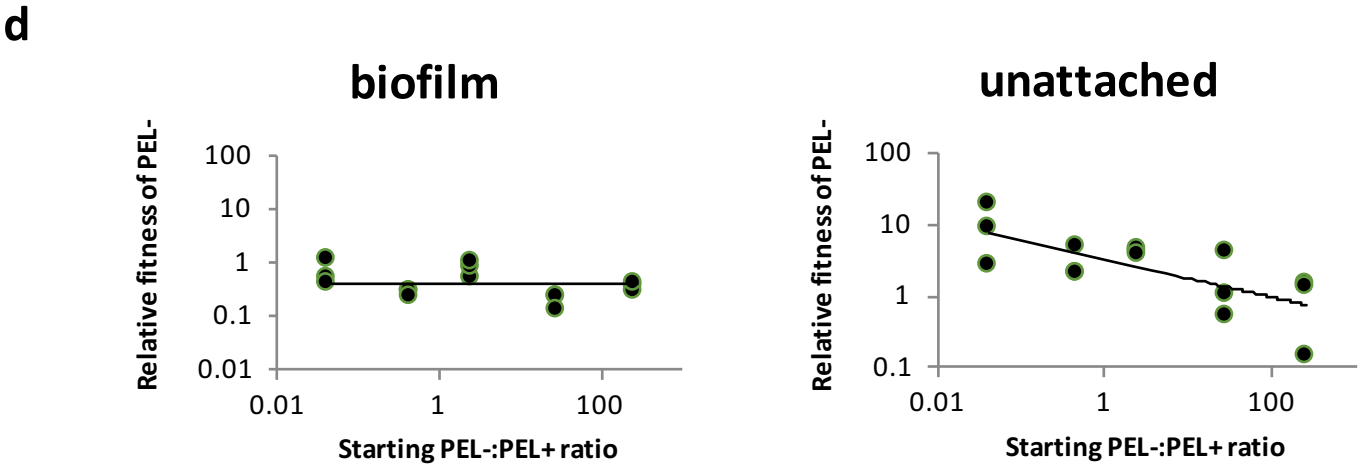


Figure S5. Schematics of the relatedness experiment. Tubes (populations) were initially inoculated with either single or multiple colonies (equating to populations that had relatively high relatedness [Hr] and relatively low relatedness [Lr], respectively) consisting of PSL+ cells, PSL- cells, or a 1:1 mixture of each. Populations were grown separately in the presence/absence of plastic beads and pooled together before the ratio of PSL+/- cells were determined. Single (Hr) or multiple (Lr) colonies were selected for progression into the next round of the experiment. Should one sub-population (PSL+ or PSL-) have increased fitness, the ratio and thus their likelihood to progress into subsequent rounds of selection will increase.


a
biofilm
unattached
Total biofilm biomass (cfu/bead)
cfu/ml
day 1
day 2
day 3
day 4
PEL+
PEL-
b
PEL- cfu/bead
Co-cultured with PEL-
Co-cultured with PEL+
biofilm
unattached
c
50µm
Green = PEL+
Red = PEL-


d
biofilm
unattached
Relative fitness of PEL-
Starting PEL-:PEL+ ratio

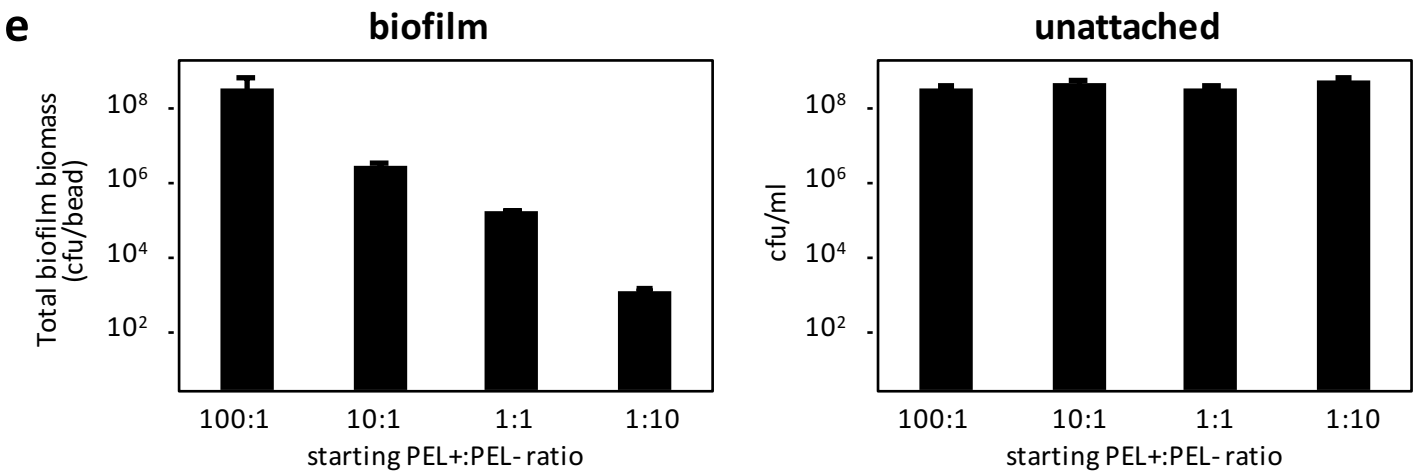


Figure S6. PEL polysaccharides, unlike PSL, are completely private goods. (**a**) Similar to PSL (Fig. 1A), PEL- strain is significantly defective in biofilm formation compared to PEL+, but no major differences are seen between their growths in the unattached fractions. (**b**) Unlike PSL, co-cultures of PEL- strains with PEL+ strains do not increase the amount of PEL- strains in neither biofilm nor unattached populations, signifying the unavailability of PEL polysaccharides to non-producing cells. * and ** $p > 0.02$. (**c**) Confocal micrograph image of surface attached populations of PEL-/PEL+ 1:1 co-cultures. PEL- cells (red) do not co-aggregate with PEL+ cells (green). (**d**) There are no frequency-dependent fitness changes for PEL-/PEL+ co-cultured biofilm, and the relative fitness is consistently slightly below 1, indicating a steady disadvantage of not expressing PEL in the biofilm. There is a frequency-dependent fitness changes in the unattached population, perhaps caused by complex regulatory system of PEL and the involvement of quorum sensing. (**e**) Due to PEL not socially affecting co-culture communities, there is a steady decline of biofilm biomass as PEL+ becomes rarer, but no change is seen in the maximum cell numbers in the unattached population regardless of the starting ratios of the strains.