

Haploid Selection, Sex Ratio Bias, and Transitions Between sex-determination systems

Michael F Scott*¹, Matthew M Osmond*², and Sarah P Otto²

* These authors contributed equally to this work

¹ Department of Botany, University of British Columbia, #3529 - 6270 University
Boulevard, Vancouver, BC, Canada V6T 1Z4

² Department of Zoology, University of British Columbia, #4200 - 6270 University
Boulevard, Vancouver, BC, Canada V6T 1Z4

email: mfscott@biodiversity.ubc.ca, mmosmond@zoology.ubc.ca

Contributions:

Abstract

2 Sex-determination systems are remarkably dynamic; many taxa display
shifts in the location of sex-determining loci or the evolution of entirely
4 new sex-determining systems. Predominant theories for why we observe
such transitions generally conclude that novel sex-determining systems are
6 favoured by selection if they equalise the sex ratio or increase linkage with
a sexually-antagonistic locus. We use population genetic models to extend
8 these theories in two ways: (1) We explicitly consider how selection on very
tightly sex-linked loci influences the spread of novel sex-determiners. We
10 find that tightly sex-linked genetic variation can favour the spread of new
sex-determination systems in which the heterogametic sex changes (XY to
12 ZW or ZW to XY) and the new sex-determining region is less closely linked
(or unlinked) to the sex-linked locus under selection; a result that is not found
14 with loose sex-linkage. (2) We also consider selection upon haploid geno-
types either during gametic competition (e.g., pollen/sperm competition) or
16 meiosis (i.e., non-Mendelian segregation); selective processes that typically
occur in one sex or the other. With haploid selection, we again find that
18 transitions between male and female heterogamety can occur even if the new
sex-determining region is less closely linked to the locus under selection, and
20 when linkage is tight haploid selection in the heterogametic sex can cause
strong sex ratio bias, which may increase or decrease with the spread of new
22 sex chromosomes. These results indicate that favourable associations that de-
velop between the ancestral sex-determining locus and selected loci can be
24 broken during the spread of a new sex-determining region. Overall, our mod-
els provide new predictions for the types of selection and the genomic loca-
26 tion of loci that can drive transitions between sex-determination systems.

Introduction

28 Animals and angiosperms exhibit extremely diverse sex-determination systems
(reviewed in Bull 1983, Charlesworth and Mank 2010, Beukeboom and Perrin
30 2014, Bachtrog et al. 2014). Among species with genetic sex determination of
diploid sexes, some taxa have heterogametic males (XY) and homogametic fe-
32 males (XX), including mammals and most dioecious plants (Ming et al. 2011);
whereas other taxa have homogametic males (ZZ) and heterogametic females (ZW),
34 including Lepidoptera and birds. Within several taxa, the chromosome that har-
bours the master sex-determining region changes. For example, transitions of the
36 master sex-determining gene between chromosomes or the evolution of new mas-
ter sex-determining genes have occurred in Salmonids (Li et al. 2011, Yano et al.
38 2012), Diptera (Vicoso and Bachtrog 2015), and *Oryzias* (Myosho et al. 2012). In
addition, many gonochoric clades with genetic sex determination exhibit transi-
40 tions between male (XY) and female (ZW) heterogamety, including snakes (Gam-
ble et al. 2017, *Current Biology*), lizards (Ezaz et al. 2009), eight of 26 teleost
42 fish families (Mank et al. 2006), true fruit flies (Tephritids, Vicoso and Bachtrog
2015), amphibians (Hillis and Green 1990), the angiosperm genus *Silene* (Slancar-
44 ova et al. 2013), and Coleoptera and Hemiptera (Beukeboom and Perrin 2014, plate
2). Indeed, in some cases, both male and female heterogametic sex-determination
46 systems can be found in the same species, as exhibited by some cichlid species (Ser
et al. 2010) and *Rana rugosa* (Ogata et al. 2007). In addition, multiple transitions
48 have occurred between genetic and environmental sex-determination systems, e.g.,
in reptiles and fishes (Conover and Heins 1987, Mank et al. 2006, Pokorná and
50 Kratochvíl 2009, Ezaz et al. 2009, Pen et al. 2010, Holleley et al. 2015).

Predominant theories accounting for the spread of new sex-determination sys-
52 tems by selection involve fitness differences between sexes (e.g., sexually antag-
onistic selection) or sex-ratio selection. van Doorn and Kirkpatrick (2007; 2010)
54 show that new sex-determining loci can be favoured if they arise in closer link-
age with a locus that experiences sexual antagonism. Tighter linkage allows a
56 stronger favourable association to build up between a male-beneficial allele, and

a neo-Y chromosome, for example. Such associations can favour a new master
58 sex-determining gene on a new chromosome (van Doorn and Kirkpatrick 2007)
and can also favour a transition between male and female heterogamety (e.g., a
60 ZW to XY transition, van Doorn and Kirkpatrick 2010). However, any sexually-
antagonistic loci that are more closely linked to the ancestral sex-determination
62 locus will develop similar, favourable associations and hinder the spread of a new
sex-determination system.

64 The sex ratio is directly affected by the sex-determination system, and it has
therefore been suggested that sex-ratio selection is a dominant force in the evolu-
66 tion of sex determination (e.g., Bull 1983, p 66-67; Beukeboom and Perrin 2014,
Chapter 7). ‘Fisherian’ sex-ratio selection favours a 1:1 zygotic sex ratio when as-
68 suming that males and females are equally costly to produce (Fisher 1930, Charnov
1982). This follows from the fact that, for an autosomal locus, half of the ge-
70 netic material is inherited from a male and half from a female (West 2009). Thus,
if the population sex ratio is biased towards one sex, the average per-individual
72 contribution of genetic material to the next generation from the opposite sex is
greater. Therefore, a mutant that increases investment in the rarer sex will spread
74 via the higher per-individual contributions made by that sex. In the case of sex-
chromosome evolution, Kozielska et al. (2010) consider systems in which the an-
76 cestral sex chromosomes experience meiotic drive (e.g., where driving X or Y
chromosomes are inherited disproportionately often), which causes sex ratios to
78 become biased (Hamilton 1967). They find that new, unlinked sex-determining
loci (masculinizing or feminizing mutations, i.e., neo-Y or neo-W loci) can then
80 spread, which restore an even sex ratio.

Here we extend current theory by using mathematical models to find the con-
82 ditions under which new sex-determination systems spread when individuals ex-
perience selection at both diploid and haploid stages. Even in animal and plant
84 species that have much larger and more conspicuous diploid phases than haploid
phases, many loci experience significant haploid selection through gamete compe-
86 tition and/or meiotic drive (Mulcahy et al. 1996, Joseph and Kirkpatrick 2004). We

use the term ‘meiotic drive’ to refer to the biased (non-Mendelian) segregation of
 88 genotypes during gamete production (from one parent) and the term ‘gametic com-
 petition’ to refer to selection upon haploid genotypes within a gamete/gametophyte
 90 pool (potentially from multiple parents); the term ‘haploid selection’ encompasses
 both processes. Meiotic drive generally occurs either during the production of
 92 male or female gametes only (Úbeda and Haig 2005, Lindholm et al. 2016). Be-
 cause there are typically many more pollen/sperm than required for fertilization,
 94 gametic competition is also typically sex specific, occurring primarily among male
 gametes. Gametic competition may be particularly common in plants, in which 60-
 96 70% of all genes are expressed in the male gametophyte and these genes exhibit
 stronger signatures of selection than random genes (Borg et al. 2009, Arunkumar
 98 et al. 2013, Gossmann et al. 2014). In addition, artificial selection pressures ap-
 plied to male gametophytes are known to cause a response to selection (e.g., Hor-
 100 maza and Herrero 1996, Ravikumar et al. 2003, Hedhly et al. 2004, Clarke et al.
 2004). A smaller proportion of genes are thought to be expressed and selected dur-
 102 ing competition in animal sperm, although precise estimates are uncertain (Zheng
 et al. 2001, Joseph and Kirkpatrick 2004, Vibrationovski et al. 2010). Recent stud-
 104 ies have demonstrated that sperm competition can alter haploid allele frequencies
 and increase offspring fitness (Immler et al. 2014) (Alavioon et al. 2017). Ge-
 106 netic mapping experiments, which are typically designed to minimize selection in
 diploids, have revealed segregation distortion in various species, including mice,
 108 *Drosophila*, Rice, Maize, Wheat, Barley, Cotton... In some of these cases, biased
 segregation has been shown to be attributable to meiotic drive and/or gametic se-
 110 lection (Leppala et al. 2013, Didion et al. 2015, 2016 Xu et al 2013 (rice), Fish-
 man...).

112 There are various ways in which a period of haploid selection could influence
 transitions between sex-determination systems. If we assume that haploid selec-
 114 tion at any particular locus predominantly occurs in one sex (e.g., meiotic drive
 during spermatogenesis), then such loci experience a form of sex-specific selec-
 116 tion. In this respect, we might expect that haploid selection would affect transitions

between sex-determination systems in a similar manner to sex-specific diploid selection (as explored by van Doorn and Kirkpatrick 2007; 2010). That is, new masculinizing mutations (neo-Y chromosomes) could be favoured via associations with alleles that are beneficial in the male haploid stage. On the other hand, sex ratios can also become biased by linkage between the sex-determining region and a locus that harbours genetic variation in haploid fitness. For example, there are several known cases of sex-ratio bias caused by sex-linked meiotic drive alleles (Burt and Trivers 2006, Chapter 3) or selection among X- and Y-bearing pollen (Lloyd 1974, Conn and Blum 1981, Stehlik and Barrett 2005; 2006, Field et al. 2012; 2013). It is not immediately clear how the spread of new sex-determination systems would be influenced by the combination of sex-ratio biases and associations between haploid selected loci and sex-determining regions.

Our models have two important new features. Firstly, when considering loci that are under selection and also in very tight linkage with the ancestral sex-determining region we explicitly calculate equilibrium allele frequencies. This allows us to show that transitions between male and female heterogamety can evolve even when the neo-sex-determining locus is less closely linked to a locus under selection and therefore disrupts favourable ancestral associations between sex and the alleles selected in that sex. Secondly, we allow sex-specific haploid selection to occur on a locus in tight or loose linkage with the ancestral sex-determining region. We find that sex-ratio biases caused by haploid selection can exert Fisherian sex-ratio selection upon novel sex-determiners but that their spread is also determined by selection on genetically-associated alleles. Consequently, it is possible for selection on linked alleles to drive turnover between sex-determining systems despite causing transitory or even permanent increases in sex-ratio bias.

Model

Change all α^ϕ to $(1 + \alpha_\Delta^\phi)$.

We consider transitions between ancestral and novel sex-determining systems

146 using a three-locus model, each locus having two alleles. Locus **X** is the ancestral sex-determining region, with alleles X and Y (or Z and W). Locus **A** is a locus under selection, with alleles A and a . Locus **M** is a novel sex-determining region, at which the null allele (M) is initially fixed in the population such that sex of zygotes is determined by the genotype at the ancestral sex-determining region, **X**; XX genotypes become females and XY become males (or ZW become females and ZZ become males). To evaluate the evolution of new sex-determination systems, we consider the invasion, fixation, maintenance, and/or loss of novel sex-determining alleles (m) at the **M** locus. We assume that the **M** locus is epistatically dominant over the **X** locus such that zygotes with at least one m allele develop as females with probability k and as males with probability $1 - k$, regardless of the **X** locus genotype. With $k = 0$, the m allele is a masculinizer (i.e., a neo- Y) and with $k = 1$ the m allele is a feminizer (i.e., a neo- W). With intermediate k , we can interpret m as an environmental sex determination (ESD) allele, such that zygotes develop as females in a proportion (k) of the environments they experience. We also analyze a model of maternally-controlled environmental sex-determination, where mothers with at least one m allele produce daughters with probability k .

162 In each generation, we census the genotype frequencies in male and female gametes/gametophytes (hereafter gametes) before gametic competition. A full description of our model, including recursion equations, is given in the Appendix. First, competition occurs among male gametes (sperm/pollen competition) and among female gametes (egg/ovule competition) separately. Selection during gametic competition depends on the **A** locus genotype, relative fitnesses are given by w_A^{\varnothing} and w_a^{\varnothing} ($\varnothing \in \{\varnothing, \delta\}$; see table 1). We assume that all gametes compete for fertilization during gametic competition, which assumes a polygamous mating system. Gametic competition in monogamous mating systems is, however, equivalent to meiotic drive in our model (described below), as both only alter the frequency of gametes produced by heterozygotes. After gametic competition, random mating occurs between male and female gametes. The resulting zygotes develop as males or females, depending on their genotypes at the **X** and **M** loci. Diploid males and

females then experience selection, with relative fitnesses w_{AA}^{ϕ} , w_{Aa}^{ϕ} , and w_{aa}^{ϕ} . The
 176 next generation of gametes is produced by meiosis, during which recombination
 and sex-specific meiotic drive can occur. Recombination (i.e., an odd number of
 178 cross-overs) occurs between loci **X** and **A** with probability r , between loci **A** and
M with probability R , and between loci **X** and **M** with probability χ . Any linear
 180 order of the loci can be modelled with appropriate choices of r , R , and χ (see Ta-
 ble S.1). Individuals that are heterozygous at the **A** locus may experience meiotic
 182 drive; a gamete produced by Aa heterozygotes of sex ϕ bear allele A with probab-
 ility α^{ϕ} . Thus, the **A** locus can experience sex-specific gametic competition, diploid
 184 selection, and/or meiotic drive.

Table 1: Relative fitness of different genotypes in sex $\phi \in \{\varnothing, \delta\}$

Genotype	Relative fitness during gametic competition
A	$w_A^{\phi} = 1 + t^{\phi}$
a	$w_a^{\phi} = 1$
Genotype	Relative fitness during diploid selection
AA	$w_{AA}^{\phi} = 1 + s^{\phi}$
Aa	$w_{Aa}^{\phi} = 1 + h^{\phi} s^{\phi}$
aa	$w_{aa}^{\phi} = 1$
Genotype	Transmission during meiosis in Aa heterozygotes
A	$\alpha^{\phi} = 1/2 + \alpha_{\Delta}^{\phi}/2$
a	$1 - \alpha^{\phi} = 1/2 - \alpha_{\Delta}^{\phi}/2$

Results

186 The model outlined above describes both ancestrally- XY and ancestrally- ZW
 sex-determination systems if we relabel the two sexes as being ancestrally ‘het-
 188 erogametic’ or ancestrally ‘homogametic’. Without loss of generality, we primar-
 ily refer to the ancestrally heterogametic sex as male and the ancestrally homoga-

190 metic sex as female. That is, we describe an ancestral XY sex-determination system but our model is equally applicable to an ancestral ZW sex-determination system (relabelling the ancestrally-heterogametic sex as female and the ancestrally-homogametic sex as male).

194 **Generic invasion by a neo-Y or neo-W**

The evolution of a new sex-determination system requires that a rare mutant allele at the novel sex-determining locus, m , increases in frequency when rare. The spread of a rare mutant m at the \mathbf{M} locus is determined by the leading eigenvalue, λ , of the system of eight equations describing the frequency of eggs and sperm carrying the m allele in the next generation (equations S.1). This system simplifies substantially in a number of cases of interest. Dominant neo-Y (when $k = 0$) or neo-W alleles (when $k = 1$) are only found in male diploids (neo-Y) or female diploids (neo-W) such that their growth rate ultimately depends only on the change in frequency of m -bearing gametes produced by males or by females, respectively. Furthermore, if the m allele is fully epistatically dominant over the ancestral sex-determining system, phenotypes are not affected by the genotype at the ancestral sex-determining region (\mathbf{X} locus). Thus, the invasion of rare dominant neo-Y or neo-W alleles is determined by the largest eigenvalue that solves a quadratic characteristic polynomial, $\lambda^2 + b\lambda + c = 0$. Here, $b = -(\lambda_{mA} + \lambda_{ma}) + (\rho_{mA} + \rho_{ma})$ and $c = (\lambda_{mA} - \rho_{mA})(\lambda_{ma} - \rho_{ma}) - \rho_{mA}\rho_{ma}$, where λ_{mi} is the multiplicative growth rate of mutant haplotypes on background $i \in \{A, a\}$, without accounting for loss due to recombination, and ρ_{mi} is the rate at which mutant haplotypes on background $i \in \{A, a\}$ recombine onto the other \mathbf{A} locus background in heterozygotes (see Table 2). The λ_{mi} and ρ_{mi} , and thus the spread of the mutant m allele, depend on the frequency of alleles at the \mathbf{A} and \mathbf{X} loci in the ancestral population. In the ancestral population, it is convenient to follow the frequency of the A allele among female gametes (eggs), p_X^ϕ , and among X-bearing, p_X^δ , and among Y-bearing, p_Y^δ , male gametes (sperm/pollen). We also track the fraction of male gametes that are Y-bearing, q , which may deviate from $1/2$ due to meiotic drive in males.

Table 2: Parameters determining invasion of mutant neo-Y and neo-W alleles into an ancestrally XY system

neo-Y ($k = 0$)
$\lambda_{mA} = \{2(1 - \zeta)\}^{-1} [p_X^\varnothing w_A^\varnothing w_A^\delta w_{AA}^\delta + 2(1 - p_X^\varnothing) w_a^\varnothing w_A^\delta w_{Aa}^\delta \alpha^\delta] / (\bar{w}_H^\varnothing \bar{w}_H^\delta \bar{w}^\delta)$ $\lambda_{ma} = \{2(1 - \zeta)\}^{-1} [(1 - p_X^\varnothing) w_a^\varnothing w_a^\delta w_{aa}^\delta + 2p_X^\varnothing w_A^\varnothing w_a^\delta w_{Aa}^\delta (1 - \alpha^\delta)] / (\bar{w}_H^\varnothing \bar{w}_H^\delta \bar{w}^\delta)$ $\rho_{mA} = R \{2(1 - \zeta)\}^{-1} [2(1 - p_X^\varnothing) w_a^\varnothing w_A^\delta w_{Aa}^\delta \alpha^\delta] / (\bar{w}_H^\varnothing \bar{w}_H^\delta \bar{w}^\delta)$ $\rho_{ma} = R \{2(1 - \zeta)\}^{-1} [2p_X^\varnothing w_A^\varnothing w_a^\delta w_{Aa}^\delta (1 - \alpha^\delta)] / (\bar{w}_H^\varnothing \bar{w}_H^\delta \bar{w}^\delta)$
neo-W ($k = 1$)
$\lambda_{mA} = (2\zeta)^{-1} [\bar{p}^\delta w_A^\delta w_A^\varnothing w_{AA}^\varnothing + 2(1 - \bar{p}^\delta) w_a^\delta w_A^\varnothing w_{Aa}^\varnothing \alpha^\varnothing] / (\bar{w}_H^\varnothing \bar{w}_H^\delta \bar{w}^\varnothing)$ $\lambda_{ma} = (2\zeta)^{-1} [(1 - \bar{p}^\delta) w_a^\delta w_a^\varnothing w_{aa}^\varnothing + 2\bar{p}^\delta w_A^\delta w_a^\varnothing w_{Aa}^\varnothing (1 - \alpha^\varnothing)] / (\bar{w}_H^\varnothing \bar{w}_H^\delta \bar{w}^\varnothing)$ $\rho_{mA} = R (2\zeta)^{-1} [2(1 - \bar{p}^\delta) w_a^\delta w_A^\varnothing w_{Aa}^\varnothing \alpha^\varnothing] / (\bar{w}_H^\varnothing \bar{w}_H^\delta \bar{w}^\varnothing)$ $\rho_{ma} = R (2\zeta)^{-1} [2\bar{p}^\delta w_A^\delta w_a^\varnothing w_{Aa}^\varnothing (1 - \alpha^\varnothing)] / (\bar{w}_H^\varnothing \bar{w}_H^\delta \bar{w}^\varnothing)$

$\bar{p}^\delta = (1 - q)p_X^\delta + qp_Y^\delta$ is the average frequency of the A allele among X- and Y-bearing male gametes.

ζ is the zygotic sex ratio (fraction female)

\bar{w}^\varnothing is the mean fitness of diploids of sex \varnothing , see Table S.2

\bar{w}_H^\varnothing is the mean fitness of haploids from sex \varnothing , see Table S.2

220

We are particularly concerned with the conditions under which a rare neo-sex-determining allele increases in frequency, which occurs when the largest eigenvalue, λ , is greater than one. If the average change in frequency of the two haplotypes that carry the m allele (Am and am) is positive, invasion will always occur, i.e., if $(\lambda_{mA} + \lambda_{ma})/2 > 1$ then $\lambda > 1$. If neither haplotype increases in frequency ($\lambda_{mA}, \lambda_{ma} < 1$), the m allele will not invade. Otherwise, the new sex-determining allele increases in frequency on one **A** background and declines on the other, and invasion requires

228

$$\rho_{ma} (\lambda_{mA} - 1) + \rho_{mA} (\lambda_{ma} - 1) > 0. \quad (1)$$

For example, if we assume that only the mA haplotype has a positive growth rate

($\lambda_{ma} < 1 < \lambda_{mA}$), the second term on the left-hand side of (1) is negative and

230

invasion requires that the growth rate of mA haplotypes and the rate at which they
 232 are produced by recombination is sufficiently large relative to that of ma haplo-
 types. In other words, invasion requires that the average growth rate of the two
 234 haplotypes, weighted by the rates they are created by recombination, is positive.

Table 2 illustrates a number of key points about the invasion of neo-Y and
 236 neo-W mutations. First, Fisherian sex-ratio selection will favour the spread of a
 neo-Y if the ancestral zygotic sex ratio is biased towards females, $\zeta > 1/2$ (i.e.,
 238 $\zeta > 1/2$ causes the first factor of the λ_{mi} to be greater than one for a neo-Y and
 vice versa for a neo-W). However, the spread of a neo-Y (neo-W) also depends on
 240 the male (female) fitness of associated alleles (terms in square brackets). Second,
 invasion by a neo-Y (neo-W) allele does not directly depend on the fitness of female
 242 (male) diploids (for a given set of equilibrium allele frequencies). This is because
 a dominant neo-Y (neo-W) is always found in males (females), and therefore the
 244 frequency of the neo-Y (neo-W) allele, m , only changes in males (females). Finally,
 invasions by a neo-Y and a neo-W are qualitatively different. This is because a
 246 gamete with the ancestral- or neo-Y always pairs with a female gamete containing
 an X, and both develop into males. By contrast, a gamete with a neo-W can pair
 248 with an X or Y male gamete, developing into a female, while female gametes
 without the neo-W can become female (when paired with X) or male (when paired
 250 with Y). Consequently, the types of females produced differ in the frequency of A
 alleles they obtain from mating.

252 In order to explicitly determine the conditions under which a rare neo-sex-
 determining allele spreads, we must calculate the equilibrium frequency of the A
 254 allele in the ancestral population (i.e., \hat{p}_X° , \hat{p}_X^{δ} , and \hat{p}_Y^{δ}). Since only the A locus expe-
 riences selection directly, any deterministic evolution requires that there is a poly-
 256 morphism at the A locus. Polymorphisms can be maintained by mutation-selection
 balance or transiently present during the spread of beneficial alleles. However,
 258 polymorphisms maintained by selection can maintain alleles at higher allele fre-
 quencies for longer periods. Here, we focus of polymorphisms maintained by se-
 260 lection, where the A allele reaches a stable intermediate equilibrium frequency

under the ancestral sex-determination system before the neo-sex-determining allele (m) arises. We can analytically calculate the allele frequency of the A allele using two alternative simplifying assumptions: (1) the A locus is within (or tightly linked to) the non-recombining region around the ancestral SDR ($r \approx 0$) or (2) selection is weak relative to recombination ($s^\phi, t^\phi, \alpha_\Delta^\phi$ of order $\epsilon \ll 1$).

Change to \hat{p} throughout as we assume that allele frequencies change slowly such that lambda is unaffected

Tight linkage with the ancestral sex-determining region

The equilibrium allele frequencies and their stability conditions are given in the appendix, when there is complete linkage between the ancestral sex-determining region and the A locus ($r = 0$). Here, either the A allele or the a allele must be fixed on the Y. Because the labelling of alleles is arbitrary, we will assume that the a locus is fixed on the Y ($p_Y^\phi = 0$), without loss of generality. If there are two alleles maintained at the A locus, the X can either be fixed for the A allele ($p_X^\phi = p_X^\phi = 1$) or polymorphic ($0 < p_X^\phi, p_X^\phi < 1$).

A neo-Y will never invade an ancestral XY system that already has tight linkage with the locus under selection ($r = 0$, for details see supplementary *Mathematica* file). A neo-Y haplotype with the same allele as the ancestral Y is neutral ($\lambda_{ma} = 1$) and does not change in frequency. The other neo-Y haplotype will not spread ($\lambda_{mA} < 1$) given that the initial equilibrium is stable. Therefore, a neo-Y mutation cannot spread ($\lambda \leq 1$) in an ancestral XY system that is at equilibrium with all selected loci within the non-recombining region around the SDR. In essence, through tight linkage with the A locus, the ancestral Y becomes strongly specialized on the allele that has the highest fitness across male haploid and diploid phases. Given that the ancestral Y is at this equilibrium, it is not possible for a neo-Y to create males that have higher fitness than the ancestral Y.

Sally edits only looked at up to this point. Next task: figures to match with this tight linkage section.

Neo-W alleles, on the other hand, can invade an ancestral XY system under

290 some conditions (the full invasion conditions are given in the appendix; equations
 S.6 and S.7). Significantly, we note that it is possible for both neo-W haplotypes
 292 to spread ($\lambda_{mA} > 1$ and $\lambda_{ma} > 1$), in which case neo-W invasion can occur re-
 gardless of linkage to the selected locus. That is, selection on loci within the non-
 294 recombining region of the SDR can favour the invasion of a less closely linked
 neo-W (e.g., on an autosome). Although haploid selection can favour neo-W alle-
 296 les because the ancestral sex ratio becomes male biased, this is not the only circum-
 stance in which less tightly linked neo-W alleles invade. For example, unlinked
 298 neo-W alleles can invade in the absence of any haploid selection. This result is
 unexpected given the results of van Doorn and Kirkpatrick (2010), who did not ex-
 300 plicitly calculate equilibrium allele frequencies under tight linkage and generally
 concluded that heterogametic transitions occur when neo-sex-determining alleles
 302 are in tighter linkage with loci under sex-specific diploid selection. Therefore, we
 focus on cases where there is no haploid selection and discuss the effects of haploid
 304 selection in the appendix.

If we categorise the a allele as being ancestrally ‘male-beneficial’ via the fact
 306 that it is fixed on the Y, then $\lambda_{mA} > 1$ indicates that the neo-W spreads when found
 with the ancestrally ‘female-beneficial’ allele. Intuitively, this is possible because
 308 the ancestral X chromosome is not able to specialise on the ‘female-beneficial’
 allele due to the fact that X’s are sometimes found in males. For example, a poly-
 310 morphism of A and a alleles can be maintained on the X despite directional se-
 lection in favour of the A allele in females ($s^{\varphi} > 0$, $0 < h^{\varphi} < 1$) because the a
 312 allele is favoured in males. W- A haplotypes will only create females with high
 fitness AA or Aa genotypes and can therefore have higher fitness than ancestral
 314 females, which sometimes also produce aa females. Thus, the neo-W can spread
 by allowing increased specialization on female beneficial alleles.

316 Given that the a allele can be considered ancestrally ‘male-beneficial’ because
 it is fixed on the Y, it might be surprising that neo-W- a haplotypes can be favoured
 318 by selection in females ($\lambda_{ma} > 1$). Again, this occurs because ancestral X’s also
 experience selection in males, in which they will always be paired with a Y- a .

320 Hence, if there is overdominance in males, X-A Y-*a* males have high fitness and
the *A* allele is favoured by selection on the X in males. Therefore, the X can be
322 polymorphic or even fixed for the *A* allele despite favouring the *a* allele during
selection in females (Lloyd and Webb 1977, Otto 2014). In such cases, neo-W-*a*
324 haplotypes, which are never found in males, can spread because they both create
more *Aa* and *aa* females when pairing with an X from males and they bring Y-*a*
326 haplotypes into females, in which case females are always *aa*. Indeed, it is possible
for both W-*A* and W-*a* haplotypes to spread, as is the case when *AA* individuals
328 have low fitness in females yet the *A* is fixed on the X due to strong overdominance
in males. Both neo-W-*A* and neo-W-*a* haplotypes then produce fewer unfit *AA*
330 females. This is true for the neo-W-*A* haplotype because it can pair with a Y - *a*
haplotype and still be female.

332 In Figure ??A we show the region of parameter space within which both neo-W
haplotypes invade ($\lambda_{mA} > 1$ and $\lambda_{ma} > 1$) when there is overdominance in females
334 and no haploid selection (corresponding to Figure 2a in Otto 2014). Wherever
both haplotypes have positive growth rates (gray region of Figure ??), invasion
336 by a neo-W is expected regardless of its linkage with the selected locus (i.e., even
unlinked neo-W alleles can invade). In regions where only one haplotype can
338 spread (white region of Figure ??), a neo-W can invade as long as equation (1) is
satisfied, which can require that the recombination rate, *R*, is small enough and
340 yet still indicates that more loosely linked sex-determining regions can spread. It
is also possible for haploid selection to drive the invasion of a loosely linked neo-
342 W. Take, for instance, selection directionally favouring *A* in both diploid sexes and
meiotic drive in males. Figure ??B then shows that ploidy-antagonistic selection
344 can allow both neo-W haplotypes to invade.

Loose linkage with the ancestral sex-determining region

346 Assuming that selection is weak relative to all recombination rates (*r*, *R* and χ),
we denote the leading eigenvalues describing the invasion of a neo-Y (*k* = 0) and
348 a neo-W (*k* = 1) into an ancestrally XY system by $\lambda_{Y',XY}$ and $\lambda_{W',XY}$, respectively,

which are

$$\lambda_{Y',XY} = 1 + V_A S_A^2 \frac{(r-R)}{rR} + O(\epsilon^3) \quad (2)$$

350 and

$$\lambda_{W',XY} = \lambda_{Y',XY} + (2\alpha_\Delta^\delta - 2\alpha_\Delta^\varphi + t^\delta - t^\varphi) (\hat{p}_Y^\delta - \hat{p}_X^\delta) / 2 + O(\epsilon^3) \quad (3)$$

where $V_A = \bar{p}(1 - \bar{p})$ is the variance in the frequency of A and $S_A = (D^\delta + \alpha_\Delta^\delta + t^\delta) - (D^\varphi + \alpha_\Delta^\varphi + t^\varphi)$ describes sex differences in selection for the A versus a across diploid selection, meiosis, and gametic competition. The diploid selection term, $D^\varphi = (\bar{p}s^\varphi + (1 - \bar{p})h^\varphi s^\varphi) - (\bar{p}h^\varphi s^\varphi + (1 - \bar{p}))$, is the difference in fitness between A and a alleles in diploids of sex $\varphi \in \{\varphi, \delta\}$, where \bar{p} is the leading-order probability of mating with an A -bearing gamete from the opposite sex (see Appendix).

The neo-sex-determining allele, m , will spread if $\lambda_{m,XY} > 1$. Equation (2) demonstrates that under weak selection a neo-Y will invade an XY system if and only if it is more closely linked to the selected locus than the ancestral sex-determining region (i.e., if $R < r$; note that V_A and S_A^2 are strictly positive as long as \mathbf{A} is polymorphic). This echoes our tight linkage results above and the results of van Doorn and Kirkpatrick (2007), who considered diploid selection only and also found that homogametic transitions (XY to XY or ZW to ZW) can only occur when the neo-sex-determining locus is more closely linked to a locus under sexually-antagonistic selection.

Equation (3) shows that, in contrast to the tight linkage results of the previous section, with weak selection and no haploid selection ($t^\varphi = \alpha_\Delta^\varphi = 0$), as considered by van Doorn and Kirkpatrick (2010), the spread of a neo-W is equivalent to the spread of a neo-Y ($\lambda_{W',XY} = \lambda_{Y',XY}$), such that heterogametic transitions (XY to ZW or ZW to XY) can also occur only if the neo-sex-determining region is more closely linked to a locus under selection ($R < r$). However, if there is any haploid selection, the additional term in equation (3) can be positive, which can allow,

for example, neo-W invasion ($\lambda_{W',XY} > 1$) even when the neo-sex-determining
 374 region is less closely linked to the selected locus ($R > r$). These transitions are
 unusual because, when $R > r$, associations that selection has built up between
 376 alleles more favourable in one sex and alleles that determine sex will be weak-
 ened. Mean diploid fitness therefore decreases during heterogametic transitions
 378 that create looser sex-linkage (Figure ??B,D).

Equation (3) shows that, with weak selection, neo-W alleles can invade an XY
 380 system for a large number of selective regimes. To clarify the parameter space
 under which $\lambda_{W',XY} > 1$, we consider several special cases. Firstly, if the A locus
 382 is unlinked to the ancestral sex-determining region ($r = 1/2$), a more closely linked
 neo-W ($R < 1/2$) can always invade because there is then no association between
 384 A alleles and sex chromosomes, $(\hat{p}_Y^\delta - \hat{p}_X^\delta) = 0$. The second term in equation (3)
 then disappears and invasion depends only on the sign of $(r - R)$. Indeed, invasion
 386 typically occurs when the neo-W is more closely linked to the selected locus than
 the ancestral sex-determining region, under a variety of selective regimes (Figure
 388 4). Secondly, we can simplify cases where invasion occurs despite looser sex-
 linkage, $R > r$, using the special case where $R = 1/2$ and $r < 1/2$ (e.g., the
 390 selected locus is on the ancestral sex chromosome and the novel sex-determining
 locus arises on an autosome). In table 3 we give the conditions where invasion
 392 occurs when we further assume that haploid selection only occurs in one sex (e.g.,
 during male meiosis only) and dominance coefficients are equal in the two sexes,
 394 $h^\varnothing = h^\delta$. When there is no gametic competition and meiotic drive is in one sex
 only, an unlinked neo-W can invade as long as the same allele is favoured during
 396 diploid selection in males and females ($s^\varnothing s^\delta > 0$, see Figure 4B). When there
 is no meiotic drive and gametic competition occurs in one sex only, an unlinked
 398 neo-W can invade as long as the same allele is favoured in male and female diploid
 selection and there are sex differences in selection of one type (e.g., $s^\varnothing(s^\delta - s^\varnothing) > 0$,
 400 see Figure 4C,D). These special cases indicate that neo-W invasion can occur for
 a relatively large fraction of parameter space, even if the neo-W uncouples the
 402 sex-determining locus from a locus under selection.

Table 3: Invasion conditions for unlinked neo-W ($R = 1/2$, $r < 1/2$) into ancestral XY with one form of haploid selection

Scenario	Assumptions	neo-W spreads ($\lambda_{W',XY} > 1$) if
male drive only	$h^\sigma = h^\varphi, t^\varphi = t^\sigma = \alpha_\Delta^\varphi = 0$	$s^\varphi s^\sigma > 0$
female drive only	$h^\sigma = h^\varphi, t^\varphi = t^\sigma = \alpha_\Delta^\sigma = 0$	$s^\varphi s^\sigma > 0$
sperm competition only	$h^\sigma = h^\varphi, t^\varphi = \alpha_\Delta^\varphi = \alpha_\Delta^\sigma = 0$	$s^\varphi(s^\sigma - s^\varphi) > 0$
egg competition only	$h^\sigma = h^\varphi, t^\sigma = \alpha_\Delta^\varphi = \alpha_\Delta^\sigma = 0$	$s^\sigma(s^\varphi - s^\sigma) > 0$

Previous research suggests that when the ancestral sex-determining locus is
404 linked to a locus that experiences haploid selection (e.g., meiotic drive), a new,
unlinked sex-determining locus invades in order to restore equal sex ratios (Koziel-
406 ska et al. 2010). Consider, for example, the case where the **A** locus is linked to the
ancestral-SDR ($r < 1/2$) and experiences meiotic drive in males only (e.g., during
408 spermatogenesis but not during oogenesis, $\alpha^\sigma \neq 1/2$, $\alpha^\varphi = 1/2$). Disregarding
gametic competition ($t^\varphi = t^\sigma = 0$) such that zygotic sex ratios are only biased
410 by meiotic drive in males. In this case, the zygotic sex ratio can be initially bi-
ased only if the ancestral sex-determining system is XY (Figure ??B). We might
412 therefore expect a difference in the potential for XY to ZW and ZW to XY tran-
sitions. However, to leading order with selection weak relative to recombination,
414 we find that sex ratio selection (first terms in table 2) is equal in magnitude to
the fitness effects of alleles associated with new sex-determining alleles (second
416 terms in table 2). Thus, invasion by a neo-W into an XY system and invasion by
a neo-Y into a ZW system occur under the same conditions ($\lambda_{Y',XY} = \lambda_{W',ZW}$
418 and $\lambda_{Y',ZW} = \lambda_{W',XY}$, at least up to order ϵ^2). As selection becomes stronger (or
linkage becomes tighter), this symmetry between sex-ratio selection and haploid
420 selection is lost, causing differences in the strength of selection favouring the two
heterogametic transitions (compare red to black near -25cM and 25 cM in Figure
422 4).

Environmental sex determination

424 We next consider the case where the new sex-determining mutation, m , causes sex
to be determined probabilistically or by heterogeneous environmental conditions
426 (environmental sex determiner, ESD). We assume that individuals carrying the m
allele develop as females with probability k (e.g., in a fraction k of the environ-
428 ments they randomly experience). The characteristic polynomial determining the
eigenvalues of the 8 equation system (equations S.1) does not reduce for ESD mu-
430 tants as it does for $k = 0$ or $k = 1$. We therefore focus on weak selection here.
Assuming weak selection, the spread of these mutations is given by

$$\begin{aligned} \lambda_{ESD',XY} = & 1 + (1 - 2k)^2 V_A S_A^2 \frac{r - R}{rR} \\ & + \frac{k(\hat{p}_Y^\delta - \hat{p}_X^\delta)}{2} (k(2\alpha_\Delta^\delta - 2\alpha_\Delta^\varnothing + t^\delta - t^\varnothing) - 4(1 - k)S_A) + O(\epsilon^3), \end{aligned} \quad (4)$$

432 which reduces to $\lambda_{Y',XY}$ when $k = 0$ and $\lambda_{W',XY}$ when $k = 1$.

Of particular interest are ESD mutations that cause half of their carriers to
434 develop as females and half as males ($k = 1/2$, creating equal sex ratios), the
spread of which is given by

$$\lambda_{ESD',XY} = 1 + \frac{1}{2} \frac{(\lambda_{Y',XY} - 1) + (\lambda_{W',XY} - 1)}{2} \Big|_{R=1/2} + O(\epsilon^3), \quad (5)$$

436 where we have indicated that $\lambda_{Y',XY}$ and $\lambda_{W',XY}$ are evaluated at $R = 1/2$. That is,
recombination between the selected locus and the novel sex-determining locus, R ,
438 doesn't enter into the $k = 1/2$ results. This is because sex is essentially randomized
each generation, preventing associations from building up between allele A and
sex. An important result from equation (5) is that ESD can invade if there is haploid
440 selection. When evaluated at $R = 1/2$, $\lambda_{Y',XY} \leq 1$ but $\lambda_{W',XY}$ can be greater than
one if there is haploid selection, as discussed above. Previous studies where ESD
442 is favoured have typically assumed that environmental conditions (e.g., maternal

444 condition, mate quality, age, or host size) can differentially affect the fitness of
males versus females such that ESD invades because it allows sex determination
446 to depend on the environment (reviewed in Charnov 1982, Bull 1983, West 2009).
Here, ESD mutations can spread because they generate females that are either rare
448 or have high fitness, in the same manner as a neo-W.

Equation (5) also shows that invasion by a novel ‘perfect’ ESD (equal sex ra-
450 tio, $k = 1/2$) mutation is the same for an ancestrally XY or ZW system (since
 $\lambda_{Y',XY} = \lambda_{W',ZW}$, $\lambda_{W',XY} = \lambda_{Y',ZW}$). Thus, by the same argument as above (if
452 drive only occurs in males then the sex ratio is only biased when the ancestral
sex-determination system is XY), Fisherian sex-ratio selection alone does not ex-
454 plain the invasion of an offspring-controlled neo-ESD allele under weak selection.
Rather, the neo-ESD gets half of the fitness of a feminizing mutation (neo-W) and
456 half of the fitness of a masculinizing mutation (neo-Y), but only has an effect one
half of the time (the other half of the time it produces the same sex as the ancestral
458 system would have, to leading order). The net result can be that perfect ESD will
not invade, even if current sex ratios are biased. For example, if there is haploid
460 selection in males (either drive or pollen/sperm competition) but the conditions in
table 3 are not met, perfect ESD will not invade, even though it would equalize the
462 zygotic sex ratio from an initially biased case (assuming $r < 1/2$).

Discussion

464 Two predominant theories explaining the remarkably high frequency of transitions
between sex-determination systems are sexually-antagonistic selection and sex-
466 ratio selection (reviewed in Blaser et al. 2012) (van Doorn, 2014, sexual develop-
ment). The former predicts that neo-sex-determining alleles can invade when they
468 arise in closer linkage with a sexually-antagonistic locus (van Doorn and Kirk-
patrick 2007; 2010). The latter predicts that neo-W alleles will invade an XY
470 system when there is a male bias caused by haploid selection in males, and vice-
versa, a neo-Y will invade a ZW system when there is a female bias caused by

472 haploid selection in females (Kozielska et al. 2010, Úbeda et al. 2015). Here we
have shown that both predictions must be amended when recombination is weak
474 relative to selection or selection happens in both diploid and haploid phases.

When the rate of recombination between the ancestral sex-determining locus
476 and a locus under selection is small relative to the strength of selection (i.e., sex-
linkage is tight, or selection is strong), heterogametic transitions (XY to ZW or
478 ZW to XY) that reduce sex-linkage are possible, with or without haploid selection
or sexually-antagonistic selection (Figure ??). The likelihoods of these transitions
480 are driven by sex-ratio selection, direct selection on alleles linked to the neo-sex-
determining allele, the ability of the neo-sex-determining allele to avoid selection
482 in one sex, and the ability of the neo-sex-determining allele to bring alleles on the
sex-specific chromosome in the ancestor into the other sex (given that the neo-sex
484 determining allele is epistatically dominant to its predecessor). This possibility
that looser sex-linkage could evolve, even in the absence of haploid selection (Fig-
486 ure ??A), was overlooked in van Doorn and Kirkpatrick (2010), likely because
they did not explicitly calculate the resident equilibria (equation S.2; Lloyd and
488 Webb 1977, Otto 2014). Interestingly, there is substantial overlap between the pa-
rameter space that allows both neo-W-A and neo-W-a haplotypes to spread in an
490 XY system and that which selects for increased recombination between X and Y
chromosomes (e.g., compare gray region of Figure ??A with coloured regions of
492 Figure 2(a) in Otto 2014). This makes sense, as when both neo-W haplotypes can
spread the neo-W can invade despite reducing sex-linkage, i.e., the rate of recom-
494 bination between the sex-determining allele and the selected locus increases.

Under weak selection (or loose sex-linkage), transitions to new sex-determining
496 systems can occur when they arise more closely linked to a sexually-antagonistic
locus (van Doorn and Kirkpatrick 2007; 2010). Our results show that genetic vari-
498 ation at loci that experience haploid selection can generate selection in favour of
new sex-determining systems in a similar way. New sex-determining alleles are
500 again favoured if they are more closely linked to a locus under haploid selection.
However, with haploid selection, heterogametic transitions (XY to ZW or ZW to

502 XY) can also occur when the new sex-determining region is less closely linked
 to the locus under selection. Neo-W (neo-Y) alleles invade when their fitness in
 504 females (males) is greater than the mean fitness of females (males) under the an-
 cestral sex-determination system and/or females (males) are the rarer sex. With
 506 sexually-antagonistic selection (between diploid sexes) only, linkage between a se-
 lected locus and the sex-determining region strengthens associations between male
 508 beneficial alleles and the male-determining allele (Y or Z) and between female ben-
 efitial alleles and the female-determining allele (X or W). Thus, the mean fitness
 510 of both males and females increases with closer linkage to the sex-determining re-
 gion. Therefore, new sex-determining alleles only invade if they are more closely
 512 linked than the ancestral sex-determining region. However, if there is haploid se-
 lection on loci linked to an XY (ZW) sex-determining region, selection can main-
 514 tain polymorphisms at which the product of the frequency of females (males) and
 the mean fitness of females (males) is lower than it would be without sex-linkage.
 516 In these cases, unlinked neo-W (neo-Y) alleles can increase the frequency and/or
 fitness of the only sex they are found in, at a cost to the other sex, and invade despite
 518 lowering population mean fitness (Figure ??).

Sex ratio biases caused by gametic competition or meiotic drive have been
 520 shown to exert Fisherian sex-ratio selection on various autosomal (Stalker 1961,
 Smith 1975, Frank 1989, Hough et al. 2013, Úbeda et al. 2015, Otto et al. 2015)
 522 and sex-linked (Úbeda et al. 2015) modifiers. We find that sex-ratio biases caused
 by haploid selection can also affect transitions between sex-determining systems
 524 (e.g., see ζ terms in Table 2). For instance, when an allele that drives in males
 is linked to an XY locus it will often become associated with the Y and therefore
 526 produce a male bias ($\zeta < 1/2$). This male bias increases the potential for a neo-W
 to invade (as we then have $(2\zeta)^{-1} > 1$ in Table 2), which can equalize the sex-ratio
 528 (for a related example see Úbeda et al. 2015). However, this sex-ratio selection
 can be overwhelmed when the driving allele has additional selective effects (e.g.,
 530 when it is beneficial for male diploids but detrimental for female diploids; Table
 3), preventing the neo-W from invading. Indeed, these additional selective effects

532 can even favour transitions between sex-determining systems that create new sex-
ratio biases. For example, in an ancestral ZW system, an allele that drives only
534 in males can allow a linked neo-Y to invade, despite the fact it creates a male bias
(Figure ??C). Furthermore, with weak selection, there is no asymmetry between
536 XY to ZW and ZW to XY transitions, indicating that sex-ratio selection does not
dominate (i.e., the sex-ratio bias created by haploid selection impacts the spread
538 of a neo-W into an XY system the same way it impacts the spread of a neo-Y into
a ZW system with a 1:1 sex ratio). An asymmetry can develop when sex-linkage
540 is tight (e.g., Figure 4 near -25cM and 25cM) but under most circumstances we
do not predict asymmetry between XY to ZW and ZW to XY transitions despite
542 the presence/absence of sex ratio selection. Thus, haploid selection can favour
heterogametic transitions both via sex-ratio selection and via fitness effects of al-
544 leles that are associated with the neo-sex-determining allele, and these selection
pressures are often of equal magnitude.

546 We assume that sex-determining alleles do not experience direct selection ex-
cept via their associations with sex and alleles at a selected locus. However, in
548 some cases, there may be significant degeneration around the sex-limited allele (Y
or W) in the ancestral sex-determining region because recessive deleterious muta-
550 tions and/or deletions may fix around the Y or W allele (Rice 1996, Charlesworth
and Charlesworth 2000, Bachtrog 2006, Marais et al. 2008). During heterogametic
552 transitions (XY to ZW or ZW to XY), the formally sex-limited allele fixes such
that all individuals have YY or WW genotypes (Figure ??). Any recessive deleter-
554 ious alleles linked to the Y or W will therefore be revealed to selection during a
heterogametic transition. This phenomenon was studied by van Doorn and Kirk-
556 patrick (2010), who found that degeneration can prevent fixation of a neo-W or
a neo-Y allele, leading to a mixed sex-determination system where the ancestral-
558 and neo- sex-determining loci are both polymorphic. However, they noted that
very rare recombination events around the ancestral sex-determining region can
560 allow these heterogametic transitions to complete. While not explicitly studied,
we also predict that Y or W degeneration would prevent fixation of the new sex-

determiners considered here.

In addition, our model of meiotic drive is simple, involving a single locus with two alleles. However, many meiotic drive systems involve an interaction with another locus at which alleles may ‘suppress’ the action of meiotic drive (Burt and Trivers 2006, Lindholm et al. 2016). Thus, the dynamics of meiotic drive alleles can be heavily dependent on the interaction between two loci and the recombination rate between them, which in turn can be affected by sex-linkage if there is reduced recombination between sex chromosomes (Hurst and Pomiankowski 1991). Furthermore, in some cases, a driving allele may act by killing any gametes that carry a ‘target’ allele at another locus, in which case there is a two-locus drive system and the total number of gametes produced can be reduced by meiotic drive. Where gamete number is reduced by meiotic drive, the number of mates competing for fertilization (mating system) can affect the equilibrium frequency of a meiotic drive allele (Holman et al. 2015). In polygamous mating systems, the intensity of pollen/sperm competition can depend on the density of males available to donate pollen/sperm, which can itself depend on the sex ratio (Taylor and Jaenike 2002). Since the sex ratio is partly determined by the sex-determination system, the evolution of new sex-determination system could be influenced by these dynamics. How the evolution of new sex-determining mechanisms could be influenced by two-locus meiotic drive and/or by ecological feedbacks under different mating systems remains to be studied.

The hypotheses presented here can be empirically investigated in a similar manner to the idea that transitions between sex-determining systems are favoured by linkage to sexually-antagonistic variation. In the case of sexually-antagonistic variation, one supporting observation is that genes expected to be under sexually-antagonistic selection (e.g., those causing bright male colouration) have been found on recently derived sex chromosomes (Lindholm and Breden 2002, Tripathi et al. 2009, Ser et al. 2010). Our results suggest that polymorphic loci that are ancestrally sex-linked and under sex-specific selection could also drive heterogametic transitions between sex-determination systems. As noted by van Doorn and Kirkpatrick

(2010), it would be prudent to compare closely related clades in order to determine whether observed polymorphisms pre-dates a transition in sex-determination or arose afterwards, particularly because sex-linkage allows sexually-antagonistic selection to maintain polymorphisms under a different and larger parameter space (Rice 1987, Jordan and Charlesworth 2011). As with sexually-antagonistic selection, the presence of haploid selected loci around ancestral- or novel-sex-determining regions could support their role in sex chromosome turnover. A recent transcriptome analysis in *Rumex*, suggests a role for haploid competition in the evolution of sex-determination systems by showing that Y-linked genes are overexpressed in pollen but not in male diploids, indicating variation currently or previously maintained by haploid selection; over-expression also occurs on the autosome that is orthologous to the sex chromosomes in closely related species (Sandler et al., 2017, Personal Communication).

Taken at face value, our results indicate that transitions in heterogamete (XY to ZW or vice versa) are more likely than transitions in homogamete when genetic conflict is predominately between the haploids of each sex (e.g., with $|D^\delta - D^\varphi| \ll |\alpha_\Delta^\delta - \alpha_\Delta^\varphi + t^\delta - t^\varphi|$ we have $\lambda_{W',XY} > \lambda_{Y',XY}$; equations 3 and S.5). In addition, because haploid selection can cause transitions that increase or decrease sex-linkage, haploid selection may lead to less stability, and greater potential for cycling, in sex-determination systems (e.g., the final state in Figure ??C is the starting state in Figure ??B). Potentially, successive heterogametic transitions between master regulators of sex-determination could be inferred from careful examination of the molecular pathways by which sex is determined. Our predictions could also be examined using a suitable proxy for haploid selection, for example, Lenormand and Dutheil (2005) use the outcrossing rate in plants as a proxy for the strength of pollen competition. Furthermore, assuming that transitions from dioecy to hermaphroditism (equal parental investment in male and female gametes) are favoured in a similar manner to the ESD examined here (equal probability of zygotes developing as males or females), our results suggest that haploid competition during the multicellular haploid stage could drive transitions between dioecy

622 and hermaphroditism in plants (Käfer et al., 2017, Sabath et al., 2017). In ani-
mals, one might expect gametic competition to be stronger in species where sperm
624 is required to live for a long time after spermatogenesis because transcripts shared
during spermatogenesis may become depleted, revealing the haploid phenotype of
626 the sperm (Immler et al. 2014). Given the caveats mentioned above about the form
of meiotic drive modelled, we would also expect that heterogametic transitions in
628 sex determination would be more common in clades where there is meiotic drive.

We have shown that tight sex-linkage and haploid selection can drive previ-
630 ously unexpected transitions between sex-determination systems. In particular,
both can select for neo-sex-determining loci that are more loosely linked. In ad-
632 dition, haploid selection alone can cause transitions analogous to those caused
by purely sexually-antagonistic selection, eliminating the need for differences in
634 selection between male and female diploids. Perhaps counterintuitively, transi-
tions involving haploid selection can be driven by sex-ratio selection, or cause
636 sex-ratio biases to evolve. We therefore argue that haploid selection should be
considered, alongside sexually-antagonistic and sex-ratio selection, as a poten-
638 tially pivotal factor in the evolution of many sex-determination systems. Overall,
our results suggest several new scenarios under which new sex-determination sys-
640 tems are favoured, including sex-specific selection on ancestrally sex-linked loci,
which could help to explain why the evolution of sex-determination systems is so
642 dynamic.

References

- 644 Arunkumar, R., E. B. Josephs, R. J. Williamson, and S. I. Wright. 2013. Pollen-
specific, but not sperm-specific, genes show stronger purifying selection and
646 higher rates of positive selection than sporophytic genes in *Capsella grandiflora*.
Molecular biology and evolution 30:2475–2486.
- 648 Bachtrog, D. 2006. A dynamic view of sex chromosome evolution. Current opin-
ion in genetics & development 16:578–585.

- 650 Bachtrog, D., J. E. Mank, C. L. Peichel, M. Kirkpatrick, S. P. Otto, T.-L. Ashman,
M. W. Hahn, J. Kitano, I. Mayrose, R. Ming, N. Perrin, L. Ross, N. Valenzuela,
652 J. C. Vamosi, and Tree of Sex Consortium. 2014. Sex determination: why so
many ways of doing it? *PLoS Biol* 12:e1001899.
- 654 Beukeboom, L. W., and N. Perrin. 2014. The evolution of sex determination.
Oxford University Press, Oxford, UK.
- 656 Blaser, O., C. Grossen, S. Neuenschwander, and N. Perrin. 2012. Sex-chromosome
turnovers induced by deleterious mutation load. *Evolution* 67:635–645.
- 658 Borg, M., L. Brownfield, and D. Twell. 2009. Male gametophyte development: a
molecular perspective. *Journal of Experimental Botany* 60:1465–1478.
- 660 Bull, J. J. 1983. Evolution of sex determining mechanisms. The Benjamin Cum-
mings Publishing Company.
- 662 Burt, A., and R. Trivers. 2006. Genes in conflict: the biology of selfish genetic
elements. Belknap Press, Cambridge, MA.
- 664 Charlesworth, B., and D. Charlesworth. 2000. The degeneration of Y chromo-
somes. *Philosophical transactions of the Royal Society of London. Series B,*
666 *Biological sciences* 355:1563–1572.
- Charlesworth, D., and J. E. Mank. 2010. The birds and the bees and the flowers
668 and the trees: lessons from genetic mapping of sex determination in plants and
animals. *Genetics* 186:9–31.
- 670 Charnov, E. L. 1982. The theory of sex allocation. *Monographs in population
biology*.
- 672 Clarke, H. J., T. N. Khan, and K. H. M. Siddique. 2004. Pollen selection for chill-
ing tolerance at hybridisation leads to improved chickpea cultivars. *Euphytica*
674 139:65–74.

- 676 Conn, J. S., and U. Blum. 1981. Sex ratio of *Rumex hastatulus*: the effect of
environmental factors and certation. *Evolution* 35:1108–1116.
- 678 Conover, D. O., and S. W. Heins. 1987. Adaptive variation in environmental and
genetic sex determination in a fish. *Nature* 326:496–498.
- 680 Ezaz, T., S. D. Sarre, and D. O’Meally. 2009. Sex chromosome evolution in lizards:
independent origins and rapid transitions. *Cytogenetic and Genome Research*
127:249–260.
- 682 Field, D. L., M. Pickup, and S. C. H. Barrett. 2012. The influence of pollina-
tion intensity on fertilization success, progeny sex ratio, and fitness in a wind-
684 pollinated, dioecious plant. *International Journal of Plant Sciences* 173:184–
191.
- 686 ———. 2013. Comparative analyses of sex-ratio variation in dioecious flowering
plants. *Evolution* 67:661–672.
- 688 Fisher, R. 1930. The genetical theory of natural selection. Clarendon Press, Lon-
don.
- 690 Frank, S. A. 1989. The Evolutionary Dynamics of Cytoplasmic Male Sterility.
American Naturalist 133:345–376.
- 692 Gossmann, T. I., M. W. Schmid, U. Grossniklaus, and K. J. Schmid. 2014.
Selection-driven evolution of sex-biased genes Is consistent with sexual selec-
694 tion in *Arabidopsis thaliana*. *Molecular biology and evolution* 31:574–583.
- Haldane, J. B. S. 1919. The combination of linkage values and the calculation of
696 distances between the loci of linked factors. *Journal of Genetics* 8:299–309.
- Hamilton, W. D. 1967. Extraordinary sex ratios. *Science* 156:477–488.
- 698 Hedhly, A., J. I. Hormaza, and M. Herrero. 2004. Effect of temperature on pollen
tube kinetics and dynamics in sweet cherry, *Prunus avium* (Rosaceae). *Ameri-
700 can journal of botany* 91:558–564.

- Hillis, D. M., and D. M. Green. 1990. Evolutionary changes of heterogametic sex in the phylogenetic history of amphibians. *Journal of Evolutionary Biology* 3:49–64.
- Holleley, C. E., D. O’Meally, S. D. Sarre, J. A. Marshall Graves, T. Ezaz, K. Matsubara, B. Azad, X. Zhang, and A. Georges. 2015. Sex reversal triggers the rapid transition from genetic to temperature-dependent sex. *Nature* 523:79–82.
- Holman, L., T. A. R. Price, N. Wedell, and H. Kokko. 2015. Coevolutionary dynamics of polyandry and sex-linked meiotic drive. *Evolution* 69:709–720.
- Hormaza, J. I., and M. Herrero. 1996. Male gametophytic selection as a plant breeding tool. *Scientia horticultrae* 65:321–333.
- Hough, J., S. Immler, S. Barrett, and S. P. Otto. 2013. Evolutionarily stable sex ratios and mutation load. *Evolution* 7:1915–1925.
- Hurst, L. D., and A. Pomiankowski. 1991. Causes of sex ratio bias may account for unisexual sterility in hybrids: a new explanation of Haldane’s rule and related phenomena. *Genetics* 128:841–858.
- Immler, S., G. Arnqvist, and S. P. Otto. 2012. Ploidally antagonistic selection maintains stable genetic polymorphism. *Evolution* 66:55–65.
- Immler, S., C. Hotzy, G. Alavioon, E. Petersson, and G. Arnqvist. 2014. Sperm variation within a single ejaculate affects offspring development in Atlantic salmon. *Biology letters* 10:20131040.
- Jordan, C. Y., and D. Charlesworth. 2011. The potential for sexually antagonistic polymorphism in different genome regions. *Evolution* 66:505–516.
- Joseph, S., and M. Kirkpatrick. 2004. Haploid selection in animals. *Trends in Ecology & Evolution* 19:592–597.

- 726 Karlin, S., and J. McGregor. 1972*a*. Application of method of small parameters to
multi-niche population genetic models. *Theoretical Population Biology* 3:186–
209.
- 728 ———. 1972*b*. Polymorphisms for genetic and ecological systems with weak
coupling. *Theoretical Population Biology* 3:210–238.
- 730 Kozielska, M., F. J. Weissing, L. W. Beukeboom, and I. Pen. 2010. Segregation
distortion and the evolution of sex-determining mechanisms. *Heredity* 104:100–
732 112.
- Lenormand, T., and J. Dutheil. 2005. Recombination difference between sexes: a
734 role for haploid selection. *PLoS Biol* 3:e63.
- Li, J., R. B. Phillips, A. S. Harwood, B. F. Koop, and W. S. Davidson. 2011. Iden-
736 tification of the Sex Chromosomes of Brown Trout (*Salmo trutta*) and Their
Comparison with the Corresponding Chromosomes in Atlantic Salmon (*Salmo*
738 *salar*) and Rainbow Trout (*Oncorhynchus mykiss*). *Cytogenetic and Genome*
Research 133:25–33.
- 740 Lindholm, A., and F. Breden. 2002. Sex chromosomes and sexual selection in
poeciliid fishes. *The American Naturalist* 160 Suppl 6:S214–24.
- 742 Lindholm, A. K., K. A. Dyer, R. C. Firman, L. Fishman, W. Forstmeier, L. Hol-
man, H. Johannesson, U. Knief, H. Kokko, A. M. Larracuenta, A. Manser,
744 C. Montchamp-Moreau, V. G. Petrosyan, A. Pomiankowski, D. C. Presgraves,
L. D. Safronova, A. Sutter, R. L. Unckless, R. L. Verspoor, N. Wedell, G. S.
746 Wilkinson, and T. A. R. Price. 2016. The Ecology and Evolutionary Dynamics
of Meiotic Drive. *Trends in Ecology & Evolution* 31:315–326.
- 748 Lloyd, D. G. 1974. Female-predominant sex ratios in angiosperms. *Heredity*
32:35–44.
- 750 Lloyd, D. G., and C. Webb. 1977. Secondary sex characters in plants. *Botanical*
Review 43:177–216.

- 752 Mank, J. E., D. E. L. Promislow, and J. C. Avise. 2006. Evolution of alternative sex-determining mechanisms in teleost fishes. *Biological Journal of the*
754 *Linnean Society* 87:83–93.
- Marais, G. A. B., M. Nicolas, R. Bergero, P. Chambrier, E. Kejnovsky, F. Monéger,
756 R. Hobza, A. Widmer, and D. Charlesworth. 2008. Evidence for degeneration of the Y chromosome in the dioecious plant *Silene latifolia*. *Current Biology*
758 18:545–549.
- Ming, R., A. Bendahmane, and S. S. Renner. 2011. Sex chromosomes in land
760 plants. *Annu. Rev. Plant Biol.* 62:485–514.
- Mulcahy, D. L., M. Sari-Gorla, and G. B. Mulcahy. 1996. Pollen selection - past,
762 present and future. *Sexual Plant Reproduction* 9:353–356.
- Myosho, T., H. Otake, H. Masuyama, M. Matsuda, Y. Kuroki, A. Fujiyama,
764 K. Naruse, S. Hamaguchi, and M. Sakaizumi. 2012. Tracing the Emergence of a Novel Sex-Determining Gene in Medaka, *Oryzias luzonensis*. *Genetics*
766 191:163–170.
- Ogata, M., Y. Hasegawa, H. Ohtani, M. Mineyama, and I. Miura. 2007. The
768 ZZ/ZW sex-determining mechanism originated twice and independently during evolution of the frog, *Rana rugosa*. *Heredity* 100:92–99.
- 770 Otto, S. P. 2014. Selective maintenance of recombination between the sex chromosomes. *Journal of Evolutionary Biology* 27:1431–1442.
- 772 Otto, S. P., M. F. Scott, and S. Immler. 2015. Evolution of haploid selection in predominantly diploid organisms. *Proc Natl Acad Sci* 112:15952–15957.
- 774 Pen, I., T. Uller, B. Feldmeyer, A. Harts, G. M. While, and E. Wapstra. 2010. Climate-driven population divergence in sex-determining systems. *Nature*
776 468:436–438.

- 778 Pokorná, M., and L. Kratochvíl. 2009. Phylogeny of sex-determining mechanisms in squamate reptiles: are sex chromosomes an evolutionary trap? *Zoological Journal of the ...* 156:168–183.
- 780 Ravikumar, R. L., B. S. Patil, and P. M. Salimath. 2003. Drought tolerance in sorghum by pollen selection using osmotic stress. *Euphytica* 133:371–376.
- 782 Rice, W. R. 1987. The accumulation of sexually antagonistic genes as a selective agent promoting the evolution of reduced recombination between primitive sex
784 chromosomes. *Evolution* 41:911.
- . 1996. Evolution of the Y Sex Chromosome in Animals. *BioScience*
786 46:331–343.
- 788 Ser, J. R., R. B. Roberts, and T. D. Kocher. 2010. Multiple interacting loci control sex determination in lake Malawi cichlid fish. *Evolution* 64:486–501.
- 790 Slancarova, V., J. Zdanska, B. Janousek, M. Talianova, C. Zschach, J. Zluvova, J. Siroky, V. Kovacova, H. Blavet, J. Danihelka, B. Oxelman, A. Widmer, and B. Vyskot. 2013. Evolution of sex determination systems with heterogametic
792 males and females in *Silene*. *Evolution* 67:3669–3677.
- 794 Smith, D. A. S. 1975. All-female broods in the polymorphic butterfly *Danaus chrysippus* L. and their ecological significance. *Heredity* 34:363–371.
- 796 Stalker, H. D. 1961. The Genetic Systems Modifying Meiotic Drive in *Drosophila Paramelanica*. *Genetics* 46:177–202.
- 798 Stehlik, I., and S. Barrett. 2005. Mechanisms governing sex-ratio variation in dioecious *Rumex nivalis*. *Evolution* 59:814–825.
- 800 Stehlik, I., and S. C. H. Barrett. 2006. Pollination intensity influences sex ratios in dioecious *Rumex nivalis*, a wind-pollinated plant. *Evolution* 60:1207–1214.
- 802 Taylor, J. E., and J. Jaenike. 2002. Sperm competition and the dynamics of X chromosome drive: stability and extinction. *Genetics* 160:1721–1731.

- Tripathi, N., M. Hoffmann, E.-M. Willing, C. Lanz, D. Weigel, and C. Dreyer.
 804 2009. Genetic linkage map of the guppy, *Poecilia reticulata*, and quantitative
 trait loci analysis of male size and colour variation. *Proceedings. Biological*
 806 *sciences / The Royal Society* 276:2195–2208.
- Úbeda, F., and D. Haig. 2005. On the evolutionary stability of Mendelian segre-
 808 gation. *Genetics* 170:1345–1357.
- Úbeda, F., M. M. Patten, and G. Wild. 2015. On the origin of sex chromosomes
 810 from meiotic drive. *Proceedings of the Royal Society B: Biological Sciences*
 282:20141932.
- 812 van Doorn, G. S., and M. Kirkpatrick. 2007. Turnover of sex chromosomes in-
 duced by sexual conflict. *Nature* 449:909–912.
- 814 ———. 2010. Transitions Between Male and Female Heterogamety Caused by
 Sex-Antagonistic Selection. *Genetics* 186:629–645.
- 816 Vibrationovski, M. D., D. S. Chalopin, H. F. Lopes, M. Long, and T. L. Karr. 2010.
 Direct evidence for postmeiotic transcription during *Drosophila melanogaster*
 818 spermatogenesis. *Genetics* 186:431–433.
- Vicoso, B., and D. Bachtrog. 2015. Numerous transitions of sex chromosomes in
 820 Diptera. *PLoS Biol* 13:e1002078.
- West, S. 2009. Sex allocation. Princeton University Pres.
- 822 Yano, A., B. Nicol, E. Jouanno, E. Quillet, A. Fostier, R. Guyomard, and
 Y. Guiguen. 2012. The sexually dimorphic on the Y-chromosome gene (sdY)
 824 is a conserved male-specific Y-chromosome sequence in many salmonids. *Evo-*
lutionary Applications 6:486–496.
- 826 Zheng, Y., X. Deng, and P. A. Martin-DeLeon. 2001. Lack of sharing of Spam1
 (Ph-20) among mouse spermatids and transmission ratio distortion. *Biology of*
 828 *Reproduction* 64:1730–1738.

Figures

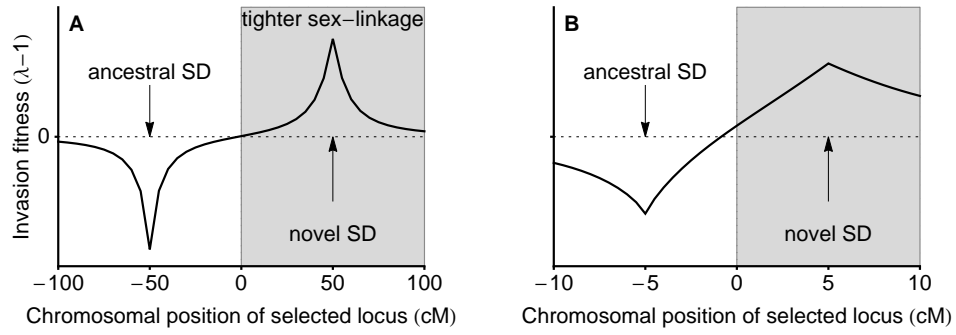


Figure 1: In the absence of haploid selection, tight linkage allows looser sex-linkage to evolve in transitions between XY and ZW systems. In panel A, linkage is loose enough relative to selection that the weak selection analytical results hold, and a neo-W can only invade when it is more tightly linked with the selected locus ($R < r$; shaded region). In panel B, linkage is tight enough relative to selection that the weak selection analytical results do not hold, and a neo-W can only invade even when it is less tightly linked with the selected locus ($r < R$; unshaded region). Parameters: $w_{AA}^{\varnothing} = w_{aa}^{\delta} = 1.05$, $w_{aa}^{\varnothing} = w_{AA}^{\delta} = 0.85$, $w_{Aa}^{\varnothing} = 1$, $w_{Aa}^{\delta} = 0.925$, $t^{\varnothing} = \alpha_{\Delta}^{\varnothing} = 0$.

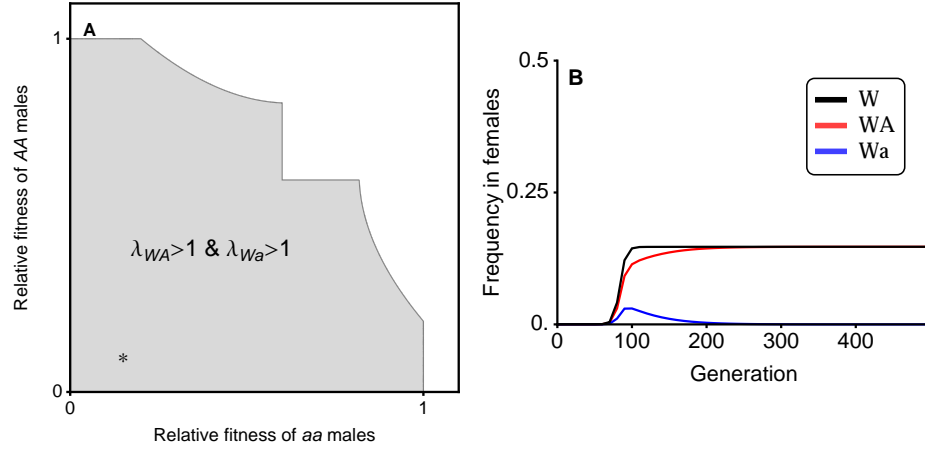


Figure 2: In the absence of haploid selection, both neo-W haplotypes can spread in an XY system when there is overdominance. Panel A shows the range of male homozygote fitnesses that allow both neo-W haplotypes to invade. Panel B shows the temporal dynamics of the invading neo-W haplotypes; in this case the neo-W does not fix, leading to a polymorphic sex-determining system. Asterisk in panel A marks parameter values ($w_{aa}^{\delta} = 0.15$, $w_{AA}^{\delta} = 0.1$) used in panel B. Parameters: $w_{AA}^{\varnothing} = w_{aa}^{\varnothing} = 0.6$, $w_{Aa}^{\varnothing} = 1$, $t^{\varnothing} = \alpha_{\Delta}^{\varnothing} = 0$, $r = R = 0$.

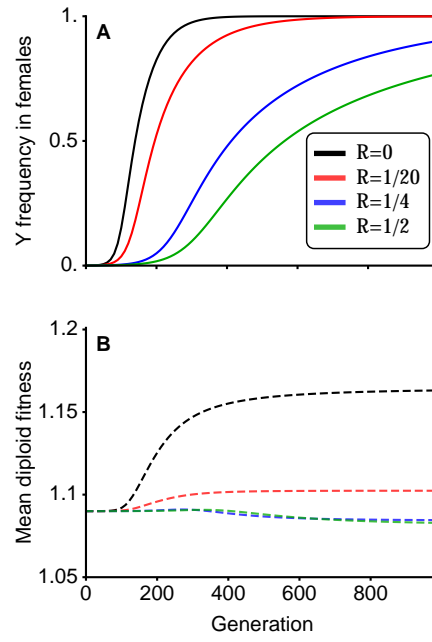


Figure 3: With weak selection, a less tightly linked neo-W can invade (and fix in) an XY system (causing the Y to fix in females) when there is some haploid selection (blue and green curves in panel A), and this invasion decreases mean diploid fitness (green and blue curves in panel B). Parameters: $s^{\delta} = 0.2$, $h^{\delta} = 0.7$, $t^{\delta} = \alpha_{\Delta}^{\delta} = 0$, $\alpha_{\Delta}^{\circ} = -0.1$, $r = 1/10$.

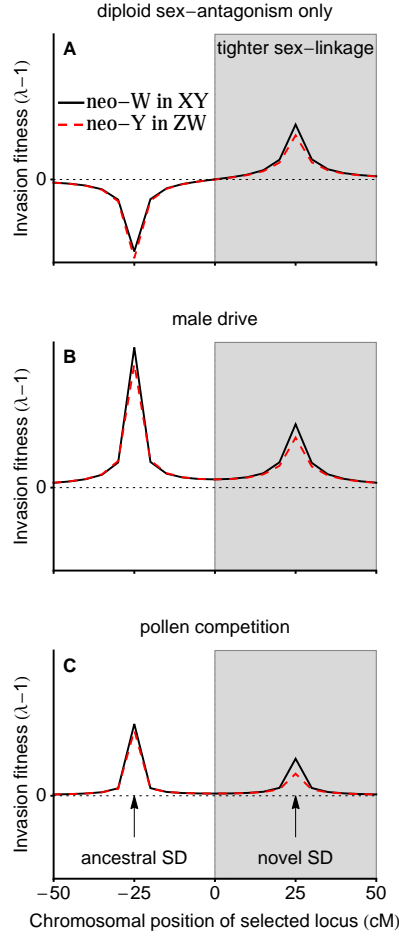


Figure 4: A neo-W can invade an XY system under a large number of selective regimes. In panel A, there is no haploid selection ($t^\delta = \alpha_\Delta^\delta = 0$) and selection in diploids is sexually antagonistic ($s^\delta = -s^\varnothing = 1/10$, $h^\delta = 1 - h^\varnothing = 3/10$), in which case the neo-sex-determining allele can only invade if it is more closely linked to the selected locus ($R < r$, gray region; but see Figure 1B for the case of very tight linkage). In panel B, male drive ($\alpha_\Delta^\delta = -1/20$, $t^\delta = \alpha_\Delta^\varnothing = 0$) opposes selection in diploids (no sex-differences: $s^\delta = 1/10$, $h^\delta = 7/10$), in which case the neo-sex-determining allele can invade regardless of linkage. In panel C, haploid competition in males ($t^\delta = -1/10$, $t^\varnothing = \alpha_\Delta^\delta = 0$) opposes selection in diploids (sex-differences: $s^\delta = 3s^\varnothing = 3/20$, $h^\delta = 7/10$), in which case the neo-sex-determining allele can once again invade regardless of linkage. We use Haldane's map function (Equation 3 in Haldane 1919) to convert from map distance (centiMorgans, cM) to the probability of recombination (an odd number of cross-over events).

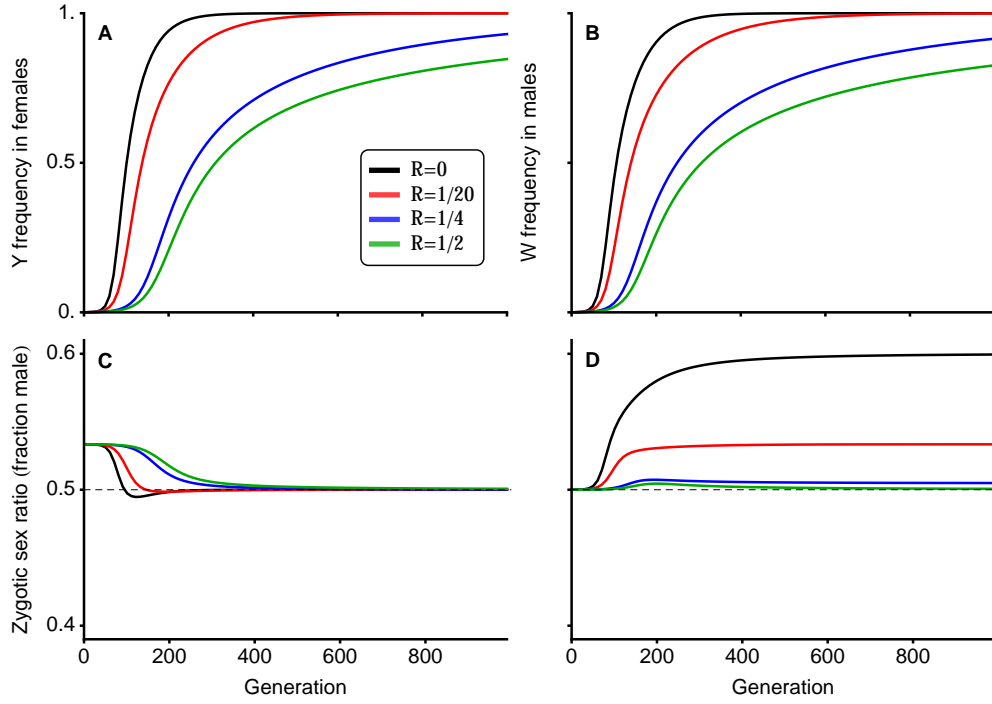


Figure 5: Sex-ratio selection alone is not a good predictor of turnover between sex-determining systems. In panels A and C, male drive in an ancestral XY system causes a male bias, allowing a neo-W to invade and fix (causing the Y to fix in females), which balances the sex ratio (it also avoids selection in males, and thus makes better females in this case of sex-specific ploidally-antagonistic selection). In panels B and D, male drive in an ancestral ZW system has no affect on the sex ratio, yet a neo-Y can invade and fix (causing the W to fix in males) because it becomes linked with the driving allele, and this imparts a sex ratio bias. Parameters: $s^{\varnothing} = s^{\delta} = 0.2$, $h^{\varnothing} = h^{\delta} = 0.7$, $t^{\varnothing} = t^{\delta} = \alpha_{\Delta}^{\delta} = 0$, $\alpha_{\Delta}^{\varnothing} = -1/10$, $r = 1/20$.

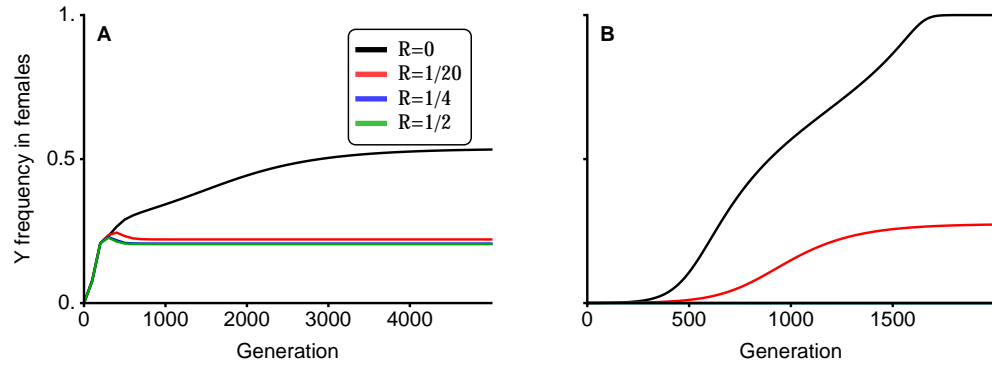


Figure 6: Tight linkage (relative to selection) and/or haploid selection can cause stable polymorphic sex-determining systems. In panel A, there is strong overdominance in both sexes and no haploid selection (parameters as in Figure 2B with $r = 1/10$), in which case a neo-W can invade regardless of sex-linkage, but cannot not fix (i.e., the Y does not fix in females, and X, Y, W, and Z all segregate at equilibrium). In panel B, there is sex-antagonistic selection at the diploid stage and drive in females (parameters as in Figure 1 with $\alpha_{\Delta}^{\circ} = -1/20$ and $r = 1/10$), in which case a sufficiently tightly linked neo-W can invade ($R < \sim r$), but only fixes if $R = 0$.

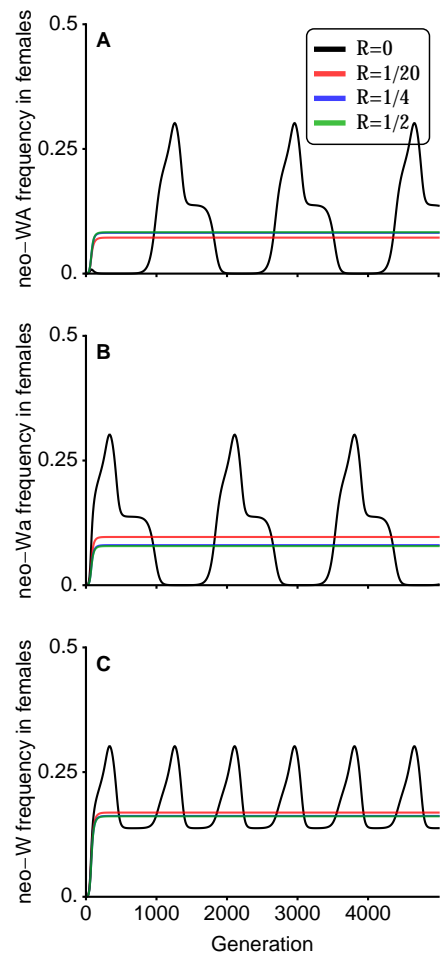


Figure 7: Thought I'd show this just for fun (not for publication).

830 Appendix

Recursion Equations

832 Should we adjust the subscripts throughout this subsection? Right now we end up
 re-defining i and j (when switching from haploid to diploid; this might have been
 834 my doing!) and then introduce three new subscripts b , c , and l , all of which can
 be derived from i and j . Might be more straightforward to just use $p_{x_1, x_2, a_1, a_2, m_1, m_2}^{\phi}$
 836 where 1 is maternal and 2 is paternal? We then no longer have to switch indices
 from haploid to diploid and the connection to other variables is clear: $b = m_1 m_2$,
 838 $c = x_1 x_2$, and $l = a_1 a_2$. I guess the downside will be re-writing the recursion
 equations... which is why I haven't gone ahead and tried this.

840 In each generation we census the genotype frequencies in male and female gametes/gametophytes (hereafter, gametes) between meiosis (and any meiotic drive)
 842 and gametic competition. At this stage we denote the frequencies of X- and Y-bearing gametes from males and females x_{ij}^{ϕ} and y_{ij}^{ϕ} , where $\phi \in \{\delta, \varphi\}$ specifies the sex of the diploid that the gamete came from, $i \in \{A, a\}$ specifies the allele at the selected locus **A**, and $j \in \{M, m\}$ specifies the allele at the novel sex-determining locus **M**. The gamete frequencies from each sex sum to one,
 846 $\sum_{i,j} x_{ij}^{\phi} + y_{ij}^{\phi} = 1$.

848 Competition then occurs among gametes of the same sex (e.g., among eggs and among sperm separately) according to the **A** locus allele, i (see Table 1). The
 850 genotype frequencies after gametic competition are $x_{ij}^{\phi, s} = w_i x_{ij}^{\phi} / \bar{w}_H^{\phi}$ and $y_{ij}^{\phi, s} = w_i y_{ij}^{\phi} / \bar{w}_H^{\phi}$, where $\bar{w}_H^{\phi} = \sum_{i,j} w_i x_{ij}^{\phi} + w_i y_{ij}^{\phi}$ is the mean fitness of male ($\phi = \delta$) or
 852 female ($\phi = \varphi$) gametes.

Random mating then occurs between gametes to produce diploid zygotes. To
 854 shorten notation we now use index i (and j) to denote the alleles at both the **A** and **M** loci and label $MA = 1$, $Ma = 2$, $mA = 3$, and $ma = 4$, such that
 856 $i, j \in \{1, 2, 3, 4\}$. The frequencies of XX zygotes are then denoted as xx_{ij} , XY zygotes as xy_{ij} , and YY zygotes as yy_{ij} . In XX and YY zygotes, individuals with
 858 diploid genotype ij are equivalent to those with diploid genotype ji ; for simplicity,

we use xx_{ij} and yy_{ij} with $i \neq j$ to denote the average of these frequencies, $xx_{ij} =$
860 $(x_i^{\varphi,s} x_j^{\delta,s} + x_j^{\varphi,s} x_i^{\delta,s})/2$ and $yy_{ij} = (y_i^{\varphi,s} y_j^{\delta,s} + y_j^{\varphi,s} y_i^{\delta,s})/2$.

Denoting the **M** locus genotype by $b \in \{MM, Mm, mm\}$ and the **X** locus
862 genotype by $c \in \{XX, XY, YY\}$, zygotes develop as females with probability
 k_{bc} . Therefore, the frequencies of XX females are given by $xx_{ij}^{\varphi} = k_{bc}xx_{ij}$, XY
864 females are given by $xy_{ij}^{\varphi} = k_{bc}xy_{ij}$, and YY females are given by $yy_{ij}^{\varphi} = k_{bc}yy_{ij}$.
Similarly, XX male frequencies are $xx_{ij}^{\delta} = (1 - k_{bc})xx_{ij}$, XY male frequencies
866 are $xy_{ij}^{\delta} = (1 - k_{bc})xy_{ij}$, and YY males frequencies are $yy_{ij}^{\delta} = (1 - k_{bc})yy_{ij}$. This
notation allows both the ancestral and novel sex-determining regions to determine
868 zygotic sex according to an XY system, a ZW system, or an environmental sex-
determining system. In addition, we can consider any epistatic dominance rela-
870 tionship between the two sex-determining loci. For example, here we assume that
the ancestral sex-determining system (**X** locus) is XY ($k_{MMXX} = 1$ and $k_{MMXY} =$
872 $k_{MMYY} = 0$) or ZW ($k_{MMZZ} = 0$ and $k_{MMZW} = k_{MMWW} = 1$) and epistatically
recessive to a dominant novel sex-determining locus, **M** ($k_{Mmc} = k_{mmc} = k$).

Selection among diploids then occurs according to the diploid genotype at the
874 **A** locus, $l \in \{AA, Aa, aa\}$, for an individual of type ij (see Table 1). The diploid
frequencies after selection in sex φ are given by $xx_{ij}^{\varphi,s} = w_l^{\varphi}xx_{ij}/\bar{w}^{\varphi}$, $xy_{ij}^{\varphi,s} =$
876 $w_l^{\varphi}xy_{ij}/\bar{w}^{\varphi}$, and $yy_{ij}^{\varphi,s} = w_l^{\varphi}yy_{ij}/\bar{w}^{\varphi}$, where $\bar{w}^{\varphi} = \sum_{i=1}^4 \sum_{j=1}^4 w_l^{\varphi}xx_{ij} + w_l^{\varphi}xy_{ij} +$
878 $w_l^{\varphi}yy_{ij}$ is the mean fitness of individuals of sex φ .

Finally, these diploids undergo meiosis to produce the next generation of gam-
880 etes. Recombination and sex-specific meiotic drive occur during meiosis. Here,
we allow any relative locations for the SDR, **A**, and **M** loci by using three param-
882 eters to describe the recombination rates between them. R is the recombination
rate between the **A** locus and the **M** locus, χ is the recombination rate between the
884 **M** locus and the **X** locus, and r is the recombination rate between the **A** locus and
the **X** locus. Table S.1 shows how χ can be substituted to give any linear order of
886 loci. During meiosis in sex φ , meiotic drive occurs such that, in Aa heterozygotes,
a fraction α^{φ} of gametes produced carry the A allele and $(1 - \alpha^{\varphi})$ carry the a allele.

888 Among gametes from sex φ (sperm/pollen when $\varphi = \delta$, eggs/ovules when

Table S.1: χ substitutions for different loci orders (assuming no interference)

Order of loci	
SDR-A-M	$\chi = R(1 - r) + r(1 - R)$
SDR-M-A	$\chi = (r - R)/(1 - 2R)$
A-SDR-M	$\chi = (R - r)/(1 - 2r)$

$\phi = \varphi$), the frequencies of haplotypes (before gametic competition) in the next
890 generation are given by

$$\begin{aligned}
x_{MA}^{\phi'} = & x x_{11}^{\phi,s} + x x_{13}^{\phi,s} / 2 + (x x_{12}^{\phi,s} + x x_{14}^{\phi,s}) \alpha^{\phi} \\
& - R(x x_{14}^{\phi,s} - x x_{23}^{\phi,s}) \alpha^{\phi} \\
& + (x y_{11}^{\phi,s} + x y_{13}^{\phi,s}) / 2 + (x y_{12}^{\phi,s} + x y_{14}^{\phi,s}) \alpha^{\phi} \\
& - r(x y_{12}^{\phi,s} - x y_{21}^{\phi,s}) \alpha^{\phi} - \chi(x y_{13}^{\phi,s} - x y_{31}^{\phi,s}) / 2 \\
& + \{ -(R + r + \chi) x y_{14}^{\phi,s} + (r + \chi - R) x y_{41}^{\phi,s} \\
& + (R + r - \chi) x y_{23}^{\phi,s} + (R + \chi - r) x y_{32}^{\phi,s} \} \alpha^{\phi} / 2
\end{aligned} \tag{S.1a}$$

$$\begin{aligned}
x_{Ma}^{\phi'} = & x x_{22}^{\phi,s} + x x_{24}^{\phi,s} / 2 + (x x_{12}^{\phi,s} + x x_{23}^{\phi,s}) \alpha^{\phi} \\
& - R(x x_{23}^{\phi,s} - x x_{14}^{\phi,s}) \alpha^{\phi} \\
& (x y_{22}^{\phi,s} + x y_{24}^{\phi,s}) / 2 + (x y_{21}^{\phi,s} + x y_{23}^{\phi,s}) (1 - \alpha^{\phi}) \\
& - r(x y_{21}^{\phi,s} - x y_{12}^{\phi,s}) (1 - \alpha^{\phi}) - \chi(x y_{24}^{\phi,s} - x y_{42}^{\phi,s}) / 2 \\
& + \{ -(R + r + \chi) x y_{23}^{\phi,s} + (r + \chi - R) x y_{32}^{\phi,s} \\
& + (R + r - \chi) x y_{14}^{\phi,s} + (R + \chi - r) x y_{41}^{\phi,s} \} (1 - \alpha^{\phi}) / 2
\end{aligned} \tag{S.1b}$$

$$\begin{aligned}
x_{mA}^{\tilde{\phi}'} = & x x_{33}^{\tilde{\phi},s} + x x_{13}^{\tilde{\phi},s} / 2 + (x x_{23}^{\tilde{\phi},s} + x x_{34}^{\tilde{\phi},s}) \alpha^{\tilde{\phi}} \\
& - R(x x_{23}^{\tilde{\phi},s} - x x_{14}^{\tilde{\phi},s}) \alpha^{\tilde{\phi}} \\
& (x y_{33}^{\tilde{\phi},s} + x y_{31}^{\tilde{\phi},s}) / 2 + (x y_{32}^{\tilde{\phi},s} + x y_{34}^{\tilde{\phi},s}) \alpha^{\tilde{\phi}} \\
& - r(x y_{34}^{\tilde{\phi},s} - x y_{43}^{\tilde{\phi},s}) \alpha^{\tilde{\phi}} - \chi(x y_{31}^{\tilde{\phi},s} - x y_{13}^{\tilde{\phi},s}) / 2 \\
& + \{ -(R + r + \chi) x y_{32}^{\tilde{\phi},s} + (r + \chi - R) x y_{23}^{\tilde{\phi},s} \\
& + (R + r - \chi) x y_{41}^{\tilde{\phi},s} + (R + \chi - r) x y_{14}^{\tilde{\phi},s} \} \alpha^{\tilde{\phi}} / 2
\end{aligned} \tag{S.1c}$$

$$\begin{aligned}
x_{ma}^{\tilde{\phi}'} = & x x_{44}^{\tilde{\phi},s} + x x_{34}^{\tilde{\phi},s} / 2 + (x x_{14}^{\tilde{\phi},s} + x x_{24}^{\tilde{\phi},s}) \alpha^{\tilde{\phi}} \\
& - R(x x_{14}^{\tilde{\phi},s} - x x_{23}^{\tilde{\phi},s}) \alpha^{\tilde{\phi}} \\
& (x y_{44}^{\tilde{\phi},s} + x y_{42}^{\tilde{\phi},s}) / 2 + (x y_{41}^{\tilde{\phi},s} + x y_{43}^{\tilde{\phi},s}) (1 - \alpha^{\tilde{\phi}}) \\
& - r(x y_{43}^{\tilde{\phi},s} - x y_{34}^{\tilde{\phi},s}) (1 - \alpha^{\tilde{\phi}}) - \chi(x y_{42}^{\tilde{\phi},s} - x y_{24}^{\tilde{\phi},s}) / 2 \\
& + \{ -(R + r + \chi) x y_{41}^{\tilde{\phi},s} + (r + \chi - R) x y_{14}^{\tilde{\phi},s} \\
& + (R + r - \chi) x y_{32}^{\tilde{\phi},s} + (R + \chi - r) x y_{23}^{\tilde{\phi},s} \} (1 - \alpha^{\tilde{\phi}}) / 2
\end{aligned} \tag{S.1d}$$

$$\begin{aligned}
y_{MA}^{\tilde{\phi}'} = & y y_{11}^{\tilde{\phi},s} + y y_{13}^{\tilde{\phi},s} / 2 + (y y_{12}^{\tilde{\phi},s} + y y_{14}^{\tilde{\phi},s}) \alpha^{\tilde{\phi}} \\
& - R(y y_{14}^{\tilde{\phi},s} - y y_{23}^{\tilde{\phi},s}) \alpha^{\tilde{\phi}} \\
& (x y_{11}^{\tilde{\phi},s} + x y_{31}^{\tilde{\phi},s}) / 2 + (x y_{21}^{\tilde{\phi},s} + x y_{41}^{\tilde{\phi},s}) \alpha^{\tilde{\phi}} \\
& - r(x y_{21}^{\tilde{\phi},s} - x y_{12}^{\tilde{\phi},s}) \alpha^{\tilde{\phi}} - \chi(x y_{31}^{\tilde{\phi},s} - x y_{13}^{\tilde{\phi},s}) / 2 \\
& + \{ -(R + r + \chi) x y_{41}^{\tilde{\phi},s} + (r + \chi - R) x y_{14}^{\tilde{\phi},s} \\
& + (R + r - \chi) x y_{32}^{\tilde{\phi},s} + (R + \chi - r) x y_{23}^{\tilde{\phi},s} \} \alpha^{\tilde{\phi}} / 2
\end{aligned} \tag{S.1e}$$

$$\begin{aligned}
y_{Ma}^{\tilde{\phi}'} = & y y_{22}^{\tilde{\phi},s} + y y_{24}^{\tilde{\phi},s} / 2 + (y y_{12}^{\tilde{\phi},s} + y y_{23}^{\tilde{\phi},s}) \alpha^{\tilde{\phi}} \\
& - R(y y_{23}^{\tilde{\phi},s} - y y_{14}^{\tilde{\phi},s}) \alpha^{\tilde{\phi}} \\
& (x y_{22}^{\tilde{\phi},s} + x y_{42}^{\tilde{\phi},s}) / 2 + (x y_{12}^{\tilde{\phi},s} + x y_{32}^{\tilde{\phi},s}) (1 - \alpha^{\tilde{\phi}}) \\
& - r(x y_{12}^{\tilde{\phi},s} - x y_{21}^{\tilde{\phi},s}) (1 - \alpha^{\tilde{\phi}}) - \chi(x y_{42}^{\tilde{\phi},s} - x y_{24}^{\tilde{\phi},s}) / 2 \\
& + \{ -(R + r + \chi) x y_{32}^{\tilde{\phi},s} + (r + \chi - R) x y_{23}^{\tilde{\phi},s} \\
& + (R + r - \chi) x y_{41}^{\tilde{\phi},s} + (R + \chi - r) x y_{14}^{\tilde{\phi},s} \} (1 - \alpha^{\tilde{\phi}}) / 2
\end{aligned} \tag{S.1f}$$

$$\begin{aligned}
y_{mA}^{\phi'} = & yy_{33}^{\phi,s} + yy_{13}^{\phi,s}/2 + (yy_{23}^{\phi,s} + yy_{34}^{\phi,s})\alpha^{\phi} \\
& - R(yy_{23}^{\phi,s} - yy_{14}^{\phi,s})\alpha^{\phi} \\
& (xy_{33}^{\phi,s} + xy_{13}^{\phi,s})/2 + (xy_{23}^{\phi,s} + xy_{43}^{\phi,s})\alpha^{\phi} \\
& - r(xy_{43}^{\phi,s} - xy_{34}^{\phi,s})\alpha^{\phi} - \chi(xy_{13}^{\phi,s} - xy_{31}^{\phi,s})/2 \\
& + \{ -(R + r + \chi)xy_{23}^{\phi,s} + (r + \chi - R)xy_{32}^{\phi,s} \\
& + (R + r - \chi)xy_{14}^{\phi,s} + (R + \chi - r)xy_{41}^{\phi,s} \}\alpha^{\phi}/2
\end{aligned} \tag{S.1g}$$

$$\begin{aligned}
y_{ma}^{\phi'} = & yy_{44}^{\phi,s} + yy_{34}^{\phi,s}/2 + (yy_{14}^{\phi,s} + yy_{24}^{\phi,s})\alpha^{\phi} \\
& - R(yy_{14}^{\phi,s} - yy_{23}^{\phi,s})\alpha^{\phi} \\
& (xy_{44}^{\phi,s} + xy_{24}^{\phi,s})/2 + (xy_{14}^{\phi,s} + xy_{34}^{\phi,s})(1 - \alpha^{\phi}) \\
& - r(xy_{34}^{\phi,s} - xy_{43}^{\phi,s})(1 - \alpha^{\phi}) - \chi(xy_{24}^{\phi,s} - xy_{42}^{\phi,s})/2 \\
& + \{ -(R + r + \chi)xy_{14}^{\phi,s} + (r + \chi - R)xy_{41}^{\phi,s} \\
& + (R + r - \chi)xy_{23}^{\phi,s} + (R + \chi - r)xy_{32}^{\phi,s} \}(1 - \alpha^{\phi})/2
\end{aligned} \tag{S.1h}$$

892 The full system is therefore described by 16 recurrence equations (three diallelic
 loci in two sexes, $2^3 \times 2 = 16$). However, some diploid types are not produced
 894 under a given sex-determination system. For example, with the M allele fixed and
 ancestral XY sex determination, there are no m alleles, XX males, XY females,
 896 or YY females ($xx_{11}^{\phi} = xx_{12}^{\phi} = xx_{22}^{\phi} = xy_{11}^{\phi} = xy_{12}^{\phi} = xy_{21}^{\phi} = xy_{22}^{\phi} = yy_{11}^{\phi} =$
 $yy_{12}^{\phi} = yy_{22}^{\phi} = 0$). In this case, the system only involves six recursion equations,
 898 which yields equilibrium (S.4).

Resident equilibrium and stability

900 In the resident population (allele M fixed), we choose to follow the frequency
 of A in female gametes (eggs) from an XX female, p_X^{ϕ} , and in X -bearing, p_X^{δ} ,
 902 and Y -bearing, p_Y^{δ} , male gametes (sperm). We also track the total frequency of
 Y among male gametes, q , which may deviate from $1/2$ due to meiotic drive in
 904 males. These four variables determine the frequencies of the six resident gamete

types: $x_{MA}^{\varphi} = p_X^{\varphi}$, $x_{Ma}^{\varphi} = 1 - p_X^{\varphi}$, $x_{MA}^{\delta} = (1 - q)p_X^{\delta}$, $x_{Ma}^{\delta} = (1 - q)(1 - p_X^{\delta})$,
 906 $y_{MA}^{\delta} = qp_Y^{\delta}$, and $y_{Ma}^{\delta} = q(1 - p_Y^{\delta})$. Mean fitnesses in the resident population are
 given in table S.2.

908 Various forms of selection can maintain a polymorphism at the **A** locus, in-
 cluding sexually antagonistic selection, overdominance, conflicts between diploid
 910 selection and selection upon haploid genotypes (ploiddally antagonistic selection,
 Immler et al. 2012), and a combination of these selective regimes.

Table S.2: mean fitnesses in the resident population (M fixed, XY sex determination)

Sex & Life Cycle Stage	Mean Fitness
female gametes (\bar{w}_H^{φ})	$p_X^{\varphi} w_A^{\varphi} + (1 - p_X^{\varphi}) w_a^{\varphi}$
male gametes (\bar{w}_H^{δ})	$\bar{p}^{\delta} w_A^{\delta} + (1 - \bar{p}^{\delta}) w_a^{\delta}$
females (\bar{w}^{φ})	$\{p_X^{\varphi} w_A^{\varphi} p_X^{\delta} w_A^{\delta} w_{AA}^{\varphi} + (1 - p_X^{\varphi}) w_a^{\varphi} p_X^{\delta} w_A^{\delta} w_{Aa}^{\varphi} + p_X^{\varphi} w_A^{\varphi} (1 - p_X^{\delta}) w_a^{\delta} w_{Aa}^{\varphi} + (1 - p_X^{\varphi}) w_a^{\varphi} (1 - p_X^{\delta}) w_a^{\delta} w_{aa}^{\varphi}\} / \{\bar{w}_H^{\varphi} \bar{w}_H^{\delta} \zeta\}$
males (\bar{w}^{δ})	$\{p_X^{\varphi} w_A^{\varphi} p_Y^{\delta} w_A^{\delta} w_{AA}^{\delta} + (1 - p_X^{\varphi}) w_a^{\varphi} p_Y^{\delta} w_A^{\delta} w_{Aa}^{\delta} + p_X^{\varphi} w_A^{\varphi} (1 - p_Y^{\delta}) w_a^{\delta} w_{Aa}^{\delta} + (1 - p_X^{\varphi}) w_a^{\varphi} (1 - p_Y^{\delta}) w_a^{\delta} w_{aa}^{\delta}\} / \{\bar{w}_H^{\varphi} \bar{w}_H^{\delta} (1 - \zeta)\}$
zygotic sex ratio ζ	$\{(1 - q)(p_X^{\delta} w_A^{\delta} + (1 - p_X^{\delta}) w_a^{\delta})\} / \bar{w}_H^{\delta}$

912 In particular special cases, e.g., no sex-differences in selection or meiotic drive
 ($s^{\delta} = s^{\varphi}$, $h^{\delta} = h^{\varphi}$, and $\alpha^{\delta} = \alpha^{\varphi} = 1/2$), the equilibrium allele frequency and sta-
 914 bility can be calculated analytically without assuming anything about the relative
 strengths of selection and recombination. However, here, we focus on two regimes
 916 (tight linkage and weak selection) in order to make fewer assumptions about fit-
 nesses.

918 **Recombination weak relative to selection (tight linkage between A and X)**

We first calculate the equilibrium frequency of the Y and A alleles in the ancestral
 920 population when the recombination rate between the X and A loci is small (r of
 order ϵ). The A locus will not affect evolution at the novel sex-determining locus,
 922 M, if one A allele is fixed on all backgrounds. We therefore focus on the five
 equilibria that maintain both A and a alleles, four of which are given to leading
 924 order by:

$$(A) \quad \hat{p}_Y^\delta = 0, \quad \hat{q} = \frac{1}{2} - \frac{(\alpha^\delta - 1/2)w_{Aa}^\delta \phi}{w_{Aa}^\delta \phi + w_{aa}^\delta \psi}, \quad (S.2a)$$

$$\hat{p}_X^\varnothing = \frac{w_a^\varnothing \phi}{w_a^\varnothing \phi + w_A^\varnothing \psi}, \quad \hat{p}_X^\delta = \frac{2\alpha^\delta w_{Aa}^\delta \phi}{2\alpha^\delta w_{Aa}^\delta \phi + w_{AA}^\delta \psi}$$

$$(A') \quad \hat{p}_Y^\delta = 1, \quad \hat{q} = \frac{1}{2} + \frac{(\alpha^\delta - 1/2)w_{Aa}^\delta \phi'}{w_{Aa}^\delta \phi' + w_{AA}^\delta \psi'}, \quad (S.2b)$$

$$\hat{p}_X^\varnothing = 1 - \frac{w_A^\varnothing \phi'}{w_A^\varnothing \phi' + w_a^\varnothing \psi'}, \quad \hat{p}_X^\delta = 1 - \frac{2(1 - \alpha^\delta)w_{Aa}^\delta \phi'}{2(1 - \alpha^\delta)w_{Aa}^\delta \phi' + w_{aa}^\delta \psi'}$$

$$(B) \quad \hat{p}_Y^\delta = 0, \quad \hat{p}_X^\varnothing = 1, \quad \hat{p}_X^\delta = 1, \quad \hat{q} = 1 - \alpha^\delta \quad (S.2c)$$

$$(B') \quad \hat{p}_Y^\delta = 1, \quad \hat{p}_X^\varnothing = 0, \quad \hat{p}_X^\delta = 0, \quad \hat{q} = \alpha^\delta \quad (S.2d)$$

$$\begin{aligned} \phi &= \alpha^\varnothing w_A^\varnothing w_{Aa}^\varnothing (w_a^\delta w_{aa}^\delta + 2\alpha^\delta w_A^\delta w_{Aa}^\delta) - w_a^\delta w_a^\varnothing w_{aa}^\delta w_{aa}^\varnothing \\ \psi &= (1 - \alpha^\varnothing) w_a^\varnothing w_{Aa}^\varnothing (w_a^\delta w_{aa}^\delta + 2\alpha^\delta w_A^\delta w_{Aa}^\delta) - 2\alpha^\delta w_A^\delta w_A^\varnothing w_{Aa}^\delta w_{AA}^\varnothing \\ \phi' &= (1 - \alpha^\varnothing) w_a^\varnothing w_{Aa}^\varnothing (w_A^\delta w_{AA}^\delta + 2(1 - \alpha^\delta) w_a^\delta w_{Aa}^\delta) - w_A^\delta w_A^\varnothing w_{AA}^\delta w_{AA}^\varnothing \\ \psi' &= \alpha^\varnothing w_A^\varnothing w_{Aa}^\varnothing (w_A^\delta w_{AA}^\delta + 2(1 - \alpha^\delta) w_a^\delta w_{Aa}^\delta) - 2(1 - \alpha^\delta) w_a^\delta w_a^\varnothing w_{Aa}^\delta w_{aa}^\varnothing \end{aligned}$$

A fifth equilibrium (C) also exists where A is present at an intermediate frequency
 926 on the Y chromosome ($0 < \hat{p}_Y^\delta < 1$). However, equilibrium (C) is never locally
 stable when $r \approx 0$ and is therefore not considered further. Thus, the Y can either
 928 be fixed for the a allele (equilibria A and B) or the A allele (equilibria A' and
 B'). The X chromosome can then either be polymorphic (equilibria A and A')

930 or fixed for the alternative allele (equilibria B and B'). Since equilibria (A) and
 (B) are equivalent to equilibria (A') and (B') with the labelling of A and a alleles
 932 interchanged, we discuss only equilibria (A) and (B) , in which the Y is fixed for the
 a allele. If there is no haploid selection ($\alpha^\phi = 1/2$, $w_A^\phi = w_a^\phi = 1$), these equilibria
 934 are equivalent to those found by Lloyd and Webb (1977) and Otto (2014).

We next calculate when (A) and (B) are locally stable for $r = 0$. According
 936 to the ‘small parameter theory’ (Karlin and McGregor 1972a;b), these stability
 properties are unaffected by small amounts of recombination between the SDR and
 938 A locus, although equilibrium frequencies may be slightly altered. For the a allele
 to be stably fixed on the Y requires that $\bar{w}_{Ya}^\phi > \bar{w}_{YA}^\phi$ where $\bar{w}_{Ya}^\phi = w_a^\phi(2p_X^\phi(1 -$
 940 $\alpha^\phi)w_A^\phi w_{Aa}^\phi + (1 - p_X^\phi)w_a^\phi w_{aa}^\phi)$ and $\bar{w}_{YA}^\phi = w_A^\phi(p_X^\phi w_A^\phi w_{AA}^\phi + 2(1 - p_X^\phi)\alpha^\phi w_a^\phi w_{Aa}^\phi)$.
 That is, Ya haplotypes must have higher fitness than YA haplotypes. Substituting
 942 in $p_X^\phi = \hat{p}_X^\phi$ from above, fixation of the a allele on the Y requires that $\gamma_i > 0$ where
 $\gamma_{(A)} = w_a^\phi(2(1 - \alpha^\phi)w_{Aa}^\phi \phi + w_{aa}^\phi \psi) - w_A^\phi(w_{AA}^\phi \phi + 2\alpha^\phi w_{Aa}^\phi \psi)$ for equilibrium
 944 (A) and $\gamma_{(B)} = 2(1 - \alpha^\phi)w_a^\phi w_{Aa}^\phi - w_A^\phi w_{AA}^\phi$ for equilibrium (B) . Stability of a
 polymorphism on the X chromosome (equilibrium A) further requires that $\phi > 0$
 946 and $\psi > 0$. Fixation of the a allele on the X (equilibrium B) is mutually exclusive
 with equilibrium (A) and requires $\psi < 0$ and $w_A^\phi w_{AA}^\phi > (1 - \alpha^\phi)w_a^\phi w_{Aa}^\phi$.

948 **Selection weak relative to recombination (weak selection)**

Here, we assume that selection and meiotic drive are weak relative to recombina-
 950 tion (s^ϕ , t^ϕ , α_Δ^ϕ of order ϵ). The maintenance of a polymorphism at the A locus
 then requires that

$$\begin{aligned} 0 &< -((1 - h^\phi)s^\phi + (1 - h^\phi)s^\phi + t^\phi + t^\phi + \alpha_\Delta^\phi + \alpha_\Delta^\phi) \\ \text{and } 0 &< (h^\phi s^\phi + h^\phi s^\phi + t^\phi + t^\phi + \alpha_\Delta^\phi + \alpha_\Delta^\phi). \end{aligned} \quad (\text{S.3})$$

952 which indicates that a polymorphism can be maintained by various selective regimes.

Given that a polymorphism is maintained at the A locus by selection, with
 954 weak selection and drive the frequencies of A in each type of gamete are the same

($\hat{p}_X^\varnothing = \hat{p}_X^\sigma = \hat{p}_Y^\sigma = \bar{p}$) and given, to leading order, by

$$\bar{p} = \frac{h^\varnothing s^\varnothing + h^\sigma s^\sigma + t^\varnothing + t^\sigma + \alpha_\Delta^\varnothing + \alpha_\Delta^\sigma}{(2h^\varnothing - 1)s^\varnothing + (2h^\sigma - 1)s^\sigma} + O(\epsilon). \quad (\text{S.4})$$

956 Differences in frequency between gamete types are of order ϵ and given, to leading order, by

$$\begin{aligned} \hat{p}_X^\sigma - \hat{p}_X^\varnothing &= V_A (D^\sigma - D^\varnothing + \alpha_\Delta^\sigma - \alpha_\Delta^\varnothing) + O(\epsilon^2) \\ \hat{p}_Y^\sigma - \hat{p}_X^\varnothing &= V_A (D^\sigma - D^\varnothing + \alpha_\Delta^\sigma - \alpha_\Delta^\varnothing + (1 - 2r)(t^\sigma - t^\varnothing)) / 2r + O(\epsilon^2) \\ \hat{p}_Y^\sigma - \hat{p}_X^\sigma &= V_A (D^\sigma - D^\varnothing + \alpha_\Delta^\sigma - \alpha_\Delta^\varnothing + t^\sigma - t^\varnothing)(1 - 2r) / 2r + O(\epsilon^2) \end{aligned} \quad (\text{S.5})$$

958 where $V_A = \bar{p}(1 - \bar{p})$ is the variance in the frequency of A and $D^\varnothing = (\bar{p}s^\varnothing + (1 - \bar{p})h^\varnothing s^\varnothing) - (\bar{p}h^\sigma s^\sigma + (1 - \bar{p}))$ corresponds to the difference in fitness between A and
960 a alleles in diploids of sex $\varnothing \in \{\varnothing, \sigma\}$ (\bar{p} is the leading-order probability of mating with an A -bearing gamete from the opposite sex). The frequency of Y among male
962 gametes depends upon the difference in the frequency of the A allele between X - and Y -bearing male gametes and the strength of meiotic drive in favour of the A
964 allele in males, $q = 1/2 + \alpha_\Delta^\sigma(\hat{p}_Y^\sigma - \hat{p}_X^\sigma)/2 + O(\epsilon^3)$. Without gametic competition or drive ($\alpha_\Delta^\varnothing = t^\varnothing = 0$) our results reduce to those of van Doorn and Kirkpatrick
966 (2007).

Invasion conditions

968 A rare neo- Y or neo- W will spread from a given ancestral equilibrium when the leading eigenvalue, λ , of the Jacobian matrix derived from the eight mutant re-
970 cursion equations (given by S.1c,d,g,h), evaluated at the ancestral equilibrium, is greater than one. However, because a neo- Y (neo- W) is always in males (fe-
972 males) and is epistatically dominant to the ancestral sex-determining locus, we need only two recursion equations (e.g., tracking the change in the frequency of
974 neo- Y - A and neo- Y - a gametes from males) and thus the leading eigenvalue is

the largest solution to a quadratic characteristic polynomial $\lambda^2 + b\lambda + c = 0$.
 976 It can be shown (see supplementary Mathematica file) that the coefficients are
 $b = -(\lambda_{mA} + \lambda_{ma}) + (\rho_{mA} + \rho_{ma})$ and $c = (\lambda_{mA} - \rho_{mA})(\lambda_{ma} - \rho_{ma}) - \rho_{mA}\rho_{ma}$, where
 978 λ_{mi} is the multiplicative growth rate of the frequency of mutants on background
 $i \in \{A, a\}$, without accounting for loss due to recombination, and ρ_{mi} is the rate at
 980 which mutants on background $i \in \{A, a\}$ recombine onto the other **A** locus back-
 ground in heterozygotes. The leading eigenvalue is then greater than one whenever
 982 $\lambda_{mA} > 1$ and $\lambda_{ma} > 1$, less than one whenever $\lambda_{mA} < 1$ and $\lambda_{ma} < 1$, and greater
 than one whenever $\lambda_{mA} > 1$ or $\lambda_{ma} > 1$ and $\rho_{ma}(\lambda_{mA} - 1) + \rho_{mA}(\lambda_{ma} - 1) > 0$.
 984 For tight linkage between the ancestral sex-determining locus and the selected
 locus we can calculate each of these terms exactly, while for weak selection we
 986 take a Taylor series of the leading eigenvalue.

Recombination weak relative to selection (tight linkage between **A** and **X**)

988 Here, we explore the conditions under which a neo-W invades an XY system as-
 suming that the **A** locus is initially in close linkage with the ancestral sex-determining
 990 region ($r \approx 0$). We disregard neo-Y mutations, which never spread given that the
 ancestral population is at a stable equilibrium.
 992 Starting with the simpler equilibrium (**B**), the terms of the characteristic poly-
 nomial are

$$\lambda_{mA} = (2\alpha^\delta)^{-1} \frac{w_A^\varnothing [w_A^\delta w_{AA}^\varnothing \alpha^\delta + 2w_a^\delta w_{Aa}^\varnothing \alpha^\varnothing (1 - \alpha^\delta)]}{w_A^\delta w_A^\varnothing w_{AA}^\varnothing} \quad (\text{S.6a})$$

$$\lambda_{ma} = (2\alpha^\delta)^{-1} \frac{w_a^\varnothing [w_a^\delta w_{aa}^\varnothing (1 - \alpha^\delta) + 2w_A^\delta w_{Aa}^\varnothing (1 - \alpha^\varnothing) \alpha^\delta]}{w_A^\delta w_A^\varnothing w_{AA}^\varnothing} \quad (\text{S.6b})$$

$$\rho_{mA} = (2\alpha^\delta)^{-1} \frac{Rw_a^\delta w_A^\varnothing w_{Aa}^\varnothing \alpha^\varnothing (1 - \alpha^\delta)}{w_A^\delta w_A^\varnothing w_{AA}^\varnothing} \quad (\text{S.6c})$$

$$\rho_{ma} = (2\alpha^\delta)^{-1} \frac{Rw_A^\delta w_a^\varnothing w_{Aa}^\varnothing (1 - \alpha^\varnothing) \alpha^\delta}{w_A^\delta w_A^\varnothing w_{AA}^\varnothing} \quad (\text{S.6d})$$

994 Haploid selection impacts the spread of neo-W haplotypes in three ways. Firstly,
 the zygotic sex ratio becomes male biased ($\zeta < 1/2$; at equilibrium (B) the sex
 996 ratio is $\zeta = \alpha^\delta w_A^\delta / [(1 - \alpha^\delta)w_a^\delta + \alpha^\delta w_A^\delta]$) when the a allele (which is fixed on
 the Y) is favoured during competition among male gametes or by meiotic drive
 998 in males. This facilitates the spread of a neo-W because neo-W alleles cause the
 zygotes that carry them to develop as the rarer, female, sex. Secondly, haploid
 1000 selection in males affects the diploid genotypes of females by altering the allele
 frequencies in the male gametes that female gametes pair with. For instance, be-
 1002 cause an epistatically dominant neo-W always causes its carrier to become female,
 it creates females who carry either Y- a or X genotypes from their father. Thus, be-
 1004 cause when there is a polymorphism the X carries some non-zero frequency of A ,
 haploid selection in males impacts the diploid genotypes of females (e.g., creating
 1006 more Aa females when drive in males favours Y- a). How this affects the spread
 of the neo-W then depends on diploid and haploid selection in females. Thirdly,
 1008 female drive and gamete competition directly select on neo-W haplotypes. Drive
 for A in females favours neo-W- A haplotypes, at a cost to neo-W- a haplotypes, and
 1010 vice-versa when there is drive for a . The impact of this drive depends on how of-
 ten XX and neo-W females are heterozygous. Competition among female gametes
 1012 acts similarly, and depends on the frequency of A on resident X chromosomes
 (e.g., competition among eggs has no affect on the initial spread of the neo-W- A
 1014 haplotype when A is fixed on the X). Because haploid selection in females favours
 one neo-W haplotype at the expense of the other, recombination off the favoured
 1016 background becomes more detrimental as it becomes more favoured. Thus higher
 rates of recombination between the neo-W and the selected locus, R , can lead to
 1018 smaller leading eigenvalues when there is haploid selection in females.

The other terms in equations (S.6) are more easily interpreted if we assume
 1020 that there is no haploid selection in either sex, in which case $\lambda_{mA} > 1$ when $w_{Aa}^\varnothing >$
 w_{AA}^\varnothing and $\lambda_{ma} > 1$ when $(w_{Aa}^\varnothing + w_{aa}^\varnothing)/2 > w_{AA}^\varnothing$. These conditions cannot be met
 1022 under purely sexually-antagonistic selection, where a is directionally favoured in
 males ($w_{AA}^\delta > w_{Aa}^\delta > w_{aa}^\delta$) and A is directionally favoured in females ($w_{AA}^\varnothing >$

1024 $w_{Aa}^{\varnothing} > w_{aa}^{\varnothing}$). Essentially, the X is already as specialized as possible for the female
beneficial allele (XA is fixed), and the neo-W often makes daughters with the Y-a
1026 haplotype, increasing the flow of a alleles into females, which reduces the fitness
of those females.

1028 If selection doesn't uniformly favour A in females, however, neo-W- A haplo-
types and/or neo-W- a haplotypes can spread ($\lambda_{mA} > 1$ and/or $\lambda_{ma} > 1$) at this
1030 equilibrium. A neo-W can spread alongside the A allele ($\lambda_{mA} > 1$), despite the
fact that a neo-W brings Ya haplotypes into females, when $w_{Aa}^{\varnothing} > w_{AA}^{\varnothing}$. In this
1032 case the a allele is favoured by selection in females despite A being fixed on the
X. For this equilibrium to be stable, X- A must be sufficiently favoured in males
1034 to keep the frequency of XA at one (specifically, from the stability conditions, we
must have $w_{Aa}^{\delta} / ((w_{aa}^{\delta} + w_{Aa}^{\delta}) / 2) > w_{Aa}^{\varnothing} / w_{AA}^{\varnothing}$).

1036 Under this same condition, $w_{Aa}^{\varnothing} > w_{AA}^{\varnothing}$, the neo-W can also spread alongside
the a allele ($\lambda_{ma} > 1$) if there is sufficiently strong underdominance in females
1038 ($w_{aa}^{\varnothing} > w_{Aa}^{\varnothing}$), such that $(w_{Aa}^{\varnothing} + w_{aa}^{\varnothing}) / 2 > w_{AA}^{\varnothing}$. In this case, a is not favored in
females near the equilibrium where females are AA (comparing Aa to AA geno-
1040 types) and yet the neo-W can spread with a because it produces female aa individ-
uals by capturing Y- a haplotypes.

1042 When both haplotypes can spread on their own ($\lambda_{mA} > 1$ and $\lambda_{ma} > 1$), the
neo-W invades regardless the recombination rate between it and the selected locus,
1044 R . When neither haplotype can spread ($\lambda_{mA} < 1$ and $\lambda_{ma} < 1$) the neo-W can never
invade. And when only one haplotype can spread on its own the neo-W invades
1046 only when the rate of recombination onto the favourable background is sufficiently
larger than the rate of recombination off this background (i.e., equation 1 is satis-
1048 fied).

Similar equations can be derived for equilibrium (A) by subbing the equilib-
1050 rium allele frequencies into Table 2.

$$\lambda_{mA} = \frac{a}{b} \left[w_{AA}^{\varphi} w_{Aa}^{\delta} w_A^{\delta} \alpha^{\delta} \phi + 2w_{Aa}^{\varphi} \alpha^{\varphi} w_a^{\delta} \frac{c}{d} \right] / w_a^{\varphi} \quad (\text{S.7a})$$

$$\lambda_{ma} = \frac{a}{b} \left[2w_{Aa}^{\varphi} (1 - \alpha^{\varphi}) w_{Aa}^{\delta} w_A^{\delta} \alpha^{\delta} \phi + w_{aa}^{\varphi} w_a^{\delta} \frac{c}{d} \right] / w_A^{\varphi} \quad (\text{S.7b})$$

$$\rho_{mA} = \frac{a}{b} R \left[2w_{Aa}^{\varphi} \alpha^{\varphi} w_a^{\delta} \frac{c}{d} \right] / w_a^{\varphi} \quad (\text{S.7c})$$

$$\rho_{ma} = \frac{a}{b} R \left[2w_{Aa}^{\varphi} (1 - \alpha^{\varphi}) w_{Aa}^{\delta} w_A^{\delta} \alpha^{\delta} \phi \right] / w_A^{\varphi} \quad (\text{S.7d})$$

where

$$a = w_a^{\varphi} \phi + w_A^{\varphi} \psi \quad (\text{S.8a})$$

$$b = w_{AA}^{\varphi} \phi (2w_{Aa}^{\delta} w_A^{\delta} \alpha^{\delta} \phi) + w_{Aa}^{\varphi} \psi (2w_{Aa}^{\delta} w_A^{\delta} \alpha^{\delta} \phi + w_{AA}^{\delta} w_a^{\delta} \psi) + w_{aa}^{\varphi} \psi (w_{AA}^{\delta} w_a^{\delta} \psi) \quad (\text{S.8b})$$

$$c = 2(w_{Aa}^{\delta} \phi)^2 (1 - \alpha^{\delta}) \alpha^{\delta} + w_{Aa}^{\delta} \phi (w_{AA}^{\delta} \psi + w_{aa}^{\delta} \psi \alpha^{\delta}) + w_{aa}^{\delta} \psi w_{AA}^{\delta} \psi \quad (\text{S.8c})$$

$$d = 2w_{Aa}^{\delta} \alpha^{\delta} \phi + w_{aa}^{\delta} \psi \quad (\text{S.8d})$$

1052 As with equilibrium (B), haploid selection again modifies invasion fitnesses
by altering the sex-ratio and the diploid genotypes of females and directly select-
1054 ing upon female gametes. The only difference is that resident XX females are no
longer always homozygote *AA* and males are no longer always heterozygote *Aa*.
1056 Thus the effect of haploid selection in males is reduced, as is the difference in fit-
ness between neo-W haplotypes and resident X haplotypes, as both can be on any
1058 diploid or haploid background.

The other terms are easier to interpret in the absence of haploid selection. For
1060 instance, without haploid selection, the neo-W-*A* haplotype spreads ($\lambda_{mA} > 1$) if
and only if

$$2(w_{Aa}^{\varphi} - w_{aa}^{\varphi}) w_{AA}^{\delta} \psi^2 > (w_{AA}^{\varphi} - w_{Aa}^{\varphi}) w_{Aa}^{\delta} \phi (\phi - \psi) \quad (\text{S.9})$$

1062 where $\phi - \psi = w_{AA}^{\varphi} w_{Aa}^{\delta} - w_{aa}^{\varphi} w_{aa}^{\delta}$ and both ϕ and ψ are positive when equilibrium

(A) is stable. In contrast to equilibrium (B), a neo-W haplotype can spread under purely sexually-antagonistic selection ($w_{AA}^\delta > w_{Aa}^\delta > w_{aa}^\delta$ and $w_{AA}^\varphi > w_{Aa}^\varphi > w_{aa}^\varphi$). In this case, the neo-W-A haplotype can spread, despite producing a lot of *Aa* daughters by obtaining the *a* from Y-gametes, when *aa* females, which the neo-W-A never makes, are strongly selected against. This can be intuited from the fact that (S.9) will be more easily met when $w_{Aa}^\varphi - w_{aa}^\varphi \approx w_{Aa}^\varphi$ and $w_{AA}^\varphi - w_{Aa}^\varphi \approx 0$, implying $w_{aa}^\varphi \approx 0$ and $w_{Aa}^\varphi \approx w_{AA}^\varphi$ (although this is complicated by the fact that w_{aa}^φ and w_{Aa}^φ affect ϕ and ψ too, the intuition holds).

Without haploid selection, the neo-W-*a* haplotype spreads ($\lambda_{ma} > 1$) if and only if

$$(w_{aa}^\varphi + w_{Aa}^\varphi - 2w_{AA}^\varphi)w_{Aa}^\delta \phi^2 + (w_{aa}^\varphi - w_{Aa}^\varphi)(w_{Aa}^\delta + 2w_{AA}^\delta)\phi\psi > 0 \quad (\text{S.10})$$

This condition cannot be met with purely sexually antagonistic selection (as both terms on the left-hand side would then be negative), but it can be met under other circumstances. For example, with overdominance in males there is selection for increased *A* frequencies on X chromosomes in males, which are always paired with *Y-a* haplotypes. Then, directional selection for *a* in females maintains a polymorphism at the **A** locus on the X and by creating selection for decreased *A* frequencies on X chromosomes in females. This scenario selects for a modifier that increases recombination between the sex chromosomes (e.g., blue region of Figure 2d in Otto 2014) and facilitates the spread of neo-W-*a* haplotypes, which create more heterozygote and *aa* females than ancestral X chromosomes do.

As with equilibrium (B), if both haplotypes can spread ($\lambda_{mA} > 1$ and $\lambda_{ma} > 1$) then the neo-W invades under any rate of recombination with the selected locus, $R \geq 0$. In addition, even when only one haplotype can spread (e.g., under purely sexually-antagonistic selection $\lambda_{mA} > 1$ and $\lambda_{ma} < 1$), neo-W invasion can still occur under modest rates of recombination between the novel sex-determining and selected loci.

Selection weak relative to recombination (weak selection)

1090 With weak selection the leading eigenvalue, λ , for any k , is given up to order ϵ^2 by equation 4. Scenarios leading to $\lambda > 1$ are discussed in the main text.