1. Introduction

Substituted heteroarenes form the core of numerous pharmaco- logically active agents and drug substances, as well as agrochemical products, ligands, secondary metabolites, polymers and electronic materials. Notwithstanding widespread recent advances in transition metal-catalysed C–H bond activation processes, Pd-catalysed Suzuki–Miyaura coupling (SMC) of (pseudo)halogenated heteroarenes with (hetero)aryl boronic acids/esters constitutes the most widely used approach to heteroarene elaboration with C–C bond formation particularly in a pharmaceutical discovery chemistry setting. This reflects the wide palette of methods available for preparation of both reaction partners, the versatility and functional group compatibility of these methods, the general stability, low toxicity, ease of handling and commercial availability of the reaction partners, the relatively environmentally benign conditions of the SMC reactions themselves (e.g. high efficiencies, low catalyst loadings etc.), as well as the opportunities the SMC disconnection affords for rapid parallel exploration of structural diversity and chemical space.

When multiple SMC reactions are to be choreographed to occur sequentially, this can sometimes be achieved by judicious site-selective introduction of different types of halogen into a substrate. However, particularly for heteroaryl substrates, the intrinsic polarities of the ring carbons also strongly influence site-selectivity and this factor is critical when coupling substrates containing two or more of the same type of halogen. These latter substrates are often the preferred precursors on cost and availability grounds and are the main focus of this review. Underscoring not only the importance of site-selective cross-coupling reactions of heteroaryl halides from a synthesis perspective, but also highlighting the challenges associated with predicting the outcome of such reactions, there have been several excellent reviews compiling and classifying published examples of these reactions including notable contributions by Bach (heteroarenes), Stanetty (azoles), Handy (heteroarenes), Fairlamb (heteroarenes), Manabe (polyaldehydes), Rossi (heteroarenes) and Langer (bis-triflates).

Notwithstanding these previous compilations, we considered that systematic interrogation of reaction databases would reveal patterns of selectivity that could reinforce and extend our understanding of the factors that affect site-selectivity in SMC reactions of heteroarenes and improve our ability to predict outcomes for new substrates. In particular, we envisioned that the in-house Pfizer global chemistry Reaction Knowledge Base (RKB) would constitute a rich source of reaction data that would extend and compliment data mined from the CAS SciFinder® database. To this end, in this review we provide a concise overview of the factors determining the site-selectivity of SMC reactions of heteroaryl halides (Section 3) and then a summary of the results of some database searches of structures of potential medicinal interest (Section 4). The overview draws on data both from the literature and from the structure-by-structure database searches.

2. Data gathering and analysis

Based on our perception of their relevance as scaffolds and/or intermediates in drug discovery programs, the heteroarene ring systems that were selected for investigation were: pyridines, pyrimidines, pyrazines, pyridazines, pyroles, furans, thiophenes, imidazoles, pyrazoles, (iso)oxazoles, (iso)thiazoles, (iso)quinolines, benzodiazines, indoles, benzoxazoles, benzothiazoles, benzodiazoles, benz(is)oxazoles, benz(is)thiazoles and aza(iso)quinolones (naphthyridines). Parallel searches were...
carried out on the CAS SciFinder® and RKB reaction databases using as similar search queries as their respective interfaces would allow (see ESIF). Only reactions with (hetero)aromatic boronic acid and ester coupling partners were retrieved,16–17 alkyl and alkynyl congeners were excluded since these motifs occur much less frequently in pharmaceuticals. Alkyl coupling partners,18 stereoselective processes,19 and non-Pd-mediated processes20 were also excluded.20 Reactions involving substrates having two (or more) of the same halide substituents were systematically retrieved; specifically, di-chlorides, di-bromides and di-iodides although selected examples containing two different halides were also noted where these enable complementary site-selectivities to be achieved.

3. Factors affecting the site-selectivity of SMC reactions of heteroaryl halides

As indicated above, we have divided our analysis into two sections. In this section factors that determine site-selectivity in SMC reactions based on published studies and our database searches are presented. In Section 4, the data from the CAS SciFinder® and RKB database searches are summarised by class of heterocycle. Hopefully, this structure will help readers both to predict the outcome of reactions on new heterocyclic systems per se and also to quickly locate relevant prior-art on key heterocyclic systems of interest. In the Schemes and Figures, the halide highlighted with a blue disk is the preferred site of reaction.

When discussing SMC reactions, it is generally accepted that the oxidative addition (OA) step is rate-determining and irreversible, and that the rate of OA is largely controlled by the bond dissociation energies (BDEs) of the C–Hal bond such that usually Ar–I > Ar–Br > Ar–Cl > Ar–F.22 Although cases where OA is not rate limiting in SMC reactions have been proposed,23 and OA can be reversible under high steric stress,24 this assumption is probably accurate for most catalytic reaction situations. The BDE is however by no means the exclusive arbiter of ease of OA (Section 3d). However, we will start by discussing the key factors that influence site-selectivity in heteroarenes containing two or more of the same type of halogen. We will see that for these cases the ‘molecular environment/electrophilicity’ of the carbon atom to which the halide is bound is a key factor and that this is reasonably predictable for a given heteroarene core (Sections 3a–c).

3a. Influence of the intrinsic relative electrophilicities of different ring carbons

For heteroarenes containing two or more of the same type of halogen (e.g. di-chlorides, tri-bromides etc.), several indicators based on experimental data have been identified to help predict the intrinsically most reactive positions for OA. Since the OA step in SMC reactions and the addition step in S$_{Ar}$ reactions have mechanistic similarities, both are generally favoured at the more electrophilic carbon when two identical halogen substituents are in competition. Consequently, experimental S$_{Ar}$ site-selectivity data has been used to predict SMC reactivity.24–26 Others have drawn the analogy with propensity to undergo lithium–halogen exchange, which generally favours the position that results in the most stable resulting arylium derivative.27–29

1$^1$C NMR chemical shift values ($\delta_C$) can similarly provide insight into the relative electrophilicities of carbons bearing halogens.26 Most notably, Handy and Zhang have advocated analysis of the $^1$H NMR chemical shift values ($\delta_H$) of the parent non-halogenated heteroarenes as a guide for predicting the site of cross-coupling reactions;8 with the position of the most deshielded proton being the favoured site for SMC. Although this has the appeal of simplicity, it is not fail-safe, particularly in cases where $\Delta\delta_H < 0.3$ ppm.25,26 For example, although the method was accurate for several polysubstituted pyrroles, for the case of 3-arylpyrrole 5, where $\Delta\delta_H$ was just 0.02 ppm, the site of SMC could be switched from C2 to C4 simply by changing the solvent from DMF to ethanol–toluene (Scheme 1).8,28

Computation has also been used to predict the order of susceptibility to OA in heteroaryl polyhalides on a case-by-case basis.29 Computation can in principle not only dissect out the heteroaryl electronic components but also account for steric factors and directing effects from adjacent functional groups during the OA process. Studies that draw out trends rather than focus on isolated examples are of particular interest. Houk et al. have noted that computed BDEs cannot account for all observed reaction selectivities and have used a DFT-based ‘distortion–interaction’ model (sometime referred to as an ‘activation-strain’ model) to better understand the origins of selectivity in Pd(0)-catalysed cross-coupling reactions of heteroaryl poly-chlorides and polybromides including isoquinolines, pyridines, benzofurans and furans.27,28 Using Pd(PH$_3$)$_2$ as a model.

![Scheme 1](image)

Scheme 1. The Handy and Zhang method for site-selectivity prediction based on the $^1$H NMR $\delta_H$ values for the corresponding non-halogenated heteroarenes – as applied to (a) 2,3-, (b) 3,4-, and (c) 2,4-dibromo-pyrroles, the last of which displays solvent dependent selectivity.8,28
di-ligated complex, the energies required to distort isolated reactants to the OA transition state geometries (the distortion energy, $\Delta E_{\text{dist}}$) were computed along with the energy of interaction between these distorted reactants (the interaction energy, $\Delta E_{\text{int}}$). It was concluded that $\Delta E_{\text{dist}}$ closely tracks the BDE and that $\Delta E_{\text{dist}}$ is dominated by a favourable back-bonding ($d_{\text{cy}} \rightarrow \pi^*$) secondary frontier molecular orbital (FMO) interaction as the bent PdL$_2$ moiety approaches the C-Hal bond $\eta^2$-fashion (i.e. side-on). The $\Delta E_{\text{dist}}$ contribution is therefore relatively invariant when one type of halogen is involved although they note that in general BDE values are (i) lower in 6-membered compared to 5-membered rings, and (ii) lowered by the presence of a sulfur atom in the ring or when the halogen is an iminonyl halide. The stabilising $\Delta E_{\text{int}}$ term is dependent on the $\pi^*$ LUMO coefficient which is generally increased for positions adjacent to ring heteroatoms (Fig. 1).

Thus for each of the three systems 8–10 shown below, the experimentally observed site for SMC reaction is not the one predicted on the basis of having the lowest calculated BDE value but the one with the lowest activation barrier ($\Delta E$). The larger the $\Delta E$ value, the more selective a reaction can be expected to be (Fig. 2).

Computational studies have also thrown significant light on how the nature of the phosphine ligands, the ligation state of the Pd and complexation of a pre-catalyst with the substrate can all influence OA activation energies, but this will be discussed later in the context of the influence of reaction conditions (Section 3c).

In general, for heteroaryl polyhalides containing a single type of halogen, the intrinsic relative electrophilicities of different ring carbons is a critical factor controlling SMC site-selectivity. In the case of otherwise unsubstituted substrates, the electronic distribution is controlled by the position of the halides in the ring-system relative to the ring heteroatoms. In cases where the heteroaryl polyhalide contains other substituents, these substituents provide additional electronic and steric perturbations but it appears that the intrinsic heterocycle polarity is usually dominant (Section 3b). These generalisations are strongly supported by the data from our database searches which show that the position at which SMC reactions occur are characteristic of the particular heterocycle and largely independent of substituents and the nature of the boronic acid/ester coupling partner (Section 4).

3b. Influence of ring substituents

The influence of substituents on site-selectivities in heteroarene SMC reactions appears to be surprisingly limited, with significant perturbations to the intrinsic directing influence of the ring-system generally being restricted to situations where the heterocycle itself is not strongly polarised and/or where substituents are strongly electron withdrawing and/or are sufficiently Lewis basic to coordinate to the catalyst and promote reaction via a palladacycle. Steric factors can sometimes be decisive but these generally appear to be of secondary importance.

To illustrate this, consider first the case of 4-substituted 3,6-dichloropyrimidines 11a–c and 13a–c (Scheme 2).

Blaise et al. have investigated a range of heteroatom-based substituents at the 4-position of 3,6-dichloropyrimidines and found that 1°, 2° and 3° amines (11a–c) promote SMC reaction at C3 (i.e. proximal to the amine) using Pd(PPh$_3$)$_2$/Na$_2$CO$_3$/toluene/EtOH/H$_2$O but that the reactivity and selectivity of these substrates decreases with increasing bulk of the amine substituents. An N-MeBoc group at C4 (13a) however promotes SMC reaction at C6 (i.e. distal to the amine); similarly, OMe and OBN groups at C4 (13b and 13c) promote SMC reactions at C6 in 60% and 50% yields respectively, implicating coordination of the Pd to a Lewis basic amine group as facilitating reaction at C3 (Scheme 2, above).

The reactivity of 2,6-dichloronicotinic acid 15 and its derivatives is also instructive and demonstrates the role that catalyst coordination to Lewis basic functional groups can have on the site-selectivity of SMC reactions (Scheme 3).
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With the methyl ester derivative (15, R = OMe), Yang et al.\textsuperscript{35a} found that Pd(PPh\textsubscript{3})\textsubscript{4} promoted SMC reactions at C6 (→ 17), but that Li’s PXPd\textsubscript{2} pre-catalyst [Pd(t-Bu\textsubscript{2}Cl)\textsubscript{2}](ref. 36) promoted SMC reactions at C2 (→ 16a). Yang et al. hypothesised that the latter, more electron rich and coordinatively unsaturated complex was able to coordinate to the ester carbonyl thereby overcoming the inherent steric bias of the substrate. To corroborate this, they showed that a more Lewis basic amide congener gave even greater selectivity for SMC reaction at C2 (→ 16b, Scheme 3, above). This notion was extended to the case of the free acid 18 by Ma et al.\textsuperscript{37} and by Houpis et al.\textsuperscript{35b} who found that Pd[PPh\textsubscript{3})\textsubscript{4} and Pd(OAc)\textsubscript{2}/PPh\textsubscript{3} promoted SMC reactions at C6 (→ 20), but that phosphate-free Pd [i.e. Pd\textsubscript{2}(db)\textsubscript{2}]- \textbullet CHCl\textsubscript{3} resulted in high levels of selectivity for SMC reaction at C2 (→ 19), presumably by virtue of its ability to coordinate to the carboxylate.

The divergent behaviour of methyl 1,4-ditrifl oxy phenyl-2-carboxylate (21)\textsuperscript{38} and phenyl 1,4-ditrifl oxynaphthalene-2-carboxylate (23)\textsuperscript{38} with respect to their SMC site-selectivity is also revealing. Although not heteroarenes, a comparison of their behaviour demonstrates how the subtle interplay between steric and electronic effects imparted by a substituent can be critical in controlling SMC reactions when intrinsic ring polarity effects are weak (Scheme 4).

Phenyl ditrifl oxide 21 undergoes SMC reactions at C4 (→ 22) whereas naphthyl ditrifl oxide 23 undergoes SMC reactions at C1 (→ 24). In both cases, the steric crowding at C1 is essentially equivalent and so the divergent behaviour is presumably electronic in origin: i.e. C1 is sufficiently electrophilic in naphthyl derivative 23 to override the steric crowding due to the ester but insufficiently electrophilic in phenyl derivative 21 to do likewise. Langer \textit{et al.} have proposed that this is consistent with the naphthalene having significant diene character and being relatively easily polarised in its substituted ring thus allowing the ester substituent to impart greater electrophilicity to the proximal C1 position than is possible for the phenyl system without incurring a concomitant energetic penalty from loss of aromaticity.\textsuperscript{38} Langer has studied several additional ditrifl oxate-containing substrates in a systematic fashion and similar conclusions regarding the delicate balance of steric vs. electronic factors emerge.\textsuperscript{35}

Notwithstanding the above studies, it is perhaps surprising how limited the influence of ring substituents is in controlling site-selectivity in SMC coupling reactions. As emphasised previously, this allows the outcome of most reactions to be predicted simply on the basis of the position of the halides in a given heteroarene. A contributory factor towards this situation is that a large proportion of the available data both in the CAS SciFinder\textregistered and the Pfizer RKB databases relates to reactions using ‘standard conditions’ (e.g. Pd(dppf)Cl\textsubscript{2} or Pd(PPh\textsubscript{3})\textsubscript{4} with Na\textsubscript{2}CO\textsubscript{3} or NaHCO\textsubscript{3} or K\textsubscript{3}CO\textsubscript{3} in DME–H\textsubscript{2}O or THF–H\textsubscript{2}O or 1,4-dioxane–H\textsubscript{2}O).\textsuperscript{14} The predominance of these conditions reflect the low cost and high convenience of these conditions and also their wide substrate scope. However, there are of course SMC reactions of heteroaryl polyhalides where the choice of reaction conditions, particularly the choice of ligand and solvent, can be decisive in dictating site-selectivity (Section 3c). This is the case for substrates containing a single type of halogen and even more so for those containing mixed halides.

### 3c. Influence of the reaction conditions – particularly the Pd pre-catalyst/ligand

The specific reaction conditions used for a SMC reaction on a heteroaryl polyhalide can sometimes strongly influence the outcome in terms of site-selectivity of coupling. Due to the mechanistic complexity of these reactions, interpretation let alone prediction of these effects is difficult, but a number of studies which have documented such reactions and sought to rationalise them have been published.

An investigation by Dai \textit{et al.} examined the effect of different phosphines on the site-selectivity of SMC reactions of 3,5-dichloropyridazine.\textsuperscript{25,27} They found that chelation and electron density played key roles and specifically that electron deficient bidentate ligands (such as dppf) favoured SMC reactions at C3 over C5 (i.e. → 26) whereas electron rich monodentate ligands (such as Qphos) favoured C5 over C3 (i.e. → 27). Electron rich bidentate ligand dtbpf also promoted reactions at C5 over C3, although this was interpreted as indicating that steric effects as
conditions 2,4-diiodooxazole (1). It was found experimentally however that under most conditions Xantphos® was found to be uniquely capable of mediating mono-SMC reactions at C2 (triaza-7-phospha-adamantane in MeCN gave high selectivity for 4-tri-azoles and -thiazoles has been studied by Strotman et al. 25,43,46,47 which Brown in 2007 showed to be replicated for Stille and Negishi type couplings but interestingly not for SMC reactions. In 2000, Fu et al. reported that the site-selective SMC reaction of 4-trifluoroiodostyrene (36) occurred selectively at the chloride (i.e. C1, → 37) when using PbCl[P(η-Bu)3] in THF (as expected on the basis of BDE), but selectively at the trihalo [i.e. C4, → 38] when using PbCl[P(η-Bu)3/PCy3 in THF 48 (Scheme 7). Subsequent theoretical and experimental studies concluded that the steric bulk of P(η-Bu)3, generally favours formation of mono-ligated, 12 electron Pd complexes (i.e. PdL) whereas the less sterically demanding PCy3 generally stabilises di-ligated, 14 electron complexes (i.e. PdL2) and that this difference accounts for their divergent behaviour. This hypothesis was tested computationally by Houk and Schoenebeck using the aforementioned ‘distortion-interaction’ DFT analysis (see Fig. 1, above). 44 Unsurprisingly, the computed activation energies (ΔE) were found to be highly sensitive to the ligation state of the Pd: e.g. PdL2 vs. [PdL2X] vs. PdL vs. [PdLX] 43,46,47. Specifically, it was shown that for PdL complexes, the computed activation energies (ΔΔE) were dominated by the ΔEdist term whereas for PdL2 complexes the ΔE values were dominated by the interaction energy (ΔEint). This situation, combined with the aforementioned expectation that the highly bulky ligand P(η-Bu)3 would favour a mono-ligated Pd[P(η-Bu)3] complex in THF whereas the less bulky PCy3 would favour a di-ligated Pd[PCy3]2 complex, explained the observed

Scheme 6 Ligand-dependent site-selectivity: (a) 2,4-diiodooxazole, (b) 2,5-dibromimidazol, (c) 2,4-dibromimidazol, and (d) 2,4- and 2,5-dibromothiazoles. 25

Scheme 7 Control of site-selectivity in the SMC reaction of 4-trifluoroiodostyrene (36) according to the conditions: (a) ligand 42,43 and (b) solvent 44 control.

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site-divergent behaviour. Decisively, the lower BDE of the 
chloride cf. the triflate minimised ΔE for insertion of the mono-
ligated PdP(t-Bu) complex into the C–Cl bond whereas the 
strong dπ–σ* interaction between the highly nucleophilic di-
ligated PdPCl3 and the distorted vinyl triflate group minimised 
ΔE for insertion into the C–OTf bond.44 Subsequent higher level 
DFT computational studies have corroborated these conclu-
sions and furnish reaction energy profiles for PdL and PdL2 
pathways that mirror experiment provided dispersion terms are 
icorporated in the calculations.

Schoenebeck et al. showed experimentally that if a polar 
solvent like MeCN was used in place of THF for the SMC reac-
tion of 4-trifluorochlorobenzene (36) then the Pd(II) complex 
conditions promote selective SMC coupling at the C4 triflate (→ 
38 in 74% yield) like Fu’s Pd(II) complex conditions (see 
Scheme 7, above).46 Schoenebeck also performed calculations to 
demonstrate that this experimental outcome was consistent 
with the formation of an anionic [PdLX2]– complex under these 
conditions (where X was either F or ArBO2H).44 Subsequent 
studies demonstrated that the Pd(dimer complex) [BrPdP(t-
Bu)3]2 also promotes these reactions and favours reaction at C1 
(→ 37) in THF and at C4 (→ 38) in MeCN.50 The behaviour of 
the dimer in these reactions was attributed to its in situ 
conversion to PdP(t-Bu)2 induced by the base acting as a nucle-
ophile;51 the bromine-bridged Pd(dimer) is more labile in this 
respect than the corresponding iodide-bridged one, although 
with an appropriately nucleophilic base both can act as 
precursors to catalytically active Pd(0) species.52

Schoenebeck has also introduced the P(i-Pr)(t-Bu)2 ligand, 
which has a Tolman cone angle53 (175°) intermediate between 
that of P(t-Bu)3 (182°) and PCy3 (170°), and which imparts P(t-
Bu)3-like behaviour (OA at C1 → 37) when added 1 : 1 relative to 
Pd [i.e. favouring monoligated PdP(i-Pr)(t-Bu)2, but PCy3-like 
behaviour (OA at C4 → 38) when added in excess (e.g. 10 : 1 
relative to Pd).54 Sigman has also recorded concentration-
dependent selectivity for other phosphines in this reaction.55

More generally, there is increasing evidence for phosphine-
free Pd (nanoparticles) being active catalytic species in SMC 
reactions (i.e. heterogeneous catalysis).56 The likelihood of 
nanoparticulate Pd being the catalytically active species is 
minimal for SMC reactions carried out at ambient temperature 
with an appropriately nucleophilic base both can act as 
precursors to catalytically active Pd(0) species.

Notwithstanding these caveats when interpreting changes in 
site-selectivity in SMC reactions, the aforementioned studies 
highlight how the steric and electronic characteristics of 
phosphines affect the ligation state of the Pd and consequently 
reaction outcomes. Although this has been most intensively 
studied for 4-trifluorochlorobenzene (36, Scheme 7), this applies 
in all SMC reactions and particularly those of substrates con-
taining mixed halides (Section 3d). These compounds are 
frequently investigated with a view to overriding the ‘intrinsic’ 
site-selectivity of the parent heterocycle.

3d. Influence of the nature of the halide
Arguably the most conceptually straightforward method to 
ensure that site-selective sequential SMC reactions take place in 
a required order is to anticipate the relative reactivity of 
different types of carbon–halogen bonds towards the initial OA 
step, by varying the halides present in the substrate. As noted 
previously, this prediction is based on the generalisation that 
OA in SMC reactions is usually rate-determining, irreversible, 
and strongly affected by the relative BDEs which in turn vary 
predictably as a function of the halide: ArI > ArBr > ArCl > Ar-
F.44,49 Although this is certainly the case for relatively unpol-
arised carboaromatic ring systems, how well does it hold for 
more intrinsically polarised systems of pharmaceutical interest? Often this can be a successful tactic, but for strongly 
polarised positions in heteroarenes it can be difficult to over-
turn the intrinsic site-selectivity trends discussed above 
(Sections 3a–c). The reactivity of mixed halide–triflates in 
particular are rather difficult to predict in this context – 
a discussion of these is provided in the ESI.†

5-Bromo-2-chloropyridine (39) and 2-bromo-3-iodypyridine 
(41) are illustrative of heteroarenes that undergo SMC reactions 
with aryl boronic acids at C5 and C3 respectively despite the fact 
that the C2 position is intrinsically ‘activated’ in both cases vide 
infra (Scheme 8).50

In both cases, OA takes place at the position bearing the 
more reactive halide as predicted on the basis of average C–Hal 
BDEs. Additional examples where judicious use of mixed 
halides can successfully allow the intrinsic electronic bias of 
a particular ring-system to be overturned are highlighted in 
Section 4 (i.e. Schemes 16, 19, 20 and 25).

By contrast, 6-bromo-2-chloroquinoline (43)51 and 
6-bromo-2-chloro-8-fluoroquinazoline (45)51 both react in SMC 
reactions first at the chlorides at C2 in preference to the 
bromides at C6 (Scheme 9).

Apparently, for these ring systems the intrinsic, strong 
electrophilicity at C2 (Section 4c) can facilitate OA to a greater 
extent than can be ‘compensated for’ by the normally lower BDE 
of C–Br relative to C–Cl.

Reactions involving isoquinolines and quinolones (Section 
4c), containing halides at C1 and C2 respectively, constitute an 
intermediate situation between these contrasting pyridine and 
quinoxaline/quinazoline cases. For these substrates, a chloride 
substituent at these intrinsically electrophilic positions some-
times reacts in preference to a bromide elsewhere in the
The intrinsic electrophilicity of C1 in isoquinolines is sufficient to override the usual ArBr > ArCl order of halide reactivity for (a) 1-chloro-5-bromoisoquinoline (47),\(^{53a}\) and (b) 1,3-dichloro-6-bromoisoquinoline (49),\(^{64}\) but not for (c) 1-chloro-3-tert-butyl-6-bromoisoquinoline (51), or (d) 1-chloro-7-bromoisoquinoline (53a) or 1,4-dichloro-7-bromoisoquinoline (53b).\(^{56}\)

Similarly, a chloride at C2 in quinolines can sometimes react in preference to a non-activated bromide elsewhere in the heterocycle but not always. For example, 2,4-dichloro-8-bromo-7-methoxyquinoline react at C2 (55 \(\rightarrow\) 56),\(^{55}\) but 2-chloro-6-bromoquinoline (57) can react (b) at C2 (\(\rightarrow\) 58) using Pd(PPh\(_3\))\(_2\)\(^{68}\) or (c) at C6 (\(\rightarrow\) 59) using Pd(dppf)Cl\(_2\)\(^{69}\) and 2-chloro-7-bromo-5-isopropylquinoline react at C7 (60 \(\rightarrow\) 61).\(^{70}\)

The foregoing discussion illustrates how the tactic of deploying different halogens to control site-selectivity in SMC reactions is often an effective strategy, but that the expected order of reactivity based on average C–Hal BDEs can be subverted for heteroarenes with strong intrinsic electronic bias and so allowance for this should be made in synthetic planning.
4. Key heteroarene ring-systems on a case-by-case basis

In this section we summarise on a heterocycle-by-heterocycle basis the results of a series of searches of the Pfizer RKB and CAS SciFinder® reaction databases as detailed in Section 2. For each ring type, a brief summary of published site-selectivity trends for the otherwise unsubstituted (i.e. unbiased ‘parent’) core molecule having two (or more) of the same halide substituents is presented. Preferred site-selectivity inferences based on published substituted cases are only mentioned if data on unsubstituted cases have not been published. Subsequent discussion of substituted derivatives is restricted to cases where substituents and/or conditions apparently induce a change in the intrinsic selectivity and to cases where a single substituent dictates the site-selectivity of systems for which the parent is symmetrical. Cases when the symmetry of the parent system make site-selectivity redundant (in the absence of additional substituents) are enclosed in hatched boxes; the number indicated below each of these structures indicates the number of reactions of this type found. Examples of selectivity in these reactions which arise from substituent effects are discussed as are some selected reactions which fall outside the scope of the searches but where intrinsic site-selectivities have been reversed by deploying two different halides.

As in Section 3, the data is depicted in the Schemes and Figures such that the halide highlighted with a blue disk is the preferred site of reaction (or yellow if there is no actual data but the site is predicted on the basis of expected ring C electrophilicity) and, where relevant, the numbers below indicate the number of hits conforming to that selectivity and, in parenthesis, number of exceptions. The hits from the Pfizer RKB and the CAS SciFinder® searches are separated and reported in blue and black text respectively. The figures in this section are reproduced the in ESI† with footnotes added giving further details of the hits retrieved (Fig. 3S-11S†).

4a. Pyridines, pyridazines, pyrimidines & pyrazines

Pyridines. Parent 2,3-, 2,4-, 2,5-, 3,5- and 2,3,5,6-tetrahalopyridines, 2,4-, 2,5-, 2,3,5-trichloropyridine, 2,3,5,6-tetachloropyridine and pentachloropyridine are known to preferentially undergo SMC reactions at C2/C6. Whereas 4-aryl-2,3,5,6-tetachloropyridine can undergo sequential SMC reactions at C2/C6 then C3/C5, 3,5-dibromo-2,6-dichloropyridine undergoes sequential SMC reactions at C3/C5 then C2/C6. 3,4-Dichloropyridine preferentially undergoes SMC at C4.

Our data, which incorporate additionally substituted cases, corroborate these trends (Fig. 3).

The greater electrophilicities of the C2 and C4 positions relative to C3 is expected from simple resonance analysis of the intrinsic polarisation of the pyridine ring-system. The retrieved exceptions have either no yield or evidence for assignment or are minor isomers (>17% yield). Ligand dependent selectivity for coupling 2,4-dichloropyridine with phenyl boronic acid at C4 over C2 (2.4 : 1) can be achieved albeit with a modest yield of 36% with Pd(OAc)2/Q-Phos/KF/toluene–H2O. Moreover, the C4 coupled product predominates when coupling methyl-4,6-dichloropyridine-2-carboxylate with a biaryl pinnacolato boronate ester using Pd(dppf)Cl2/TBAF/THF (28% yield, cf. 23% at C2), and when coupling 3-cyano-2,4-dichloropyridine with Pd(Xantphos)Cl2 (→ 63) and (b) at C4' with Pd(Qphos)2 (→ 64). These differences likely often reflect the ligation state of the Pd as these ‘non-standard’ ligands are prone to adopting low-coordination complexes and ligation state is an important factor in determining the ease of OA.

For substrates containing two or more of the same halide: selectivity is primarily controlled by the intrinsic relative electrophilicities of the different ring carbons but this can be tempered by the electronic (and to lesser extent steric) influence of ring substituents.

For substrates containing more than one kind of halide: selectivity can be controlled by the nature of the halide but the intrinsic relative electrophilicities of different ring-carbons can subvert this order in strongly polarised systems.

In both scenarios, the influence of the reaction conditions and particularly the nature of the Pd pre-catalyst/ligand can be decisive but this is generally only observed when using significantly more sterically hindered and/or electron-rich phosphines (e.g. QPhos, P(t-Bu)3, amphos, dtbpf) than the ‘standard’ phosphines employed for most SMC reactions (e.g. PPh3, dppf). These differences likely often reflect the ligation state of the Pd as these ‘non-standard’ ligands are prone to adopting low-coordination complexes and ligation state is an important factor in determining the ease of OA.

Scheme 12 The site-selectivity for SMC reactions of 2-(4-bromo-phenyl)-5-chloropyrazine (62) are ligand-dependent: it undergoes SMC (a) at C2 with Pd(Xantphos®)Cl2 (→ 63) and (b) at C4’ with Pd(Qphos)2 (→ 64).†

This feature is consistent with and reinforced by the data we retrieved from our database searches which are summarised below (Section 4).
4-aminophenyl pinnacolato boronate using \( \text{PdCl}_2(\text{dpf})/\text{Na}_2\text{CO}_3/\text{DME-H}_2\text{O} \) (no yield given but \( \text{C5 : C2} \) ratio \( \sim 2 : 1 \)).

No useful selectivity for SMC at C4 over C3/C5 could be achieved when using symmetrical 2,6-diaryl-3,4,5-trichloropyridine substrates. \(^{79}\)

Inversion of the intrinsic selectivity trends can be engineered by deploying mixed halide substrates in which a halide more susceptible to OA is placed at the intrinsically less reactive position, \(^{12}\) e.g. 2-bromo-3-iodopyridine reacts at C3 (41 \( \rightarrow \) 65) \(^{65,85,86}\) and 2-chloro-3,4-diiodopyridine reacts at C4 then C3 (66 \( \rightarrow \) 67) \(^{80}\) (Scheme 13).

Symmetrical 2,6-dichloropyridines \(^{60,77-82}\) and 3,5-dibromopyridines \(^{68,73,84}\) can undergo efficient sequential SMC reactions. For unsymmetrical 2,6-dichloropyridines, an ester or amide group at C3, as discussed earlier (cf. Scheme 3, Section 3b), promotes reaction at C6 over C2 (5 : 1) using \( \text{Pd}[\text{Ph}_3\text{P}]_2/\text{K}_2\text{CO}_3/\text{THF} \) but at C2 over C6 (2.5 : 1) using \( \text{PdCl}_2(\text{dpf})/\text{K}_2\text{CO}_3/\text{MeOH} \). The behaviour of the \( \text{PdCl}_2(\text{dpf}) \) was suggested to be as the result of chelation between the ester/amide carbonyl and the coordinatively unsaturated Pd(0). \(^{25x}\)

Similarly, a carboxylic acid group at C3 promotes reaction at C6 using \( \text{Pd(OAc)}_2/\text{PPh}_3/\text{Na}_2\text{CO}_3/\text{MeOH} \) \(^{84}\) but at C2 using \( \text{Pd}_2\text{dba}_2/\text{CHCl}_3/\text{K}_2\text{CO}_3/\text{EtOH} \) \(^{45x}\). A CF \(_3\) group at C3 of 2,6-dichloropyridine promotes reaction at C2 using \( \text{Pd(OAc)}_2/\text{PPh}_3/\text{DMF-H}_2\text{O} \) (68 \( \rightarrow \) 69), \(^{86}\) interestingly, this contrasts with the behaviour of the phenyl analogue, 2,4-dichloro-1-trifluoromethylbenzene, which couples at C4 under identical conditions (70 \( \rightarrow \) 71) \(^{80}\) (Scheme 14).

For unsymmetrical 3,5-dibromopyridines, a pyridinium ammine (\( \text{N}^-\text{N}^-\text{C}_2\text{H}_5\)) \(^{93}\) a methylamine, \(^{92}\) or a piperazine \(^{93}\) substituent at C2 promotes reaction at C3, presumably by coordination to Pd(0).

**Pyridazines.** SMC reactions of otherwise unsubstituted 3,4-dihalopyridazidine do not appear to have been reported. SMC reactions of unsubstituted 3,5-dichloro- and 3,5-dibromopyridazidine are also surprisingly rare; they generally react at C3 but selectivity for C5 can be achieved by ligand tuning (see below). \(^{39,94}\) Our data suggest that substrates containing these motifs generally favour reaction at C3 in both cases (Fig. 4).

An example from the Pfizer RKB in which C3 selectivity is observed for a SMC reaction of 3,5-dichloropyridazine (25) is shown below \(^{77a}\) (Scheme 15).

Similarly, 3,5-dichloropyridazine reacts with 2-fluoro-5-bromo-3-pyridine boronic acid using \( \text{Pd}[\text{Ph}_3\text{P}]_2/\text{Na}_2\text{CO}_3/1,4\text{-dioxane-H}_2\text{O} \) to give the C3 substituted product as the major isomer. \(^{44}\) Other cases for which C3 coupling has been observed include cases where 4-amino-3,5-dichloropyridazine \(^{85}\) reacts with 2-fluoro-4-trifluoromethylboronic acid using \( \text{PdCl}_2(\text{PPh}_3)_2/\text{Na}_2\text{CO}_3/1,4\text{-dioxane-H}_2\text{O} \) to give the C3 substituted product in 67% yield and where 6-methyl-3,5-dichloropyridazine \(^{96}\) reacts with a complex 4-substituted phenyl pinnacolato boronate using \( \text{PdCl}_2(\text{PPh}_3)_2/\text{Cs}_2\text{CO}_3/1,4\text{-dioxane} \) to give the C3 coupled product as the major isomer. However, as discussed earlier (Scheme 5, Section 3c), site selectivity for SMC reactions on 3,5-dichloropyridazine is ligand-dependent. This was highlighted by Dai et al. \(^{99}\) who screened 20 ligands for its coupling with phenyl boronic acid: e.g. \( \text{Pd(OAc)}_2/\text{dpf}/\text{Cs}_2\text{CO}_3/1,4\text{-dioxane-H}_2\text{O} \) gave C3 selectivity whereas \( \text{Pd(OAc)}_2/\text{Q-Phos}/\text{KF/toluene-H}_2\text{O} \) gave C5 selectivity. The SMC reaction of 3,5-dibromopyridazine with a complex aryl boronic acid using \( \text{Pd}[\text{Ph}_3\text{P}]_2/\text{K}_2\text{PO}_4/\text{DMF} \) also occurred selectively at C3, \(^{44}\) although caution should be associated with attributing these selectivity differences solely to the ligand given the concomitant changes in reaction conditions.

Mixed halide substrates can be employed to reverse the inherent bias of 3,5-dihalopyridazines for SMC reactions at
Pyrimidines. This heteroarene core has been widely explored for sequential SMC reactions and the order of reactivity is known to generally follow the order: C4/6 over C2 over C5.2,12 Parent 2,4-dihalopyrimidines,100 and 2,4,5,218 and 2,4,6-trihalopyrimidines,219 react at C4/6 and 2,5-bromopyrimidine122 reacts at C2. These trends are supported by our data which incorporate additionally substituted cases (Fig. 4, above).

2,4-Dihalopyrimidines which give anomalous selectivity include a case where 2,4-dibromopyrimidine reacts with 2,4-difluoro- or -butoxypyrimidine-5-boronic acid using Pd(PPh3)4/NaHCO3/DME to give the C2 substituted product in 58% yield.258 The other examples involve 2,4-dichloropyrimidines which additionally contain an amine substituent at C6.101 An alkyl,104 ether,105 thioether106 or amino106 substituent at C5 also appears to disfavour SMC reaction at C4, resulting in reaction at C2, presumably, mainly for steric reasons.

2,5-Dihalopyrimidines which give anomalous selectivity include a case where tetrachloropyrimidine reacts with 3-chloro-6-methoxypyridynyl boronic acid using Pd(OAc)2/Ph3P/Na2CO3/toluene/EtOH/H2O.144

Symmetrical 3,6-dibromo-98 and 3,6-dichloropyrimidines99 can undergo efficient mono-SMC reactions; analogous reactions with symmetrical 4,5-dichloropyrimidines are rare. SMC reactions of unsymmetrical 4-substituted-3,6-dichloropyrimidines usually result in reaction predominantly at C6, i.e. distal to alkyl, aryl,144-1 carbamate and alkoxy groups,144 but for basic amine substituents at C4, reaction is promoted at C3 as discussed earlier (cf. Scheme 2, Section 3b).144

Pyrazines. The symmetry of the pyrazine core renders all otherwise unsubstituted dihalide derivatives symmetrical (Fig. 4, above). Parent 2,5-dibromo-111 and 2,5-dichloropyrazines60,112 can undergo efficient mono-SMC reactions. Alkoxy- and amino-substituents direct OA to adjacent positions, e.g. 2,5-dibromo-3-methoxypyrazine reacts at C2 (77 → 78, Scheme 18).111

Scheme 17 5-Bromo-2-chloropyrimidine undergoes SMC at C5 (75 → 76).104b

2,3-Dichloropyrazine itself can undergo efficient mono-SMC reactions.114 Only two unsymmetrical variants were retrieved, one with a C6 (ref. 115) amino substituent and the other with a C6 (ref. 116) substituent; both gave SMC coupling at C3. Parent 2,6-dibromo-117 and 2,6-dichloropyrazines118 can undergo efficient mono-SMC reactions. 3-Amino-119 and 3-pyridinum amine (-N NC2H5)120 substituted 2,6-dibromopyrazines couple at C2 whereas interestingly 3-imide-substituted 2,6-dibromopyrazines couple at C6, albeit in low yields.121 Similarly, 3-acetyl-, 3-cyano- and 3-formyl-2,6-dichloropyrazines couple at C6.122

4b. Pyrroles, furans, thiofenes, imidazoles, pyrazoles, (is) oxazoles & (iso)thiazoles

Pyrroles. Although SMC reactions of parent 2,3- and 2,4-dihalopyrroles do not appear to have been reported, additionally C-substituted derivatives in general react at C2.125 N-Methyl-2,3,5-tribromopyrrole reacts at C3 then at C2 then at C3,126 and N-methyl tetrabromopyrrole reacts at C2 then at C5.124 These trends are supported by our data (Fig. 5).

No SMC reactions displaying anomalous selectivity were retrieved; it appears that the presence of various additional substituents does not overcome the inherent bias of the pyrrole ring system. Symmetrical 3,4-dihalopyrroles,125 2,3,4,5-tetrahalopyrroles124 and to a lesser extent 2,5-dihalopyrroles124 can undergo efficient mono-SMC reactions. Unsymmetrical cases include N-methyl-2-cyano-127 2-methoxycarbonyl-128 and N-methoxycarbonyl-3,4-dibromopyrrole-2-methyl ester (79)128 reacting at the proximal C3 position (→ 80, Scheme 19).128

Additional unsymmetrical cases include the aforementioned N-methyl-2,5-dibromopyrroles with an additional bromine substituent at C3 which undergo SMC reactions at the distal C5 position,123 and an N-methyl-2,5-dichloro-3-amidopyrrole which also reacts at C5.129

Furans. SMC reactions of 2,3-138 and 2,4-dihalofurans,178 and 2,3,4,5-tetrahalofurans,131 like pyrroles, are known to generally occur at C2. This trend is supported by our data (Fig. 5, above). As for pyrroles, no SMC reactions displaying anomalous selectivity were retrieved. Symmetrical 2,5-dibromo178,130a,112 and 2,3,4,5-tetrahalofurans112 can undergo efficient mono-SMC reactions, but no corresponding reactions of symmetrical

Scheme 16 3-Chloro-5-bromo-6-phenylpyridazine undergoes SMC reaction at C5 (73 → 74).27

Scheme 18 A 3-O Me group directs OA of 2.5-dibromopyrazine to C2 (77 → 78).111
3,4-dihalofurans have been reported. The only unsymmetrical 2,5-dibromofurans that have been coupled contain an ethyl ester at C3, which in contrast to the effect in 3,4-dibromopyrroles (cf. Scheme 1, Section 3a), directs the coupling of a 4-pyridyl pinnacolatoboronate to the C5 position (81 → 82), presumably for steric reasons (Scheme 20). 133

**Thiophenes.** SMC reactions of 2,3-134 and 2,4-dihalothiophenes135 like pyrroles and furans, are known to generally occur at C2. 2,3,4-Tribromothiophenes136 react at C4 when using Pd(OAc)2 with either XPhos, 1,3,5-triaza-7-phosphaadamantane, dpff or tris(4-trifluoromethylphenyl)phosphine but at C2 (i.e. as ‘normal’) when using Pd(OAc)2/Xantphos®. 137 The reason for the anomalous behaviour with these particular ligands is not apparent. One patent also reports a 2-amino- and a 2-aryl-4,5-dibromo-N-SEM-imidazole undergoing SMC coupling at C4 (i.e. proximal to the pyridine-like nitrogen) when using Pd[PPh3]4/Na2CO3/DME–H2O,138 but the SEM group is also present in two cases139,140 where normal C5 selectivity is observed so this does not appear to be the critical factor in the site-selectivity.

**Imidazoles.** N-protected-2,4,5-trihaloidimidazoles are known to undergo sequential SMC reactions at C2 then at C5 (i.e. proximal to the ‘pyrrole-like’ nitrogen) then at C4 (i.e. proximal to the ‘pyridine-like’ nitrogen).141 N-protected-2,4- and 2,5-dibromimidazoles generally also follow this trend (i.e. SMC reaction at C2 then either at C4 or at C5).142,143 These trends are supported by our data (Fig. 6).

The retrieved exceptions include the case of N-methyl-2,5-dibromimidazole for which SMC reaction at C5 was favoured when using Pd(OAc)2 with either XPhos, 1,3,5-triaza-7-phosphaadamantane, dpff or tris(4-trifluoromethylphenyl)phosphine but at C2 (i.e. as ‘normal’) when using Pd(OAc)2/Xantphos®. 25 The reason for the anomalous behaviour with these particular ligands is not apparent. One patent also reports a 2-amino- and a 2-aryl-4,5-dibromo-N-SEM-imidazole undergoing SMC coupling at C4 (i.e. proximal to the pyridine nitrogen) when using Pd[PPh3]4/Na2CO3/DME–H2O,138 but the SEM group is also present in two cases149 where normal C5 selectivity is observed so this does not appear to be the critical factor in the site-selectivity.

**Pyrazoles.** N-protected-3,4,5-tribromopyrazoles are known to undergo sequential SMC reactions at C5 then at C3 then at C4.58 This trend is supported by our data and no exceptions were retrieved, although the total number of examples was relatively small (Fig. 6, above).

**(Is)oxazoles.** The SMC reaction of 2,5-dibromoisoaxazole has been noted anecdotally151 to give “a complex mixture of products”, and 2,4-diiodooxazole is reported to give poor selectivityavouring reaction at C4 with most common ligand systems.25 This report relating to 2,4-diiodooxazole and which was discussed previously (cf. Scheme 6, Section 3a) is also the only one retrieved by our searches (Fig. 6, above). Interestingly, the highest level of C4 selectivity for 2,4-diiodooxazole was achieved using Pd(OAc)2/Xantphos® but SMC reaction predominantly at C2 could be achieved using Pd(OAc)2/1,3,5-triazala-7-phosphaadamantane (see Scheme 6, Section 3a).25 Reaction at C2 was also observed when coupling a 2-phenyl-4-pinnacolato-2,4-diiodooxazole with 5-phenyl-2,4-diiodooxazole using Pd3(dba)3/PCy3/K2CO3/DMF, likely due to the steric influence of the phenyl group at C5.122 There were no examples of SMC reactions on any dihaloisoxazoles retrieved by our searches (Fig. 6, above).

Cases of unsymmetrical 3,4-dibromothiophenes undergoing selective SMC reactions include ones with 2-aryl substituents which couple at C4;136 these substrates are often intermediates in sequential bis-SMC reactions of 2,3,4-tribromothiophenes. 2,5-Diaryl-3,4-dibromothiophenes appear to couple distal to most sterically demanding aryl group with good selectivity.140

2-Formyl-3,4-dibromothiophenes couple at C3.145

![Scheme 20](image)

**Scheme 20** A 3-ethoxycarbonyl group directs OA of 3,4-dibromofuran to C5 (81 → 82).125

![Scheme 21](image)

**Scheme 21** A 3-alkyl group directs OA of 2,5-dibromothiophene to C5 (83 → 84).138
3.8. 2,4-Dihaloquinolines

2,3- and 2,4-Dihaloquinolines are known to preferentially undergo SMC reactions at C2; 3,4-dihaloquinolines preferentially undergo coupling at C4.161 2,6-,162 2,8-,163 3,8-,164 3,6-,161a 3,7-,165 4,6-,166 4,7-,175a 161a 4,8-,168 Dihaloquinolines all react preferentially in the pyridyl ring. These trends are confirmed by our data which show that SMC reactions occur at C2 then at C4 then at C3 in the pyridyl ring and that all these positions are more reactive than any positions in the annelated benzo-ring (Fig. 7).

4c. (Iso)quinolines & benzodiazines

Quinolines. 2,3-159 and 2,4-Dihaloquinolines160 are known to preferentially undergo SMC reactions at C2; 3,4-dihaloquinolines preferentially undergo coupling at C4.161 2,6-,162 2,8-,163 3,8-,164 3,6-,161a 3,7-,165 4,6-,166 4,7-,175a 161a 4,8-,168 Dihaloquinolines all react preferentially in the pyridyl ring. These trends are confirmed by our data which show that SMC reactions occur at C2 then at C4 then at C3 in the pyridyl ring and that all these positions are more reactive than any positions in the annelated benzo-ring (Fig. 7). No exceptions were retrieved although inversion of the intrinsic selectivity trends can be engineered by deploying mixed halide substrates, e.g. 2-bromo-4-iodoquinoline which reacts at C4 (85 → 86)169 and 3,4-dichloro-7-bromoquinoline which reacts at C7 (87 → 88)170 (Scheme 22).

Isoquinolines. 1,3-Dihalo-171 and 1,6-dichloroisouquinolines172 are known to undergo selective SMC reactions at C1 and interestingly 4,7-dibromoisouquinoline reacts at C7.173 Our data support these trends and reveal that surprisingly few additional examples of selective SMC reactions of dihaloisouquinolines have been reported (Fig. 8).

That SMC reactions are favoured in the annelated benzo-ring over the pyridyl ring holds also for 4,7-dibromo-1-chloroisouquinoline (89 → 90, Scheme 23).173b

Benzopyridazines (cinnolines & phthalazines). 4,6-Dichloroisouquinoline174 and 1,6-dichlorophthalazine175 are known to undergo selective SMC reactions at C4 and C1 respectively. Our data confirm this and reveal that no additional substituted examples of these or any other dihalocinnolines have been investigated (Fig. 9).

Symmetrical 1,4-dichlorophthalazines can undergo mono-SMC reactions176 but unsymmetrical derivatives do not appear to have been investigated.

Benzopyrimidines (quinazolines). 2,4-Dichloroquinazoline is known to undergo SMC reactions selectively at C4177 but other parent dihaloquinazolines do not appear to have been investigated. Our data support this trend and moreover reveals that both the C4 and C2 positions in the pyrimidyl ring are favoured over the C6,178 C7179 and C8180 positions in the annelated benzo-ring (Fig. 9; also see Scheme 9, Section 3d). Interestingly, even 6-bromo-2,4-dichloroquinazoline reacts selectively at C4 using Pd(PPh3)2Cl2/K2CO3/DMF–H2O conditions (91 → 92, Scheme 24).181
Benzopyrazines (quinoxalines). 2,6-Dichloroquinoxaline is known to undergo SMC reactions selectively at C2. Our data support this and additionally indicate that substituted 2,5- and 2,8-dichloroquinoxalines undergo SMC reactions at C2 (Fig. 9, above). Symmetrical 2,3-dichloroquinoxalines can undergo efficient mono-SMC reactions. Unsymmetrical derivatives do not appear to have been investigated except the mixed halide case discussed earlier (Scheme 9, Section 3.4).

4d. Indoles, benzofurans, benzothiophenes, benzodiazoles, benz(is)oxazoles & benz(is)othiazoles

Indoles. SMC reactions of N-Me-1,86 and to a lesser extent N-PhSO2-2,3-dibromoisoxazoles187 occur preferentially at C2. Moreover, N-Me-2,3,6-tribromoisoxazole reacts at C2 then C6 then C3.186b N-2,5-Dibromoisoxazole also undergoes SMC reactions at C2 but N′-TBS-3,6-dibromoisindole184 reacts at C6. These trends are supported by our data which show that C2 in the pyrrole-like ring is the most reactive followed by the C5 and C6 positions in the benzo-fused ring and that C3 in the pyrrole-like ring is the least reactive (Fig. 10).

Benzofurans. 2,3-Dibromobenzofuran can be reacted sequentially via SMC reactions at C2 and then at C3.189 This preference is confirmed by our data which also reveals that 3,5-dibromobenzofuran undergoes selective SMC reaction at C5 (Fig. 10, above). By analogy with the selectivity displayed by Pd(0)-catalysed processes other than SMC, it can be anticipated that the order of reactivity in SMC reactions on 2,3,5-tribromobenzofuran will be: at C2 then at C5 then at C3.

Benzothiophenes. 2,3-Dibromobenzothiophene can be reacted sequentially via SMC reactions at C2 and then at C3,141c,190b,192 and 2,5-dibromobenzothiophene reacts via SMC reactions at C2.193 Our data confirms this (Fig. 10, above), and reveals that additionally a substituted 3,7-dichloro- and 3,5,7-trichlorobenzothiophene preferentially undergo SMC reactions.
at C3 (e.g. 93 → 94). However, both of the aforementioned 3,7-dichloro-substituted examples also contain a dimethyl amide substituent at C2, so it is possible that the electron-withdrawing influence of this group activates the C3 position towards OA (Scheme 25).

**Benzodiazoles (indazoles & benzimidazoles).** Interestingly, our data indicate there to be no examples known of selective SMC reactions of dihaloindazoles or benzimidazoles (Fig. 10, above). However, the selective reaction at C3 of 6-bromo-3-iodo-1-H-indazole has been reported (95 → 96, Scheme 26).\(^{197}\)

**Benz(is)oxazoles.** Although selective SMC reactions of dihalogenated benzisoxazoles appear to be unknown, reactions of 2,6-dichlorobenzoxazole are known to be selective for C2.\(^{196}\) These are the only reactions retrieved in our searches (Fig. 10, above).

**Benz(is)thiazoles.** SMC reactions of 2,5-dichloro-\(^{197}\), 2,6-dibromo-\(^{198}\), 2,6-dichloro-\(^{197,199}\), and 2,7-dichlorobenzothiazoles selectively occur at C2. Our data confirm this and also reveals that 6-methoxy-2,7-dibromobenzothiazole is reactive at C2\(^{200}\) (Fig. 10, above). The dataset is very limited however; no otherwise substituted benzothiazole examples have been reported and no benzisothiazoles at all.

4e. Aza(iso)quinolones (naphthyridines)

**Aza(iso)quinolines.** Remarkably few SMC reactions appear to have been carried out on this type of substrate. When both halides are situated in one ring then the reported cases all react as expected for the corresponding (iso)quinoline, e.g. 2,4-dichloro-8-azaquinolines ([1,8]-naphthyridines)\(^{200}\) and -7-azaquinolines ([1,7]-naphthyridine)\(^{201}\) and -5,8-diazaquinoline (pyrido[2,3-]pyrazine)\(^{202}\) all react at C2 and 5,7-dichloro-6-azaquinoline ([1,6]-naphthyridine) reacts at C1.\(^{203}\) When the halides are in different rings then there are even fewer examples (Fig. 11).

Our data show that 2,5-dichloro-6-azaquinoline ([1,6]-naphthyridine) undergoes SMC reactions at C2\(^{204}\) and 4,7-dichloro-6-azaquinoline react at C4. 7-Carbethoxy- and 7-carboxamido-2,8-dichloro-5-azaquinolines ([1,5]-naphthyridines) undergo SMC reactions at C2.\(^{205}\) 3,7-Dibromo-5-azaquinoline ([1,5]-naphthyridine, 97) is a symmetrical molecule and has been reported to undergo mono-SMC reactions with a range of aryl pinacolato boronates (→ 98, Scheme 27).\(^{69}\)

5. Conclusions

Given the complexity of the catalytic cycle involved in SMC reactions and the myriad of disparate Pd pre-catalysts, ligands, solvents and bases employed in these processes, it is not surprising that no absolutely rigid site-selectivity rules can be provided to predict the outcome of these reactions on heteroaryl polyhalides. As we have seen, experimental parameters can critically impact on the dominant catalytic species in solution and its ability to undergo the site-selectivity-determining OA step. However notwithstanding this, it is clear from the analysis presented in this review that for the majority of SMC reactions on this substrate class, particularly when using ‘standard’ conditions, the preferred site of reaction can be predicted with some confidence by paying attention to the nature of the halides present, the intrinsic relative electrophilicities of different ring-carbons (particularly for strongly polarised systems), and the electronic (and to a lesser extent steric) influence of substituents. We hope that by drawing together published data pertaining to this and summarising additional data mined from the Pfizer global chemistry RKB and the CAS SciFinder® databases, we have contributed to making the design of synthetic strategies for the construction of molecules containing poly-substituted heteroaryl motifs, for whatever purpose but especially in the context of pharmaceutical drug discovery, easier and more reliable.

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Notes and references


5 In this context, a ‘pseudo-halogen’ is a functional group capable of undergoing oxidative addition (OA) with Pd(0) (e.g. a triflate). In this article the term ‘halide’ implicitly encompasses pseudo-halides.


14 The Pfizer RKB accesses both individual reaction (CeN) and library (PMC) datasets (>2.8 million reactions, 1993 onwards) which are rich in reactions on heterocyclic systems of medicinal interest often attempted in the first instance using standard conditions: Pd[(dpf)Cl] or Pd[(dpf)Br] with NaN₃ or NaHCO₃ or K₂CO₃ in DME-H₂O or THF-H₂O or 1,4-dioxane-H₂O.
15 http://www.cas.org/products/scifinder, >60 million reactions, 1840 onwards.
16 Deploying different boron derivatives and/or controlling the speciation/ligation state of boronic esters and consequent transmetalation reaction rates can be used to effect regioselective sequential SMC reactions but this strategy lies outside the scope of our survey. For details, see e.g. the reviews of Lloyd-Jones (ref. 17a and d) and Watson (ref. 17b). Using this approach, Watson achieved an elegant one-pot sequential SMC reaction of 2,4-dichloropyrimidine at C4 then C2 using MIDA and Pin aryl boronates, see: ref. 17c.
32 The lower rates of OA of alkyl cf. aryl halides has been attributed to the absence of the requisite π* orbital in the former; see refs. 27a and 31.


The reviews of Bach (ref. 7) and Rossi (ref. 12) should generally, in these introductions, patents are only cited if reactions in our numerical data and which conform to the intrinsic selectivity trends indicated in our figures.


