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8-Methylquinoline palladacycles: stable and efficient catalysts for carbon–carbon bond formation

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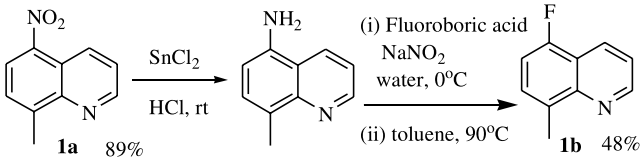
Abstract—Cyclopalladated, phosphine free, 8-methyl quinoline based complexes (**2a–j**) are excellent catalysts for the Heck vinylation of aryl iodides and bromides with turnover numbers of greater than 25 million observed in some cases. The catalysts are air and moisture stable.

Palladium mediated reactions are firmly positioned as one of the 'power tools' of modern organic synthesis. A variety of diverse catalytic manipulations may be accomplished using its salts and complexes. For example, the Heck reaction,[1] is a versatile and widely used method for C–C bond formation where much recent attention has focused on finding novel catalysts with high turnover numbers (TON). New developments in the area of high turnover palladium catalysts principally consist of palladacycles[2,3] and coordinatively unsaturated palladium catalysts featuring bulky phosphanes of high σ-donor abilities.[3] A variety of palladacycles incorporating cyclometallated phosphines,[4] phosphites,[5] carbenes,[6] imines,[7] heterocycles,[8] thioethers[9] and oximes[10] have been reported with high turnover numbers for this process. These precatalysts invariably contain sp^2 carbon–palladium bonds but the utility of palladacycles in other non-catalytic roles is also expanding.[11]

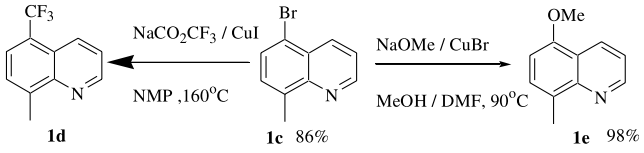
1. Introduction

We now report that palladacycles (**2a–j**) are good catalysts for both the Heck reaction and three component cascade reactions. Notably these systems differ from other phosphine free, nitrogen based palladacycles used in the Heck reaction in that they posses an sp^3 carbon–palladium bond rather than an sp^2 carbon–palladium bond. A series of 5-substituted 8-methylquinolines (**1a–d**) were synthesised from 8-methylquinoline. A standard nitration was carried out to give 5-nitro-8-methylquinoline (**1a**), which was converted to 5-fluoro-8-methylquinoline (**1b**) via the corresponding diazonium salt (Scheme 1).[12]



Scheme 1.

Bromination of 8-methylquinoline at C-(5) to afford (**1c**) was achieved by bromine in the presence of silver sulfate[13] whilst 5-trifluoromethyl 8-methylquinoline (**1d**) was prepared from (**1c**) using sodium trifluoroacetate in the presence of copper (I) iodide (Scheme 2).[13] 5-Methoxy-8-methylquninoline (**1e**) was also derived from (**1c**) using



Scheme 2.

Keywords: Precatalyst; Allene; Cascade.
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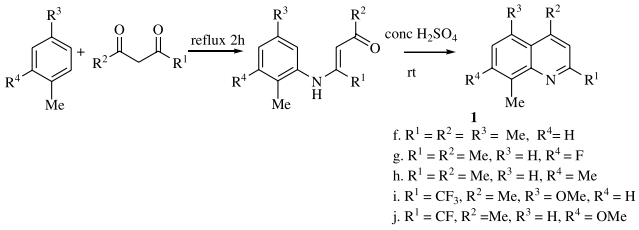
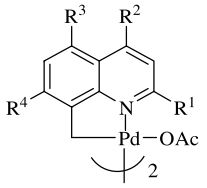
sodium methoxide together with copper (I) bromide (Scheme 2).[14]

The substituted 8-methylquinolines (**1f–j**) were synthesised by a two step procedure adapted from the literature[15] from the appropriate aniline and 1,3-diketone in 82–96% yield (Scheme 3).



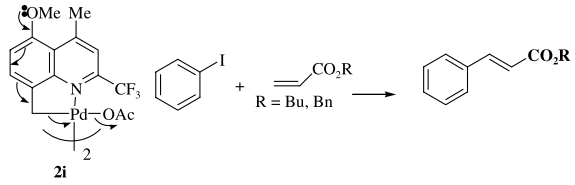
Scheme 3.



2 a. $R^1 = R^2 = R^3 = R^4 = H$
b. $R^1 = R^2 = H$, $R^3 = NO_2$, $R^4 = H$
c. $R^1 = R^2 = H$, $R^3 = F$, $R^4 = H$
d. $R^1 = R^2 = H$, $R^3 = CF_3$, $R^4 = H$
e. $R^1 = R^2 = H$, $R^3 = OMe$, $R^4 = H$
f. $R^1 = R^2 = R^3 = Me$, $R^4 = H$
g. $R^1 = R^2 = Me$, $R^3 = H$, $R^4 = F$
h. $R^1 = R^2 = Me$, $R^3 = H$, $R^4 = Me$
i. $R^1 = CF_3$, $R^2 = Me$, $R^3 = OMe$, $R^4 = H$
j. $R^1 = CF_3$, $R^2 = Me$, $R^3 = H$, $R^4 = OMe$

Following a procedure adapted from literature the 8-methyl quinoline derivatives and palladium acetate (1 equiv) were heated in glacial acetic acid at 100 °C[16] to afford the desired palladacyclic dimers (**2a–j**) in 55–65% yield. The mixture of isomeric species (cis and trans dimers) is clearly evident in the proton NMR spectra of (**2a–j**) from the set of broad AB signals, due to the diastereotopic C(8)–CH_2 protons (see Section 2) and the corresponding additional complexity of the aromatic proton signals.

We explored the Heck reaction between iodobenzene and *n*-butyl acrylate or benzyl acrylate in the presence of (**2a–j**) in DMF/DMA at 140 °C (Table 1) (Scheme 4). Introducing a C(5)-electron donating group, increases the rate of reaction and TON (Table 1, entry 6).



Scheme 4.

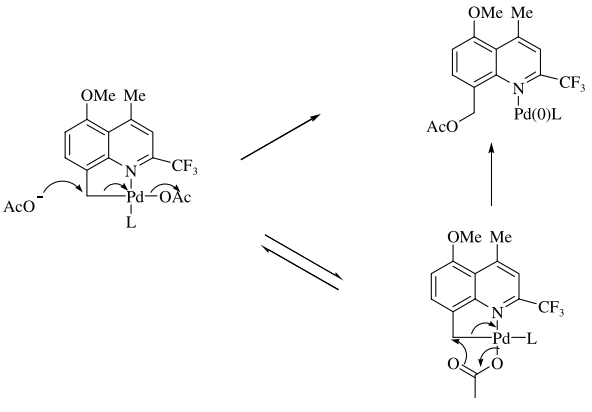
Introducing a C(2)-electron withdrawing group further increases the rate and TON (Table 1, entry 9). A C(7)-electron donating group combined with a C(2)-electron withdrawing group also produces a highly active catalyst (Table 1, entry 11). Introducing fluorine (-I and π-donor) substituents at C(5) and C(7) did not produce a higher TON (Table 1, entries 3 and 8). However, a C(5)–CF_3 group gave a good TON (Table 1, entry 5). We also carried out an experiment on (**2i**) to determine the recyclability of the catalyst. Thus, a fresh charge of iodobenzene, *n*-butyl acrylate and base were added to the reaction mixture after 100% conversion of the previous run. In this way it was found that catalyst was still active after 30 days and a TON of 25 million (Table 1, entry 10). In this latter case PVP polyvinyl pyrrolidone (Pd/PVP = 13:1) was added at the start of the reaction (Table 1, entry 10). This additive is known to prolong catalyst life by the polymer chains 'wrapping up' the individual palladium nanoparticles thus preventing them colliding with each other and aggregating, that is, stablises the nanoparticles.[17] The palladacycles (**2a–j**) could operate via Pd(II)/Pd(IV)[18] or Pd(0)/Pd(II) catalytic cycles.[19] It appears probable, on our current

Table 1. Catalytic Heck reaction of iodobenzene with *n*-butyl acrylate (2 equiv) or benzyl acrylate (2 equiv) with palladacycles (**2a–j**) precatalysts

Entry	Catalyst (mol%)	Temperature (°C)	Solvent	Time (h)	Base (2 equiv)	Conversion (%)[a]	TON[b]
1[c]	**2a** (0.01)	100	DMF	60	K_2CO_3	85	8,500
2[c]	**2b** (0.00017)	100	DMF	16	K_2CO_3	99	581,600
3	**2c** (0.001)	140	DMF	96	K_2CO_3	89	89,000
4	**2c** (0.0001)	140	DMA	96	CsOAc	34	340,000
5	**2d** (0.00001)	140	DMA	96	CsOAc	87	8,700,000
6	**2e** (0.00001)	140	DMF	96	CsOAc	98	9,800,000
7	**2f** (0.0001)	140	DMF	44	KOAc	70[d]	700,000
8	**2g** (0.001)	140	DMF	16	KOAc	100	100,000
9	**2i** (0.00001)	140	DMF	47	CsOAc	100	10,000,000
10	**2i** (0.0001)	140	DMF	720	KOAc	—[e]	25,500,000
11	**2j** (0.00001)	140	DMF	94	CsOAc	78	7,800,000

[a] Conversion by NMR.
[b] TON based on consumption of iodobenzene.
[c] Benzyl acrylate and Et_4NCl (1 equiv) were used.
[d] GC conversion.
[e] PVP (M_w 3000) (pd/PVP = 13:1) were used.

evidence, that the active species are Pd(0) nanoparticles.[20] We have also shown that treatment of palladacycles or palladium salts with carbon monoxide (1 atm) in DMF or toluene at room temperature results in a solution of palladium nanoparticles whose morphology depends on the palladacycle or palladium salt precursors.[21] Blackmond et al. have developed a detailed kinetic model of a Heck reaction catalysed by dimeric palladacycles.[22] This model explains the experimental observations and is consistent with an active species being slowly metered into the reaction. Comparison between phosphine and non-phosphine based palladacycles suggests that they follow the same reaction mechanism. They have also highlighted the role of water in accelerating the formation of the active catalyst species. Thus, the rate-determining 'metering' step is outside the true catalytic cycle, in the case of aryl iodides and activated aryl bromides and this has important consequences for the use of these catalysts. This, of course, does not apply to cases of 'unreactive' aryl chlorides and bromides where oxidative addition is rate determining. Seminal contributions to these multifactorial processes have also been made by van Leeuwen's and Hartwig's groups[19a,23] and by Amatore and Jutand.[24] TONs with these palladacycles would appear even more impressive if based on the actual amount of Pd present in the catalytic cycle itself. The function of the substitutents in (**2a–j**) can be interpreted as perturbing the sp^3 C–Pd covalent bond and the N–Pd dative bond and in so doing controlling the rate of release of Pd nanoparticles into solution. In the most active catalyst (**2i**) the substitutent effects conspire to weaken both bonds by a combination of mesomeric [C(5)–OMe] and inductive effects [C(2)–CF_3] (Scheme 4, **2i**, arrows). The reductive elimination implied by (**2i**, arrows) could also proceed via bridge splitting and intramolecular acetate transfer or an SN2 process (Scheme 5). This is considered infinitely more probable than an alternative olefin insertion in the C–Pd bond as the initiation step followed by β-hydride elimination, resulting in palladium nanoparticles, which has also been proposed.[25]



Scheme 5.

Next, we briefly studied the effects of base in the Heck reactions employing palladacycle (**2d**) and (**2f**) precatalysts. These results are summarised in Table 2. Sodium acetate was the least effective of the bases evaluated (Table 2, entries 1 and 6), closely followed by potassium carbonate. Potassium acetate and cesium acetate were the best of those studied (Table 2, entries 3, 4 and 7). The nature of the inorganic base has a clear effect on TON/conversion (Tables 1 and 2). This is ascribed to involvement of the base in formation of the catalytically active Pd(0) species as well documented by the work of Amatore and Jutand[24] and as noted in Scheme 5. Caution is necessary in applying these conclusions more widely since it is likely the base order is palladacycle dependent. The effect of inorganic bases in Heck reaction is an area that is still imperfectly understood. It is clear both anion and cation play a role and this suggests that anionic palladium complexes,[24] incorporating the base anion, associated with the base cation, play a significant role in the catalysis. Recently Beletskaya et al. briefly reported the catalytic activity of **2a**[26] in the Heck reaction. We briefly explored the Heck reaction of bromo and chlorobenzene with (**2a**) and (**2e**) and *n*-butyl acrylate in DMA at 140 °C (Table 3).

Table 2. Effect of base on the Heck reaction of iodobenzene with *n*-butyl acrylate (2 equiv) using catalysts **2d** and **2f**

Entry	Catalyst[a]	Time (h)	Base (2 equiv)	Conversion (%)[b]
1	**2d**	48	NaOAc	24
2	**2d**	48	K_2CO_3	35
3	**2d**	48	KOAc	99
4	**2d**	48	CsOAc	97
5	**2f**	24	K_2CO_3	10[c]
6	**2f**	61	NaOAc	8[c]
7	**2f**	20	KOAc	100[c]

[a] 0.001 mol% catalyst.
[b] Conversion by NMR.
[c] GC conversion.

Thus, 4-bromoacetophenone with catalyst **2e** afforded TON's of up to a million (Table 3, entry 5).In the absence of any additives, rates of the reaction, when bromobenzene was the substrate were poor (Table 3, entry 10). However, the addition of 2 mol equiv of tetrabutylammonium bromide increased the TON's to reasonable values (Table 3, entry 13). The role of halide ions in stablising Pd(0) species has been extensively studied and documented by Amatore and Jutand,[25] Reetz et al.[27] and others.[19] In the case of dimeric palladacycles the role of the soluble Bu_4NBr in bridge splitting to furnish monomeric species and in participating in processes analogus to those in Scheme 5 also needs to be considered. Again the effect is on catalyst metering and or structure with the results (Table 3) indicating the Pd(0) species is now able to process bromobenzene (oxidative—addition not rate determining) whilst oxidative addition of ArCl (Table 3, entry 14) remains rate determining.

Finally we explored a three component cascade involving aryl halides, allenes and secondary amines in the presence of K_2CO_3 as a base in DMF (Scheme 6) using precatalysts (**2d**), (**2e**) and (**2i**). All three precatalysts functioned efficiently at 80 °C at the 1 mol% level (Table 4, entries 1–7) affording the 2-arylallylamines (**4a–c**) in 76–90% yield over 24 h. When the precatalyst loading was reduced to 0.25 mol% of (**2i**) the process was less efficient at 80 °C (Table 4, entry 9) but on raising the temperature to 120 °C

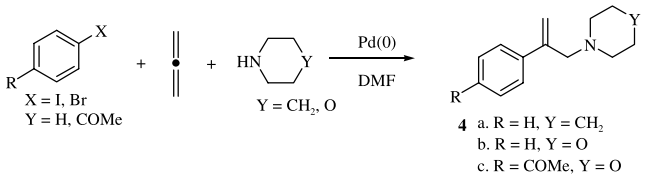
Table 3. Palladacycles in Heck reactions with aryl bromides[a]

Entry	Catalyst (mol%)	Aryl halide	Additive	Conversion (%)[b]	TON
1	**2a** (0.01)	4-Bromoacetophenone	—	100	1,000
2	**2a** (0.001)	4-Bromoacetophenone	—	88	88,000
3	**2e** (0.01)	4-Bromoacetophenone	—	100	10,000
4	**2e** (0.001)	4-Bromoacetophenone	—	100	10,0000
5	**2e** (0.0001)	4-Bromoacetophenone	—	100	1,000,000
6	**2e** (0.00001)	4-Bromoacetophenone	—	44	4,400,000
7	**2a** (0.1)	Bromobenzene	—	10	100
8	**2a** (0.1)	Bromobenzene	Bu_4NBr	100	1,000
9	**2a** (0.01)	Bromobenzene	Bu_4NBr	40	4,000
10	**2e** (0.1)	Bromobenzene	—	47	470
11	**2e** (0.1)	Bromobenzene	Bu_4NBr	100	1,000
12	**2e** (0.01)	Bromobenzene	Bu_4NBr	100	10,000
13	**2e** (0.0001)	Bromobenzene	Bu_4NBr	96	960,000
14	**2e** (1)	4-Chloroacetophenone	Bu_4NBr	0	0

[a] Reactions carried out in DMA for 48 h at 140 °C employing aryl halide (1 mmol), *n*-butyl acrylate (2 mmol), Bu_4NBr (2 mmol) and CsOAc (2 mmol).
[b] Conversion measured by GLC.

the precatalyst performed as well as the 1 mol% loading at 80 °C (Table 4, entries 8, 10 and 11). This trend accords with the temperature controlled breakdown of (**2i**) metering the release of the catalytically active Pd nanoparticles.

In summary we have developed a range of non-phosphine 8-methyl quinoline based dimeric palladacycles, possessing an sp^3 C–Pd bond, which are efficient precatalysts for both Heck reactions and a 3-component cascade process. The palladacycles function via a temperature controlled breakdown of the precatalysts (**2a**–**j**) to Pd nanoparticles, which are metered into the reaction mixture. The precatalyst → active catalyst breakdown/metering mechanism is sensitive to substitution on the quinoline ring. Substituents that facilitate sp^3 C–Pd σ-bond and N–Pd dative bond cleavage deliver Pd nanoparticles more rapidly and this process is strongly influenced by metal acetate and Bu_4NBr additives. The hitherto neglected area of sp^3 C–Pd palladacycles[28] will, we believe, find many more applications in the future.



Scheme 6.

2. Experimental

2.1. General

Melting points were determined using a Reichert apparatus and are uncorrected. Mass spectral data was obtained from a VG Autospec mass spectrometer operating at 70 cV at the National MS Service, Swansea. Nuclear magnetic resonance spectra were recorded on Bruker 250, 300, 400 and 500 MHz machines. Unless otherwise specified deutereochloroform was used as solvent with tetramethylsilane as internal standard. Microanalyses were obtained using a Carlo Erba MOD 11016 instrument. Thin-layer chromatography was carried out on Whatmann PGSILG/UV polyster plate coated with a 0.2 mm layer of silica gel 60 (Merck 9385). Petroleum ether refers to the fraction with bp 40–60 °C. anhydrous DMF and DMA were commercially available (Aldrich). PVP (M_w 30,000) was purchased from Aldrich and used as received. Conversions measured by GLC. (GC-FID was performed on a GC equipped with 12QC31 BP5 column 0.5 μm diameter, using the following program. Flow rates, He = 20 mL/min, starting temperature 70 °C rising by 20 °C/min to 170 °C then 1 °C/min. Retention time = 13 min).

2.1.1. 8-Methyl-5-nitroquinoline (1a).[12] Concentrated sulfuric acid (4.7 mL) was added dropwise over 10 min to 8-methylquinoline (3 mL, 21.60 mmol) at 0 °C. A mixture

Table 4. Three component cascade involving aryl iodide or bromide, allene and a secondary amine in the presence of (**2d**, **2e**, **2i**)[a]

Entry	Catalyst (mol%)	Temperature (°C)	Aryl halide	Product	Yield (%)[b]
1	**2d** (1.0)	80	Iodobenzene	**3a**	89
2	**2d** (1.0)	80	Iodobenzene	**3b**	94
3	**2d** (1.0)	80	4-Bromoacetophenone	**3c**	85
4	**2e** (1.0)	80	Iodobenzene	**3a**	79
5	**2e** (1.0)	80	Iodobenzene	**3b**	82
6	**2e** (1.0)	80	4-Bromoacetophenone	**3c**	76
7	**2i** (1.0)	80	Iodobenzene	**3a**	90
8	**2i** (0.25)	120	Iodobenzene	**3a**	90
9	**2i** (0.25)	80	Iodobenzene	**3b**	55
10	**2i** (0.25)	120	Iodobenzene	**3b**	80
11	**2i** (0.25)	120	4-Bromoacetophenone	**3c**	73

[a] Reactions carried out in DMF for 24 h at 80 or 120 °C employing aryl halide (1 mmol), amine (1.2 mol equiv), allene (1 atm) and K_2CO_3 (2 mol equiv).
[b] Isolated yield.

of concentrated nitric acid (2.7 mL) and concentrated sulfuric acid (2.3 mL) was then added dropwise over 20 min. The reaction mixture was stirred for 2 days at 0 °C then poured onto ice and neutralised using sodium hydroxide solution. The product was extracted into ether (×3), the combined organic extracts washed with brine, dried ($MgSO_4$), filtered and the filtrate concentrated to give the product (3.62 g, 89%) as pale yellow prisms, mp 94–95 °C (lit. 93–93.5 °C). δ_H (300 MHz): 2.91 (3H, s, Me), 7.65 (2H, m, ArH), 8.33 (1H, d, J=7.9 Hz, ArH), 9.06 (2H, m, ArH), m/z (%) (EI): 188 (M^+, 100), 158 (39), 142 (62), 115 (18).

2.1.2. 5-Amino-8-methylquinoline.[12] Concentrated hydrochloric acid (35 mL) was added dropwise over 20 min to 8-methyl-5-nitroquinoline (3.0 g, 15.94 mmol) at 0 °C. Tin (II) chloride (6.04 g, 31.88 mmol) was then added and the reaction mixture was allowed to reach room temperature and stirred for 48 h then neutralised by careful addition of sodium hydroxide solution. The product was extracted into ether (×3) and the combined organic extracts were washed with brine, dried ($MgSO_4$), filtered and the filtrate concentrated to give the product (1.99 g, 79%) as yellow prisms, mp 144–145 °C (lit. 143–143.5 °C). δ_H (300 MHz): 2.91 (3H, s, Me), 7.66 (2H, m, ArH), 8.32 (1H, d, J=7.9 Hz, ArH), 9.06 (2H, m, ArH), m/z (%) (EI): 158 (M^+, 65), 142 (100), 115 (33), 89 (15), 63 (22).

2.1.3. 5-Fluoro-8-methylquinoline (1b).[12] 5-Amino-8-methylquinoline (2.60 g, 16.43 mmol) was dissolved in fluoroboric acid (50 mL) and cooled to 0 °C. Sodium nitrite (1.19 g, 17.26 mmol) in water (10 mL) was added and the mixture stirred at 0 °C for 30 min. The resulting colourless precipitate was filtered off and thoroughly dried in a desiccator for 16 h. The dried tetrafluoroborate salt was suspended in toluene (20 mL), heated to reflux for 32 h, and quenched with 10% hydrochloric acid solution. The layers were separated, the aqueous layer basified to pH 9–10 with 2 M sodium hydroxide solution and the mixture extracted with ether (×3). The combined organic layers were washed with brine, dried ($MgSO_4$), filtered and the filtrate concentrated. The residual brown oil was purified by flash column chromatography, eluting with 2:3v/v ether–petroleum ether to give the product (1.27 g, 48% yield) as a colourless oil. δ_H (300 MHz): 2.76 (3H, s, Me), 7.12 (1H, t, J=8.0 Hz, ArH), 7.47 (2H, m, ArH), 8.42 (1H, d, J=8.4 Hz, ArH), 8.99 (1H, m, ArH), m/z (%) (EI): 161 (M^+, 100), 143 (16), 133 (13), 71 (17).

2.1.4. 5-Bromo-8-methylquinoline (1c).[13] Bromine (0.76 mL, 14.69 mmol) was added dropwise over 15 min to a solution of 8-methylquinoline (2.0 mL, 14.69 mmol) and silver sulphate (2.29 g, 7.35 mmol) in concentrated sulphuric acid (15 mL). The reaction mixture was stirred for 30 min at room temperature then poured into water and basified using sodium hydroxide solution. The mixture was extracted with ether (×3) and the combined organic extracts were washed with brine, dried ($MgSO_4$), filtered and concentrated to give the product (2.80 g, 86% yield) as pale fawn prisms, mp 38–39 °C (lit. 37–38 °C). δ_H (300 MHz): 2.76 (3H, s, Me), 7.41 (1H, d, J=7.6 Hz, ArH), 7.50 (1H, m, ArH), 7.70 (1H, d, J=7.6 Hz, ArH), 8.52 (1H, d, J=8.5 Hz, ArH), 8.95 (1H, d, J=4.2 Hz, ArH), m/z (%) (EI): 222 (M^+, 97), 142 (100), 115 (25), 70 (30), 63 (20).

2.1.5. 8-Methyl-5-(trifluoromethyl)quinoline (1d).[13] 5-Bromo-8-methylquinoline (2.50 g, 11.26 mmol), sodium trifluoroacetate (6.74 g, 49.53 mmol) and cuprous iodide (4.76 g, 24.99 mmol) were combined in *N*-methylpyrrolidone (80 mL) and heated to 160 °C for 5 days. After cooling the reaction mixture was poured into water and extracted with ether (×3). The combined organic extracts were washed with brine, dried ($MgSO_4$), filtered and the filtrate concentrated. The residual brown oil was purified by flash column chromatography, eluting with 10% ether in petroleum ether to give the product (1.40 g, 59% yield) as a pale yellow oil. Found: C, 62.55; H, 4.10; N, 6.70; $C_{11}H_8F_3N$ requires C, 62.55; H, 3.85; N, 6.65%, δ_H (300 MHz): 2.86 (3H, s, Me), 7.55 (1H, m, ArH), 7.60 (1H, d, J=7.5 Hz, ArH), 7.81 (1H, d, J=7.5 Hz, ArH), 8.49 (1H, d, J=8.7 Hz, ArH), 9.02 (1H, m, ArH), m/z (%) (EI): 211 (M^+, 100), 142 (26), ν_{max}/cm^{-1} (film): 1118.8 (s, C–F), 1321.4 (s, C–F), 1506.6 (m, aromatic ring).

2.1.6. 5-Methoxy-8-methylquinoline (1e).[14] A mixture of 5-bromo-8-methylquinoline (1.00 g, 4.50 mmol), sodium methoxide (2.43 g, 45.03 mmol), DMF (6 mL) and methanol (15 mL) was stirred and heated at 90 °C under nitrogen. Cuprous bromide (0.32 g, 2.25 mmol) was added and the reaction mixture was maintained at 90 °C for 16 h, poured into water and extracted with ether (×3). The combined organic layers were washed with water and brine, dried ($MgSO_4$), filtered and the filtrate concentrated. The residual brown oil was purified by flash column chromatography, eluting with 10% ether in petroleum ether to give the product (762 mg, 98% yield) as a pale yellow oil. Found: C, 75.40; H, 6.50; N, 8.05; $C_{11}H_{11}NO$ requires C, 76.30; H, 6.40; N, 8.10%, δ_H (300 MHz): 2.71 (3H, s, Me), 3.91 (3H, s, OMe), 6.68 (1H, d, J=7.8 Hz, ArH), 7.33 (1H, m, ArH), 7.39 (1H, d, J=7.8 Hz, ArH), 8.53 (1H, d, J=8.4 Hz, ArH), 8.92 (1H, m, ArH), m/z (%) (EI): 173 (M^+, 51), 158 (100), 130 (19), 77 (17), ν_{max}/cm^{-1} (film): 1091.8 (s, C–O), 1402.4 and 1475.7 (m, C–H deformations), 1593.4 (s, aromatic ring), 2848 (m, OMe).

2.2. General procedure for anilide synthesis[15]

Anilides were synthesised by the literature procedure. A mixture of the appropriately substituted aniline (1.0 equiv) and the dicarbonyl compound (1.1 equiv) was heated in an oil bath under reflux for 4 h. After cooling to room temperature, water (100 mL) was added and the mixture extracted with DCM (3×100 mL). The DCM layer was dried ($MgSO_4$), filtered and the filtrate evaporated under reduced pressure. The residual solid was crystallised from petroleum ether.

2.3. General procedure for quinoline synthesis from anilides[15]

Anilide (10.0 mmol) was added to 98% sulfuric acid (20 mL) and the mixture stirred for 4 h at room temperature. The reaction mixture was then carefully poured into ice-water (200 mL) with swirling. NaOH pellets were then added carefully until the mixture was strongly basic

(pH 10–12). The mixture was extracted with DCM (3× 100 mL), the combined organic layer dried ($MgSO_4$), filtered and the filtrate evaporated under reduced pressure. The solid residue was purified by crystallisation from an appropriate solvent.

2.3.1. 2,4,5,8-Tetramethyquinoline (1f). Synthesised by the general procedure from 2,5-dimethyl aniline (12.1 g, 100 mmol, 1.0 equiv) and 2,4-pentanedione (11.3 mL, 110 mmol, 1.1 equiv) over 5 h at 130 °C. The crude anilide was reacted according to the general procedure to give the product (11.0 g, 59.5%), which crystallised from petroleum ether as colourless plates, mp 36–38 °C. Found: C, 84.50; H, 8.20; N, 7.50; $C_{13}H_{15}N$ requires C, 84.30; H, 8.10; N, 7.60%. δ_H (250 MHz, $CDCl_3$) 2.65, 2.70, 2.80. 2.81 (4×3H, 4×s, 4×Me), 7.0 (1H, s, ArH), 7.1 (1H, d, J=7.2 Hz, ArH), 7.3 (1H, d, J=7.2 Hz, ArH), *m/z* (FAB): 186 (100%, M^++H), 172 (53), 158 (20), 141 (10), 128 (25) and 115 (16). ν_{max}/cm^{-1} (solid) 2962, 2918, 2840, 1864, 1721, 1602, 1572, 1460, 1438, 1383, 1366, 1328, 1144, 1041, 862, 818, 696 and 618.

2.3.2. 7-Fluoro-2,4,8-trimethyquinoline (1g). The anilide was synthesised by the general procedure from 3-fluoro-2-methyl aniline (3.13 g, 25.0 mmol, 1.0 equiv) and 2,4-pentanedione (2.83 mL, 27.4 mmol, 1.1 equiv) over 5 h at 130 °C. The crude anilide was reacted according to the general procedure to give the product (2.0 g, 98%), which crystallised from petroleum ether as colourless needles, mp 26–28 °C. Found: C, 76.10; H, 6.45; N, 7.30; $C_{12}H_{12}FN$ requires C, 76.20; H, 6.35; N, 7.40%. δ_H (250 MHz, $CDCl_3$) 2.6, 2.65, 2.70 (3×3H, 3×s, 3×Me), 7.1 (1H, s, ArH), 7.2 (1H, t, J=9.0 Hz, ArH) (J H–H≈J H–^{19}F), 7.8 (1H, dd, J= 9.0, 6.1 Hz, ArH), *m/z* (FAB): 190 (100%, M^++H), 174 (14), 146 (10), 97 (8) and 83 (16). ν_{max}/cm^{-1} (solid) 2956, 2923, 1605, 1510, 1439, 1378, 1338, 1317, 1229, 1210, 1155, 1080, 1036, 963, 936, 874, 816 and 781.

2.3.3. 2,4,7,8-Tetramethyquinoline (1h). The anilide was synthesised by the general procedure from 2,3-dimethyl aniline (30 mL, 247.0 mmol, 1.0 equiv) and 2,4-pentanedione (28 mL, 274.0 mmol, 1.1 equiv) over 4 h at 155 °C. Crystallisation from petroleum ether afforded the product (20.0 g, 79%) as colourless plates, mp 90–92 °C (lit.[15] 83–84 °C).

Anilide (2.0 g, 9.85 mmol) was converted to the quinoline **1h** by the general procedure to give the product (1.8 g, 98%) as colourless needles, mp 26–28 °C (lit.[15] 30–31 °C).

2.3.4. 5-Methoxy-4,8-dimethyl-2-(trifluoromethyl)quinoline (1i). The anilide was synthesised by the general procedure from 5-methoxy-2-methyl aniline (0.62 g, 5.0 mmol, 1.0 equiv) and 1,1,1-trifluoro-2,4-pentanedione (0.73 mL, 6.0 mmol, 1.1 equiv) over 5 h at 130 °C. Crystallisation from petroleum ether gave the product (0.92 g, 70%) as colourless plates, mp 53–55 °C. Found: C, 57.10; H, 5.20; N, 5.00; $C_{13}H_{14}F_3NO_2$ requires C, 57.10; H, 5.10; N, 5.10%. δ_H (250 MHz, $CDCl_3$) 2.0, 2.2 (2×3H, 2×s, 2×Me), 3.8 (3H, s, OMe), 5.55 (1H, s, =CH), 6.65 (1H, d, J= 2.6 Hz, ArH), 6.8 (1H, dd, J=8.4, 2.6 Hz, ArH), 7.2 (1H, d, J=8.4 Hz, ArH), *m/z* (FAB): 274 (100%, M^++H), 204 (16), 174 (7) and 162 (12). ν_{max}/cm^{-1} (solid) 3192, 3126, 3006, 2980, 2844, 2501, 2084, 1888, 1720 (CO), 1593, 1495, 1459, 1391, 1366, 1275, 1260, 1112, 1044, 1011, 975, 857, 812, 766, 748, 727, 704, 653, 584, 567, 553, 512 and 466.

The anilide (0.50 g, 1.83 mmol) was reacted according to the general procedure to give the product (**1i**) (0.38 g, 82%), which crystallised from petroleum ether as colourless needles, mp 76–78 °C. Found: C, 61.00; H, 4.80; N, 5.20; $C_{13}H_{12}F_3NO$ requires C, 61.20; H, 4.70; N, 5.50%. δ_H (250 MHz, $CDCl_3$) 2.7, 2.8 (2×3H, 2×s, 2×Me), 3.95 (3H, s, OMe), 6.9 (1H, d, J=8.0 Hz, ArH), 7.5 (1H, d, J= 8.0 Hz, ArH), 7.65 (1H, s, ArH), *m/z* (FAB): 255 (100%, M^+). ν_{max}/cm^{-1} (solid) 2978, 2923, 2851, 1607, 1581, 1513, 1471, 1388, 1343, 1257, 1155, 1140, 1099, 959, 879, 823 and 803.

2.4. General procedure for the synthesis of 8-methylquinoline palladacycles[16]

The quinoline (**1a**–**j**) (2.50 mmol) was added to a solution of palladium acetate (0.51 g, 2.27 mmol) in acetic acid (12 mL) and the reaction mixture was heated to 100 °C for 2 h. Once cooled to room temperature DCM (10 mL) and then water (10 mL) were added. The layers were separated and two more portions of DCM were used to extract the product. The combined organic extracts were washed with water and brine, dried ($MgSO_4$), filtered and the filtrate concentrated. The residue was crystallised from DCM/petroleum ether to give the product.

2.4.1. Di(μ-aceto)bis[8-methylquinoline]dipalladium (2a). 8-Methylquinoline (0.34 mL) was reacted by the general procedure. The product (1.11 g, 72% yield) was obtained as orange prisms as a 4:1 mixture of trans and cis-isomers. mp >200 °C. Found: C, 47.20; H, 3.80, N, 4.30; $C_{24}H_{22}N_2O_4Pd_2$ requires C, 46.90; H, 3.60; N, 4.60%, δ_H (250 MHz): 2.11 (6H, s, Me), 2.52 (2H, d, J=13.8 Hz, CH_2), 3.43 (2H, d, J=13.8 Hz, CH_2), 6.69 (2H, dd, J=1.1, 7.1 Hz, ArH), 6.88 (2H, t, J=7.2 Hz, ArH), 6.97–7.03 (2H, m, ArH), 7.21–7.22 (2H, m, ArH), 7.85 (2H, dd, J=1.4, 8.3 Hz, ArH), 8.51 (2H, dd, J=1.4, 5.0 Hz, ArH), *m/z* (%) (FAB): 616 (M^+, 23), 557 (37), 458 (19), 414 (69), 389 (41), 354 (49), 248 (100), 142 (73), ν_{max}/cm^{-1} (GG): 1412.1 (m, C=N), 1504.7 (s, aromatic ring), 1568.3 (s, aromatic ring).

2.4.2. Di(μ-aceto)bis[5-nitro-8-methylquinoline]dipalladium (2b). 5-Nitro-8-methylquinoline (0.47 g) was reacted by the general procedure. The product (1.20 g, 68% yield) was obtained as black prisms as a 2.3:1 mixture of trans and cis-isomers. mp >200 °C. Found: C, 41.70; H, 2.85; N, 8.20; $C_{24}H_{20}N_4O_8Pd_2$ requires: C, 41.85; H, 2.85; N, 7.95%, δ_H (300 MHz): 2.15 (6H, s, Me), 2.36 (2H, d, J=15.0 Hz, CH_2), 3.56 (2H, d, J=15.0 Hz, CH_2), 6.75 (2H, d, J= 8.0 Hz, ArH), 7.60 (2H, dd, J=5.0, 8.8 Hz, ArH), 7.85 (2H, d, J=8.0 Hz, ArH), 8.71 (2H, dd, J=1.3, 5.0 Hz, ArH), 8.97 (2H, dd, J=1.3, 8.8 Hz, ArH), *m/z* (%) (FAB): 706 (M^++H, 18), 647 (23), 295 (27), 189 (52), 149 (100), ν_{max}/cm^{-1} (GG): 1336.8 (s, CNO_2), 1414.0 (s, C=N), 1502.7 (s, CN=O), 1505.8 (m, aromatic ring), 1568.3 (s, CNO_2), 1570.4 (s, aromatic ring).

2.4.3. Di(μ-aceto)bis[5-fluoro-8-methylquinoline]dipalladium (2c). 5-Fluoro-8-methylquinoline (0.40 g) was reacted by the general procedure. The product (1.16 g, 71% yield) was obtained as orange prisms as a 4:1 mixture of trans and cis-isomers. mp >200 °C. Found: C, 44.05; H, 3.40; N, 4.15; $C_{24}H_{20}F_2N_2O_4Pd_2$ requires: C, 44.25; H, 3.10; N, 4.30%, δ_H (300 MHz): 2.13 (6H, s, Me), 2.44 (2H, d, J=14.8 Hz, CH_2), 3.48 (2H, d, J=14.8 Hz, CH_2), 6.61–6.80 (4H, m, ArH), 7.34 (2H, dd, J=5.1, 8.6 Hz, ArH), 8.13 (2H, dd, J=1.2, 5.1 Hz, ArH), 9.06 (2H, d, J=8.6 Hz, ArH), *m/z* (%) (FAB): 651 (M^+, 8), 591 (10), 391 (100), 326 (37), 279 (27), 266 (50), ν_{max}/cm^{-1} (GG): 1140.1 (m, C–F), 1408.2 (m, C=N), 1475.7 (w, aromatic ring), 1570.2 (m, aromatic ring).

2.4.4. Di(μ-aceto)bis[5-trifluoromethyl-8-methylquinoline]dipalladium (2d). 5-Trifluoromethyl-8-methylquinoline (0.53 g) was reacted by the general procedure. The product (1.41 g, 75% yield) was obtained as red prisms as a 2.3:1 mixture of trans and cis-isomers. mp >200 °C. Found: C, 41.45; H, 2.75; N, 3.55, $C_{26}H_{20}F_6N_2O_4Pd_2$ requires: C, 41.55; H, 2.70; N, 3.75%, δ_H (300 MHz): 2.15 (6H, s, Me), 2.36 (2H, d, J=14.6 Hz, CH_2), 3.48 (2H, d, J=14.6 Hz, CH_2), 6.67 (2H, d, J=7.6 Hz, ArH), 7.26–7.27 (2H, m, ArH), 7.48 (2H, dd, J=5.0, 8.7 Hz, ArH), 8.28 (2H, d, J=8.7 Hz, ArH), 8.67 (2H, dd, J=1.3, 5.0 Hz), *m/z* (%) (FAB): 752 (M^++H, 13), 693 (19), 524 (24), 421 (27), 391 (23), 315 (100), 210 (29), 149 (29), ν_{max}/cm^{-1} (GG): 781.3 (m, C–F), 884.9 (m, aromatic ring), 1317.5 (s, C–F), 1414.0 (m, C=N), 1510.4 (m, aromatic ring), 1570.2 (s, aromatic ring).

2.4.5. Di(μ-aceto)bis[5-methoxy-8-methylquinoline]dipalladium (2e). 5-Methoxy-8-methylquinoline (0.43 g) was reacted by the general procedure. The product (1.25 g, 74% yield) was obtained as orange prisms as a 9:1 mixture of trans and cis-isomers. mp >200 °C. Found: C, 46.05; H, 4.10; N, 3.90; $C_{26}H_{26}N_2O_6Pd_2$ requires C, 46.20; H, 3.90; N, 4.10%, δ_H (300 MHz): 2.13 (6H, s, Me), 2.47 (2H, d, J=12.4 Hz, CH_2), 3.35 (2H, d, J=12.4 Hz, CH_2), 3.85 (6H, s, OMe), 6.28 (2H, d, J=7.9 Hz, ArH), 6.57 (2H, d, J=7.9 Hz, ArH), 7.17 (2H, dd, J=5.0, 8.4 Hz, ArH), 8.17 (2H, dd, J=1.4, 8.4 Hz, ArH), 8.53 (2H, dd, J=1.4, 5.0 Hz, ArH), *m/z* (%) (FAB): 675 (M^+, 9), 616 (15), 448 (24), 278 (37), 172 (100), 149 (47), ν_{max}/cm^{-1} (GG): 771.6 (m, aromatic ring), 806.3 (aromatic ring), 1479.6 (m, C=N), 1574.1 (s, aromatic ring), 1614.6 (m, aromatic ring), 2841.6 (w, O–Me).

2.4.6. Di(μ-acetato)-bis[(2,4,5,8-tetramethylquinoline)]dipalladium (2f). 2,4,5,8-Tetramethylquinoline (0.93 g, 5.0 mmol) was reacted by the general procedure. The product (1.1 g, 68%) was obtained as a yellow amorphous solid, mp 160 °C (dec.), which comprised a ca. 6:1 mixture of trans and cis-isomers. Found: C, 51.70; H, 5.05; N, 3.70; $C_{30}H_{34}N_2O_4Pd_2$ requires C, 51.60; H, 4.90; N, 4.00%. δ_H (300 MHz, $CDCl_3$) 1.92* (6H, s, 2Me), 2.01 (6H, s, 2Me), 2.08*, 2.1*, 2.3* (3×6H, 3×s, 3×2Me), 2.6, 2.65, 2.67 (3×6H, 3×s, 3×2Me), 2.8 (2H, d, J=13.5 Hz, CH_2), 3.26* (2H, d, J=12.1 Hz, CH_2), 3.53 (2H, d, J=13.5 Hz, CH_2), 3.7* (2H, d, J=12.1 Hz, CH_2), 6.5–6.6 (4H, br, ArH), 6.75* (2H, s, ArH), 6.8 (2H, s, ArH, *indicates minor isomer. *m/z* (FAB): 704–694 (M^+, Pd isotope cluster, 700, 10%), 643 (7), 473 (15), 395 (20), 292 (65), 184 (100), 123 (65) and 105 (73). ν_{max}/cm^{-1} (solid) 3055, 2978, 2933, 2888, 1694, 1575, 1417, 1276, 1261, 1032, 851, 824, 763, 750 and 726.

2.4.7. Di(μ-acetato)-bis[(7-fluoro-2,4,8-trimethylquinoline)]dipalladium (2g). 7-Fluoro-2,4,8-trimethylquinoline (0.75 g, 4.0 mmol) was reacted by the general procedure. The product (0.40 g, 60%) was obtained as a yellow amorphous solid, mp 165 °C (dec.), which comprised a ca. 7: 1 mixture of trans and cis-isomers. Found: C, 47.90; H, 4.05; N, 3.70; $C_{28}H_{28}N_2O_4F_2Pd_2$ requires C, 47.60; H, 4.00; N, 4.00%. δ_H (300 MHz, $CDCl_3$) 2.0, 2.4 (2×6H, 2×s, 2×2Me), 2.65 (2H, d, J=13.8 Hz, CH_2), 2.7 (6H, s, 2Me), 2.9* (2H, d, J=13.3 Hz, CH_2), 3.2 (2H, d, J=13.8 Hz, CH_2) 3.5* (2H, d, J=13.3 Hz, CH_2), 6.6 (2H, t, J=8.7 Hz, ArH^c) (J H^c–$H^b \approx J$ H^c–^{19}F), 6.7* (2H, t, J=8.7 Hz, ArH^c) (J H^c–$H^b \approx J$ H^c–^{19}F), 6.9 (2H, s, ArH^a), 6.95* (2H, s, ArH^a), 7.1 (2H, dd, J=8.7, 5.1 Hz, ArH^b, H^b couples with H^c and F), 7.15* (2H, dd, J=8.70, 5.1 Hz, ArH^b, H^b couples with H^c and F). *Indicates minor isomer. *m/z* (FAB): 712–702 (M^+, Pd isotope cluster, 707, 10%), 648 (15), 413 (28), 391 (40), 294 (41), 188 (35), 167 (25), 149 (100), 132 (52) and 113 (25). ν_{max}/cm^{-1} (solid) 2988, 2918, 2883, 1718, 1583, 1514, 1407, 1275, 1261, 1099, 1043, 863, 812, 764 and 750.

2.4.8. Di(μ-acetato)-bis[(2,4,7,8-tetramethylquinoline)]dipalladium (2h). 2,4,7,8-Tetramethylquinoline (0.93 g, 5.0 mmol) was reacted by the general procedure. The product (1.1 g, 68%) was obtained as a yellow amorphous solid, mp 147 °C (dec.), which comprised a ca. 6.5:1 mixture of trans and cis-isomers. Found: C, 51.70; H, 4.85; N, 4.00; $C_{30}H_{34}N_2O_4Pd_2$ requires C, 51.60; H, 4.90; N, 4.00%. δ_H (300 MHz, $CDCl_3$) 1.95* (6H, s, 2Me), 2.0, 2.05 (2×6H, 2×s, 2×2Me), 2.1*, 2.15* (2×6H, 2×s, 2×2Me), 2.35 (6H, s, 2Me), 2.4* (6H, s, 2Me), 2.7 (6H, s, 2Me), 2.8 (2H, d, J=13.3 Hz, CH_2), 3.25* (2H, d, J=12.8 Hz, CH_2), 3.35 (2H, d, J=13.3 Hz, CH_2), 3.6* (2H, d, J=12.8 Hz, CH_2), 6.5* (2H, s, ArH), 6.7 (2H, d, J=8.7 Hz, ArH), 6.75 (2H, s, ArH), 6.95 (2H, d, J=8.7 Hz, ArH), 7.0* (2H, d, J=8.2 Hz, ArH), *indicates minor isomer. *m/z* (FAB): 704–694 (M^+, Pd isotope cluster, 700, 10%), 641 (25), 557 (22), 395 (16), 292 (67), 184 (100) and 115 (12). ν_{max}/cm^{-1} (solid) 3051, 2973, 2925, 2855, 1704, 1583, 1519, 1411, 1344, 1175, 1066, 1027, 856, 779 and 720.

2.4.9. Di(μ-acetato)-bis[(5-methoxy-2-trifluoromethyl-4,8-dimethyl quinoline)]dipalladium (2i). 5-Methoxy-4,8-dimethyl-2-(trifluoromethyl)quinoline (0.25 g, 1.0 mmol) was reacted by the general procedure. The product (0.42 g, 50%) was obtained as a orange amorphous solid, mp 157 °C (dec.), which comprised a ca. 12:1 mixture of trans and cis-isomers. Found: C, 42.60; H, 3.45; N, 3.10; $C_{30}H_{28}N_2O_6F_6Pd_2$ requires C, 42.90; H, 3.35; N, 3.30%. δ_H (300 MHz, $CDCl_3$) 2.0 (6H, s, 2Me), 2.1* (6H, s, 2Me), 2.73 (2H, d, J=12.5 Hz, CH_2), 2.85 (6H, s, 2OAc), 2.9* (6H, s, 2OAc), 3.33* (2H, d, J=12.5 Hz, CH_2), 3.47 (2H, d, J=12.5 Hz, CH_2) 3.73* (2H, d, J=12.5 Hz, CH_2), 3.79* (6H, s, 2OMe), 3.82 (6H, s, 2OMe), 6.38 (2H, d, J=8.1 Hz, ArH), 6.63 (2H, d, J=8.1 Hz, ArH), 6.98* (2H, d, J=8.5 Hz, ArH), 7.15* (2H, d, J=8.5 Hz, ArH), 7.42 (2H, s, ArH), 7.62* (2H, s, ArH), *indicates minor isomer. *m/z* (FAB): 844–832 (M^+, Pd isotope cluster, 839, 7%), 780 (13), 610 (8), 525 (14), 465 (17), 359 (35) and 254 (100).

ν_{max}/cm^{-1} (solid) 2951, 2887, 2849, 1708, 1675, 1612, 1575, 1515, 1472, 1403, 1342, 1327, 1166, 1141, 1087, 975, 948, 828, 751 and 685.

2.4.10. General procedure for the Heck reaction. Palladacycle (**2a–j**) was added to a stirred solution of iodobenzene or 4-bromoacetophenone (1.0 mmol), *n*-butylacrylate (2.0 mol equiv) or benzyl acrylate (2.0 mol equiv) and metal acetate (2.0 mol equiv) or potassium carbonate (2.0 mol equiv) in DMF (GPR grade 10 mL). The reaction mixture was heated at 140 °C (oil bath) for 16–96 h (see Table 1). After cooling to room temperature water (10 mL) was added and the mixture extracted with ether (2×20 mL). The combined organic layer was washed with water (2× 20 mL), dried ($MgSO_4$), filtered and the filtrate evaporated under reduced pressure to give the crude product as a light yellow oil. The conversion was determined by ^{1}H NMR spectroscopy comparing the ratio of the integrals of iodobenzene (7.1 ppm, 2H, t, J=7.5 Hz, ArH) or 4-bromoacetophenone (2.6 ppm, 3H, s, MeC=O) and that of butyl (2*E*)-3-phenylacrylate (4.21 ppm, t, 2H, J=6.6 Hz, OCH_2; 6.44 ppm, 1H, d, J=16.0 Hz, PhCH=C*H*; 7.7, 1H, d, J= 16.0 Hz, PhC*H*=CH) or that of butyl (2*E*)-3-(4-acetylphenyl)acrylate (2.62 ppm, s, 3H, MeC=O; 4.22 ppm, t, J=6.6 Hz, 2H, OCH_2; 6.53 ppm, 1H, d, J=16.0 Hz, PhCH=C*H*; 8.0 ppm, 1H, d, J=16.0 Hz, PhC*H*=CH).

2.5. General procedure for termolecular cascade involving arylhalide, allene and *N*-nucleophiles

A mixture of palladacycle (**2d**, **e** or **2i**) (0.25–1.0 mol%), iodobenzene or 4-bromoacetophenone (0.20 g, 1.0 mmol), morpholine or piperidine (1.2 mol equiv) and potassium carbonate (0.27 g, 2.0 mol equiv) in DMF (GPR grade, 10 mL) was stirred for 15 min in a Schlenk tube. The mixture was then degassed, frozen, evacuated and filled with allene gas (1 bar). After warming to room temperature, it was heated at 80–120 °C (Table 4) in an oil bath for 24 h. The reaction mixture was cooled to room temperature, excess allene vented, water (10 mL) added and the mixture extracted with ether (2×20 mL). The combined organic layer was washed with water (2×20 mL), dried ($MgSO_4$), filtered and the filtrate evaporated under reduced pressure. The residue was purified by column chromatography on silica gel.

2.5.1. 1-(2-Phenylprop-2-enyl)piperidine (3a). Synthesised by the general procedure from iodobenzene (0.21 g, 1.0 mmol), piperidine (0.12 mL, 1.2 equiv) and allene (1 bar). Purification by column chromatography eluting with 9:1 v/v petroleum ether–EtOAc gave the product (0.17 g, 92%) (R_f 0.11) as a colourless oil. δ_H (300 MHz, $CDCl_3$) 1.4–1.45 (2H, m, piperidinyl H), 1.5–1.6 (4H, m, piperidinyl H), 2.35–2.4 (4H, m, piperidinyl H), 3.3 (2H, d, J=0.8 Hz, CH_2), 5.25 (1H, d, J=1.5 Hz, C=CH_2), 5.45 (1H, d, J=1.5 Hz, C=CH_2), 7.2–7.45 (3H, m, ArH), 7.5 (2H, dd, J=6.70, 1.60 Hz, ArH), *m/z* (EI) 177 (100%, M^+).

The ^{1}H NMR and mass spectroscopic data of the compound **3a** are in full agreement with those reported in the literature.[29]

2.5.2. 4-(2-Phenylprop-2-enyl)morpholine (3b). Synthesised by the general procedure from iodobenzene (0.21 g, 1.0 mmol), morpholine (0.11 mL, 1.2 equiv) and allene (1 bar). Purification by column chromatography eluting with 4:1 v/v petroleum ether–Et_2O gave the product (0.15 g, 75%) (R_f 0.10) as a colourless oil. δ_H (300 MHz, $CDCl_3$) 2.45–2.5 (4H, m, morpholinyl H), 3.0 (2H, d, J= 0.8 Hz, CH_2), 3.65–3.7 (4H, m, morpholinyl H) 5.25 (1H, d, J=1.4 Hz, C=CH_2), 5.5 (1H, d, J=1.4 Hz, C=CH_2), 7.25–7.35 (3H, m, ArH), 7.55 (2H, dd, J=7.5, 1.0 Hz, ArH), *m/z* (EI) 203 (17%, M^+), 144 (13), 118 (48), 100 (100), 91 (24), 77 (7), 56 (30), and 42 (21).

The ^{1}H NMR and mass spectroscopic data of the compound **3b** are in full agreement with those reported in the literature.[29]

2.5.3. 1-{4-[1-(Morpholin-4-ylmethyl)vinyl]phenyl}ethanone (3c). Synthesised by the general procedure from 4-bromoacetophenone (0.20 g, 1.0 mmol), morpholine (0.11 mL, 1.2 equiv) and allene (1 bar). Purification by column chromatography eluting with 4:1 v/v petroleum ether–Et_2O gave the product (0.18 g, 73%) (R_f 0.08) as a colourless oil. δ_H (300 MHz, $CDCl_3$) 2.45–2.50 (4H, m, morpholinyl H), 2.6 (3H, s, Me), 3.35 (2H, d, J=0.6 Hz, CH_2), 3.65–3.7 (4H, m, morpholinyl H) 5.35 (1H, d, J= 1.1 Hz, C=CH_2), 5.6 (1H, d, J=1.1 Hz, C=CH_2), 7.6 (2H, d, J=8.5 Hz, ArH), 7.9 (2H, d, J=8.5 Hz, ArH), *m/z* (EI) 245 (26%, M^+), 186 (15), 160 (20), 145 (37), 115 (47), 100 (100), and 56 (50).

The ^{1}H NMR and mass spectroscopic data of the compound **3c** are in full agreement with those reported in the literature.[29]

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